Fault detection during the impulse testing of transformers

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FAULT DETECTION DURING THE IMPULSE TESTING

OF

TRANSFORMERS

By

E.G. Williams

A thesis submitted to the University of New South Wales for the Degree of Master of Engineering.

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24th June, 1959.

DECLARATION

I certify that the work described in this thesis has not been submitted to any other University or Institution for a Higher Degree.

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24th June, 1959.

SUMMARY

The thesis describes an investigation of the fault detection methods which can be used during high voltage impulse tests on transformers. The objects of the investigation are to:-

(a) provide an assessment of the relative merits of different methods.

(b) develop improved methods or combinations of methods.

(c) provide a comprehensive source of technical information for chartered engineers engaged in the introduction of the impulse testing of transformers to Australia, thereby facilitating some measure of standardisation in testing techniques.

The fundamental bases of fault detection are explored and the subsequent conclusions confirmed by experiments. The equivalent network for a two-winding transformer is the starting point for the initial theoretical examination. The voltage and current equations are considered and the difficulties of deriving the inductive parameters studied.

The modified transmission line reasoning used by Dr. Ganger[27] is described and a simpler fundamental theory developed.

This fundamental theory forms the basis for the first experiment in Part 2. In this experiment a

Summary continued...

simple transformer winding with movable earth plane and core is used to obtain oscillographic evidence of the fundamental behaviour of winding currents generated during an impulse test.

The recurrent surge generator and associated equipment used in the experiment are described. This experimental determination of the fundamental behaviour confirms the conclusions previously determined from theoretical considerations. Both full and chopped wave test conditions are considered.

The optimum connexions to be used during an impulse test are thoroughly examined in view of the important relationship between this type of high voltage test and service conditions.

Recurrent surge experiments and full scale tests are described for three classes of transformers, namely:-

(a) Voltage transformers and distribution transformers up to 50 kVA.

(b) Distribution transformers to 1,000 kVA

(c) Power transformers.

From these experiments and tests, detailed observations are made on such matters as the fault detection sensitivities obtainable, the effect of winding construction, the use of the tank current for fault location purposes, practical difficulties of high voltage impulse testing and deficiencies revealed in full scale test reports from overseas laboratories.

The nature of physical indications of failure and their value are examined. A device used for detecting shock waves generated by a fault is described.

The thesis concludes with a summary of its findings and with impulse testing recommendations. Aspects requiring further investigation are outlined.

The joint paper published by and presented to the Institution of Engineers, Australia, as a progress report on this work, is contained in an appendix, together with the resulting discussion. Section 2 of this paper, dealing with "Development and Construction of Recurrent Surge Generators", is due to Dewsnap. The balance of the paper, Sections 3 to 6 inclusive, are the work of the author of this thesis.

Several other appendices of interest are also included at the end of the thesis. An index is provided to facilitate reference to the many different aspects of the subject.

C O N T E N T S

CONTENTS - Continued.

CONTENTS - Continued.

LIST OF ILLUSTRATIONS

List of Illustrations, continued.

TABLE 1: KEY TO SYMBOLS & ABBREVIATIONS.

R,R'	- Wire resistance of each section of primary or secondary winding.
L,L'	- Self-inductance of each section of primary or secondary winding.
Le	- Equivalent self-inductance per section.
M',M'',M'''	- Mutual inductance between sections.
Cg,Cg'	- Capacitance of primary or secondary section to earth.
Cs,Cs'	- Capacitance between adjacent sections of primary or secondary winding.
C''	- Capacitance between primary and secondary sections.
G,G',G''	- Conductances between sections.
n	- Number of turns.
	- Length of winding (metres)
Cge	- Equivalent capacitance of a section to earth.
Cse	- Equivalent capacitance between sections.
N	- Total number of sections in the network.
t	- Time (microseconds).
V_{LV}	- Voltage at low voltage winding terminal with respect to earth.
V_{HV}	- Voltage at high voltage winding terminal with respect to earth.
V_L	- Applied surge (line voltage)
I_L	- Current entering transformer line terminal, i.e. line current.
I_{NC}	- Current leaving winding under test, i.e. neutral current.
I_T	- Tank current, i.e. $I_L - I_{NC}$.
X	- Relative distance from beginning of winding under test.
N.F.	- No fault.
S.F.	- Solid fault, i.e. a low resistance path exists before application of test voltage.
Sp.F.	- "Sparking" fault, i.e. the arc path is through insulation ruptured by the test voltage subsequent to the wave front.
v(mt)	- Voltage at the beginning of the (m+1)th section at time t.
m	- Typical section of the network.
K	- An integer.

INTRODUCTION.

The impulse testing of high voltage power system equipment has become increasingly important as greater knowledge has been gained of the effect of lightning or switching surges in service. The voltage distribution through a transformer winding during the passage of a voltage surge may be quite different to the distribution for power frequency voltages, and most purchasers of transformers now require impulse voltage tests to prove the ability of a transformer to withstand transient voltage stresses. It has always been appreciated by supply authorities and manufacturers that these tests must be supported by adequate fault detection methods to ascertain whether any dielectric failure has occurred during the test, such as will affect the service life of the transformer.

The equipment and methods associated with impulse testing have been well described in the literature (Ref. 1, 2, 32). Since the duration of an impulse test is only approximately 0.001 second, determination of the voltage applied and whether or not failure occurred presents greater difficulties than is the case in most other forms of high voltage tests. Experience over the last two decades has shown that the most reliable indication of the occurrence during an impulse test of one or more of the many types of possible transformer winding failures, is an electrical indication usually recorded on some type of high-speed oscillograph.

The objects of the thesis are:

(a) to provide an assessment of the relative merits of different methods from a thorough understanding of each.

(b) to develop improved methods or combinations of methods.

(c) to provide a comprehensive source of technical information for electrical engineers and technicians engaged in the introduction of the impulse testing of transformers to Australia, thereby facilitating some measure of standardisation in testing techniques.

In view of the practical difficulty of finding physical damage caused by an impulse test failure, attention is also given to oscillographic methods of fault location.

Since it has been previously established (Ref. 4) that apart from insulation failure, a transformer winding is practically a linear circuit for periods up to a few hundred microseconds, extensive use is made of recurrent surge techniques. The recurrent surge generator applies a low voltage surge with a repetition rate such that the transient voltage traces can be continuously viewed on the cathode ray tube.

The theory of fault detection is considered immediately so that experiments described later can be critically examined and the results correctly analysed. Although only full wave testing is considered the fundamental treatment enables chopped wave testing to be examined later.

PART 1 - FAULT DETECTION THEORY.

Most theoretical studies of the transient behaviour of transformer windings have been concerned with the voltage distribution since this must be known by the designer. Bewley's fundamental approach (Ref. 8) represents the most comprehensive work on the subject but Lewis' recent contribution (Ref. 9) has clarified many aspects of the voltage distribution equations. Lewis throws grave doubts upon the validity of Rudenberg's work (Ref. 7).

The major obstacle to the more general use of mathematics in problems concerning the transient behaviour of transformer windings is the work involved in deriving the equivalent ladder network for any particular design. This aspect of the theory is now considered.

1.1 The Equivalent Ladder Network.

The complete idealised circuit of a single phase transformer with only two windings is given in Fig. 1(a). Although this complete representation is too cumbersome for mathematical treatment it is the first stage in deriving an equivalent network.

For mathematical analysis the ideal network is reduced to the simplified equivalent shown in Fig. 1(b). The resistance and leakage conductance values are omitted for two reasons:

(a) The resulting expressions for voltage and current distributions would be too cumbersome for practical use to be made of them.

(b) The error resulting by neglect of the resistance and conductance values provides a safety factor in design calculations since the results are pessimistic.

The mutual inductance between sections of the winding is included in the equivalent inductance per section (Le). Derivation of the latter parameter is the most difficult aspect of this approach. The assumption that flux linkages may be accounted for by a uniformly distributed self-inductance, as in transmission line theory, proves entirely inadequate. The mutual inductance between parts of the same winding plays an important and essential part in the phenomenon. Bewley (Ref. 8) established that an assumption of linearly graded mutual inductance between parts of the winding yields the essential characteristics of the transient and is simple to handle mathematically. More recent investigations (Ref. 37) have established more accurate relationships.

It is important to establish a conception of the equivalent inductance per section (Le) and to see where it differs from the power frequency leakage inductance for the whole winding. Lewis (Ref. 9) points out that when iron is present the flux path will not necessarily be that which is present under normal low-frequency conditions in which the path is confined mainly to the iron. In fact with rapid transient conditions the flux is most likely to be confined to iron-free paths by the presence of eddy currents which considerably reduce the flux-carrying properties of the iron. Thus the flux lines now centre round the conductors themselves, and for the high frequency components the iron tends to act more and more as an earthed boundary.

The result is that the mutual inductance between sections will be considerably smaller than that operating at low frequencies and is likely to decrease rapidly as the distance between sections increases. This fact is confirmed later by experiment.

Fig. 2 illustrates the difference in the leakage fields for

(a) an oscillation within the winding with neutral earthed and the line terminal connected to a transmission line.

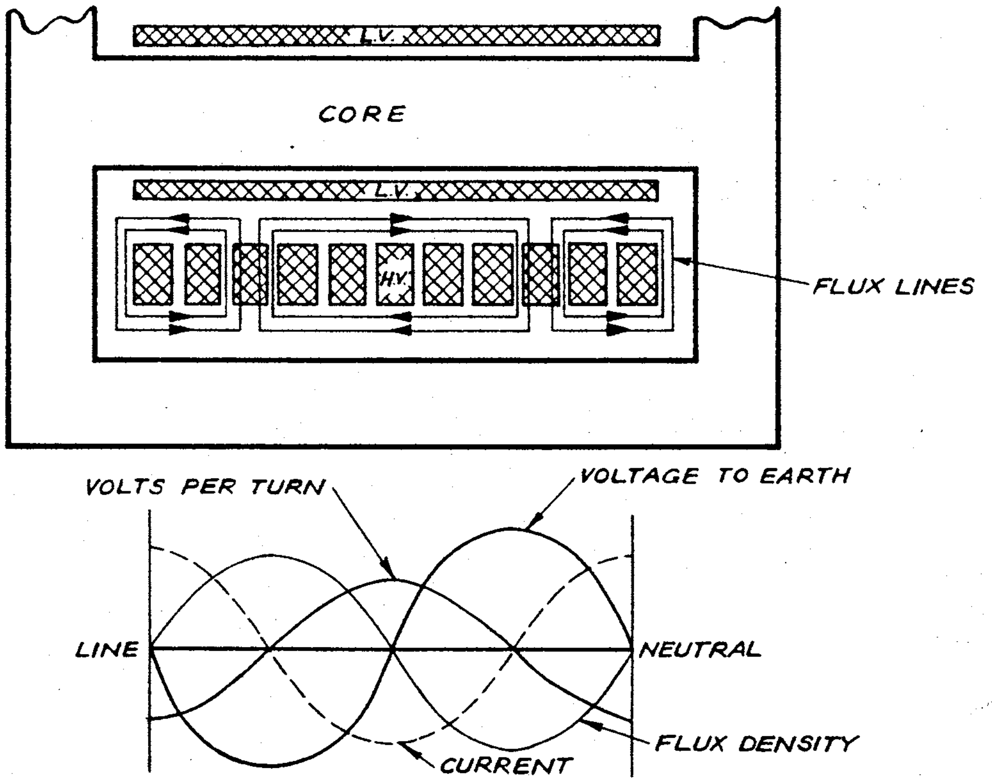
(b) power frequency conditions - neutral earthed.

It is correct to use the high-frequency oscillation conception since in any mathematical analysis of impulse phenomena in ladder networks, the parameter Le is used in expressions for the sinusoidal components of the impulse voltage and currents. Mathematical analyses for design purposes are usually only concerned with the first fifty microseconds. On the other hand during a 1 x 50 microsecond impulse test one has to allow for a gradual change in the leakage field conditions as the high frequency components decrease leaving a predominant inductive current component which may persist for 200 microseconds. During the late stages of the test the leakage field distribution would approach that for the power frequency conditions.

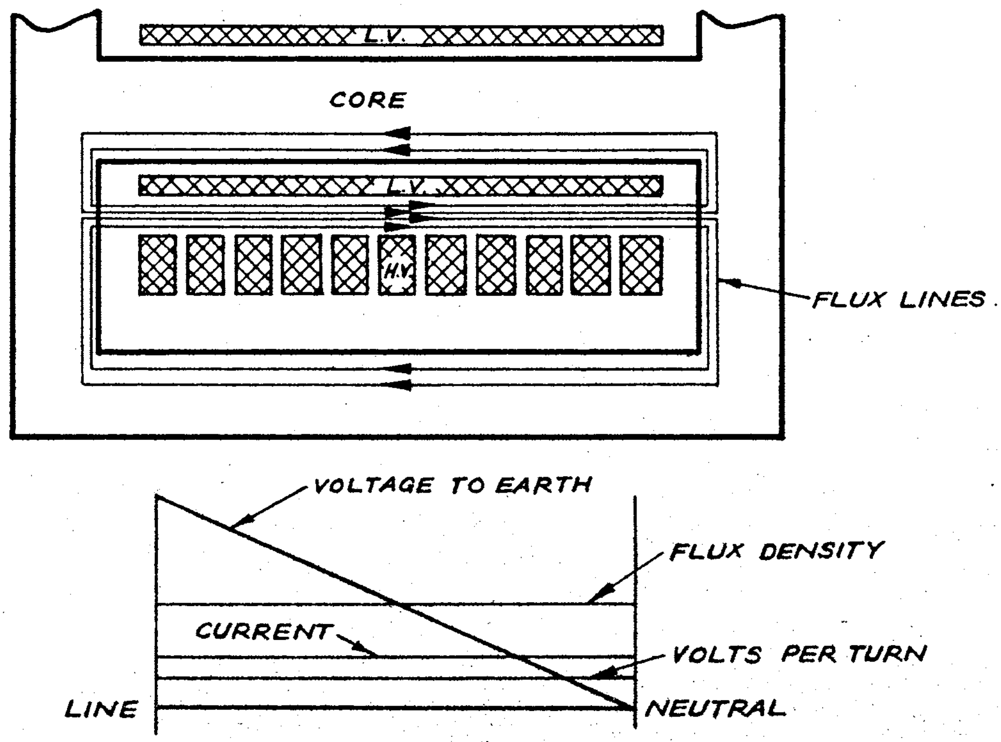
An approximate expression for disc type windings when the radial depth is comparable to the wave length of the frequency being considered, has been derived by Bewley (Ref. 8) and Blume and Boyajian (Ref. 3). This expression is:

$$L_e = \frac{0.4\, n^2 \lambda^3\, (MLT)}{10^8 hN}$$

where L_e = Equivalent self-inductance per section and includes mutual inductance effects between sections.



(a) IMPULSE TEST CONDITIONS - AN OSCILLATION WITHIN THE WINDING WITH NEUTRAL EARTHED & LINE TERMINAL CONNECTED TO A TRANSMISSION LINE.



(b) POWER FREQUENCY CONDITIONS - NEUTRAL EARTHED.

FIG: 2 LEAKAGE FIELD CONCEPTIONS UNDER IMPULSE AND POWER FREQUENCY TEST CONDITIONS.

n = total turns in winding

l = length of winding

MLT= Mean length of turn

$2h$ = length of leakage path (in air)

N = total number of sections in the equivalent network.

A new method has been recently developed by Abetti and Maginnis (Ref. 13,35). All mutual inductance linkages are taken into account for the first time and the fundamental basis of the problem is thoroughly examined. An important empirical relationship between the inductive characteristics of any transformer winding and a uniform, single-layer, helical air-cored coil is established.

Fig. 3 shows that the inductance characteristics of any air-cored coil can be completely identified by the ratio of the measured inductance of a portion of the coil to the measured inductance of the whole coil. By obtaining a similar ratio for a transformer winding by measurements, Abetti and Maginnis determine an equivalent air-cored coil whose inductive characteristics are employed in a rigorous solution of the transient behaviour of the original transformer winding. The natural frequencies determined were checked by measurements with recurrent surge equipment. Agreement is excellent for the first two harmonics of the experimental transformer winding, that is, up to 20Kc in the case quoted.

The calculations were based on the fundamental matrix equations for the ladder network and were made both by a punched card computer and an A.C. Network Analyser.

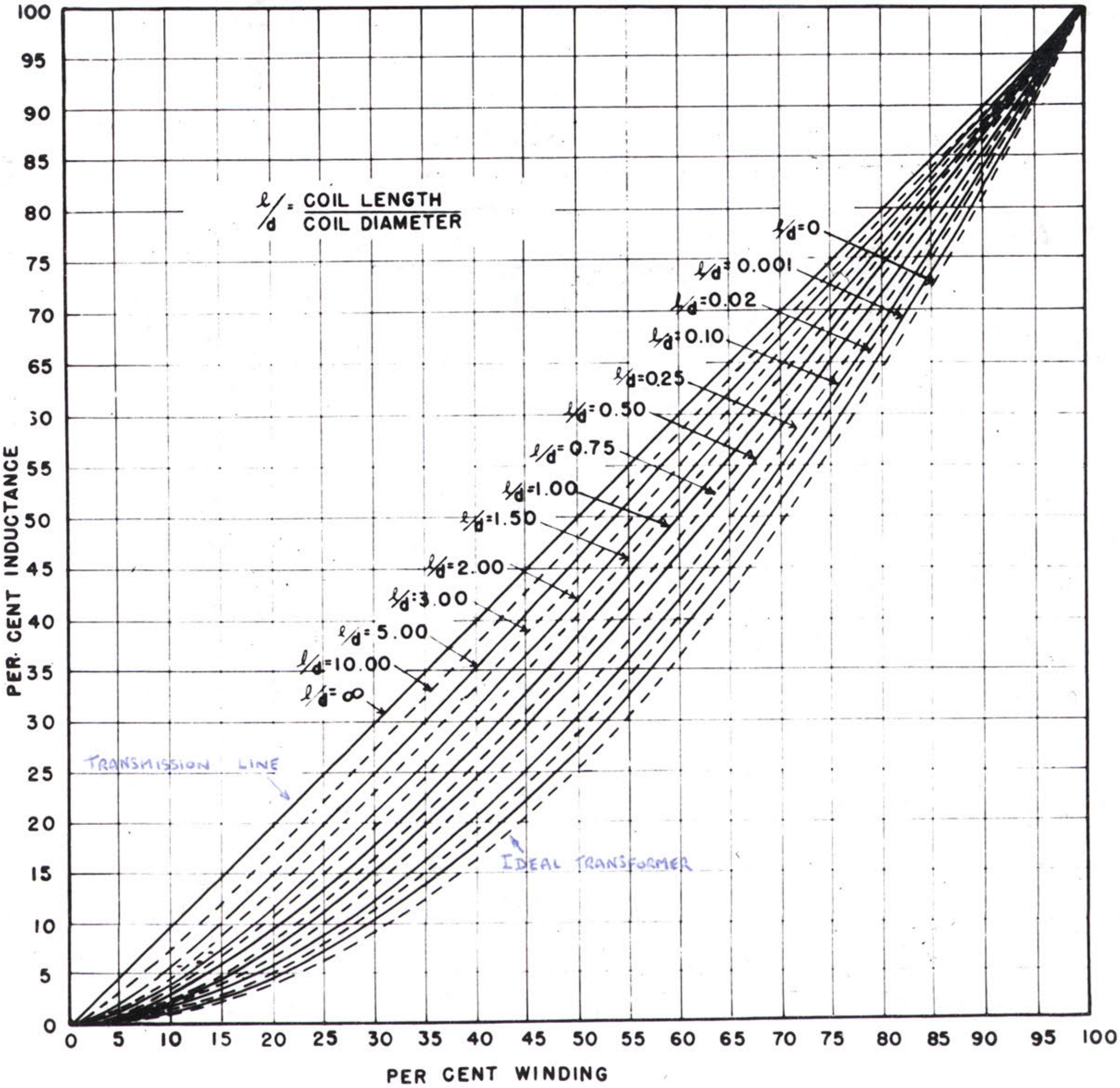


Fig.3 - Inductance functions of portions of air-cored coils with uniform single-layer helical windings.

In view of the fact that the latter method is based on an empirical relationship and that the inductive characteristics of the experimental transformer were obtained by measurements at low frequency, it is understandable that fairly large errors arose above 20Kc. Nevertheless the method offers the most accurate solution yet to the complex task of deriving the inductance parameters of the equivalent ladder network.

Further work along similar lines in England (Ref. 38) and Switzerland (Ref. 37) indicate the value of the approach. Waldvogel and Rouxel (Ref. 37) describe how to both calculate and measure the inductive and capacitive parameters. They derive mutual inductance coefficients between the various sections of the winding. It is interesting to note that when measuring these coefficients and the self-inductance values, the frequency of 16 Kcs was found to be the most satisfactory. This frequency was high enough to produce the full skin effect but sufficiently low to ensure that the electromagnetic phenomena were not disturbed by internal capacitances. During the tests it was found that the first natural frequency of the winding section (6 disc coils in series, each of 15 turns with a mean length of turn of 81 inches) was, in fact, 120 Kcs.

In the calculation of the self and mutual inductances, Waldvogel and Rouxel (Ref. 37) treat the winding as if it contained no iron, assuming that the low voltage winding screens the core from the magnetic field. This assumption would hold for distribution transformers but it is likely to be erroneous for power transformers having disc type low voltage windings rated at 33 kV or above.

The simple equivalent capacitance values shown in Fig. 1(b) are obtained by successive reductions of the actual capacitive network of the winding. This is obtained from knowledge of the conductor and insulation dimensions, the dielectric constants of the insulating materials and the arrangement of the windings relative to each other and earthed metal.

Certain simplifying assumptions are made during this reduction, viz:

(a) The secondary winding can be regarded as an earthed plane.

OR

The secondary winding must be represented in detail and the core taken as the earthed plane.

(b) The series capacitence between turns of a section of the winding (e.g. a disc section) is lumped into two or three equivalent capacitances.

(c) The shunt capacitance of each turn in a section is represented by a single capacitance to earth for that section......and so on.

Assumption (a) is dependent on the rated voltage of the secondary winding.

To illustrate the detailed steps involved, an equivalent capacitance network for portion of a 60 MVA 132/66 kV transformer winding is derived in Appendix 4.2. This derivation is not original, having been developed by the transformer design department of a large British Manufacturer. The author served a graduate apprenticeship with this company from 1949 to 1951 and spent several months in the transformer design department.

1.2 Voltage Distribution

The initial voltage distribution through the windings is governed solely by the capacitance network, since the inductive parameters present an extremely high impedance to the front of the applied wave. In practice the period of the initial voltage distribution is normally the first microsecond of the test. During this time the capacitance network is charged to the peak value of the applied wave.

The behaviour of the winding subsequent to this period is best revealed by the equations for the voltage distribution in a ladder-type network subjected to a unit [redacted] function voltage (Ref. 9). The Laplace transformation of the equivalent network shown in Fig. 1 (b) is used to derive the following standing wave solution for grounded neutral conditions:

$$v(mt) = 1 - \frac{m}{N} - \sum_{k=1}^{N} A_k \cos W_{ak} t$$

$$\text{where } W_{ak} = 2 \sin \frac{k\pi}{2N} \Big/ \left(L_e C_g + 4 L_e C_s \sin^2 \frac{k\pi}{2N} \right)^{\frac{1}{2}}$$

$$A_k = \cos \frac{k\pi}{2N} \sin \frac{mk\pi}{N} \Big/ N \sin \frac{k\pi}{2N} \left(1 + \frac{4C_s}{C_g} \sin^2 \frac{k\pi}{2N} \right)$$

The Symbols are in accordance with Table 1.

This expression shows that at any point in the winding the voltage will rise to an initial value dependent on the distance of that point from the line terminal and will then oscillate. The network will act as a type of low pass filter with a definite cut-off frequency and considerable distortion of the unit function voltage will occur in the network.

1.2 ctd.

Fig. 4 shows the voltage appearing at 33-1/3% and 66-2/3% from the line end of a six section ladder network having the following parameters:

$$C_g = C_s = 600 \text{ picrofarads}$$

$$L_e = 270 \text{ microhenries,}$$

when unit function voltage is applied to the line end, the neutral being earthed.

It can be seen that the peak voltage to earth occurs at 2½ microseconds after the application of unit function voltage. Experimental results given later confirm the findings of Ganger (Ref. 27) and Elsnar (Ref. 14) that the peak value progresses through the windings of oil-immersed transformers at approximately 500 feet per microsecond. This fact is shown later to be of great value in the location of earth faults.

Under British Standard Impulse Test conditions the applied voltage wave tail would be falling to half its peak value at 50 microseconds and in consequence the second voltage to earth peak would not be so great.

The shape of the initial voltage distribution over a uniform single-layer winding subjected to unit-function voltage is given by the relationship:

Voltage at per unit distance "X" from the line end

$$\text{equals } V_L \left\{ \frac{\sinh (1 - X)\alpha}{\sinh \alpha} \right\}$$

$$\text{where } \alpha = \frac{\text{shunt capacitance of each turn to earth}}{\text{series capacitance between turns.}}$$

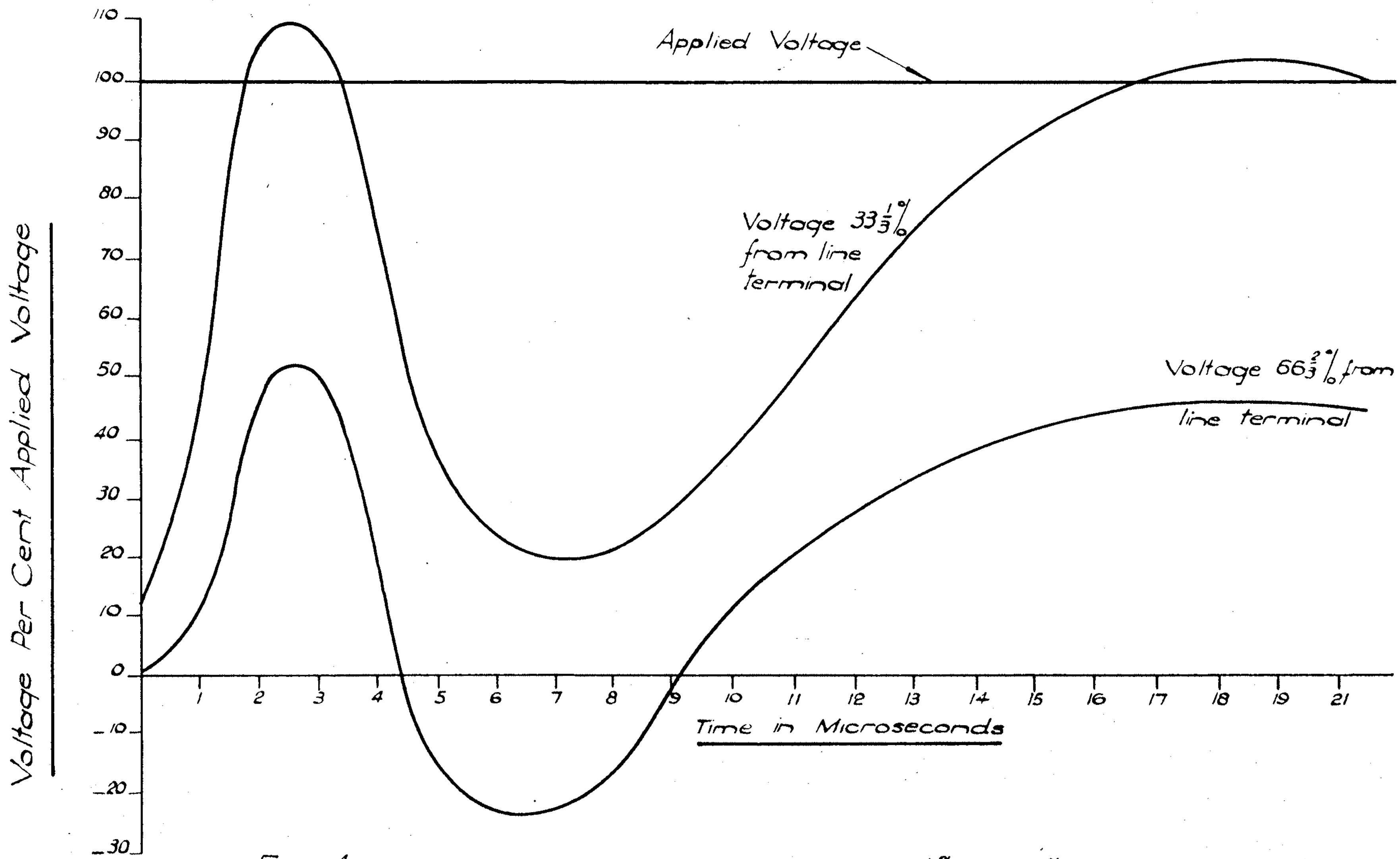


Fig 4. Calculated voltage to earth at $33\frac{1}{3}$% & $66\frac{2}{3}$% from the line terminal in a 6-section ladder network. Neutral earthed. L_e = 270 Microhenries

$C_3 = C_S$ = 600 Micro Microfarads

1.2 ctd.

Transformer designers often use an analogue network to represent the equivalent capacitance network (see Appendix 4.2). Measurements made on this analogue network, give the initial voltage distribution through the winding. The actual analogue may consist of resistive elements, adjustable in accordance with a reciprocal scale.

Although the initial voltage distribution, in itself, is not a criterion of a well-designed transformer, it does give an indication of the magnitude of the subsequent oscillations. One conception of the initial voltage distribution curve showing percentage voltage to earth versus percentage winding, is that it is like a stretched rubber band. When released the latter oscillates about the uniform distribution line in a similar way to the voltage distribution curves. The closer the initial distribution approaches the uniform the less the magnitude of the subsequent oscillations.

Analysis of the voltage to earth curves derived from the relationships set out above show that the interwinding stresses also reach a maximum progressively through the winding. This fact is demonstrated in Fig. 5 where results obtained by Norris (Ref. 17) for a power transformer disc-type winding are reproduced.

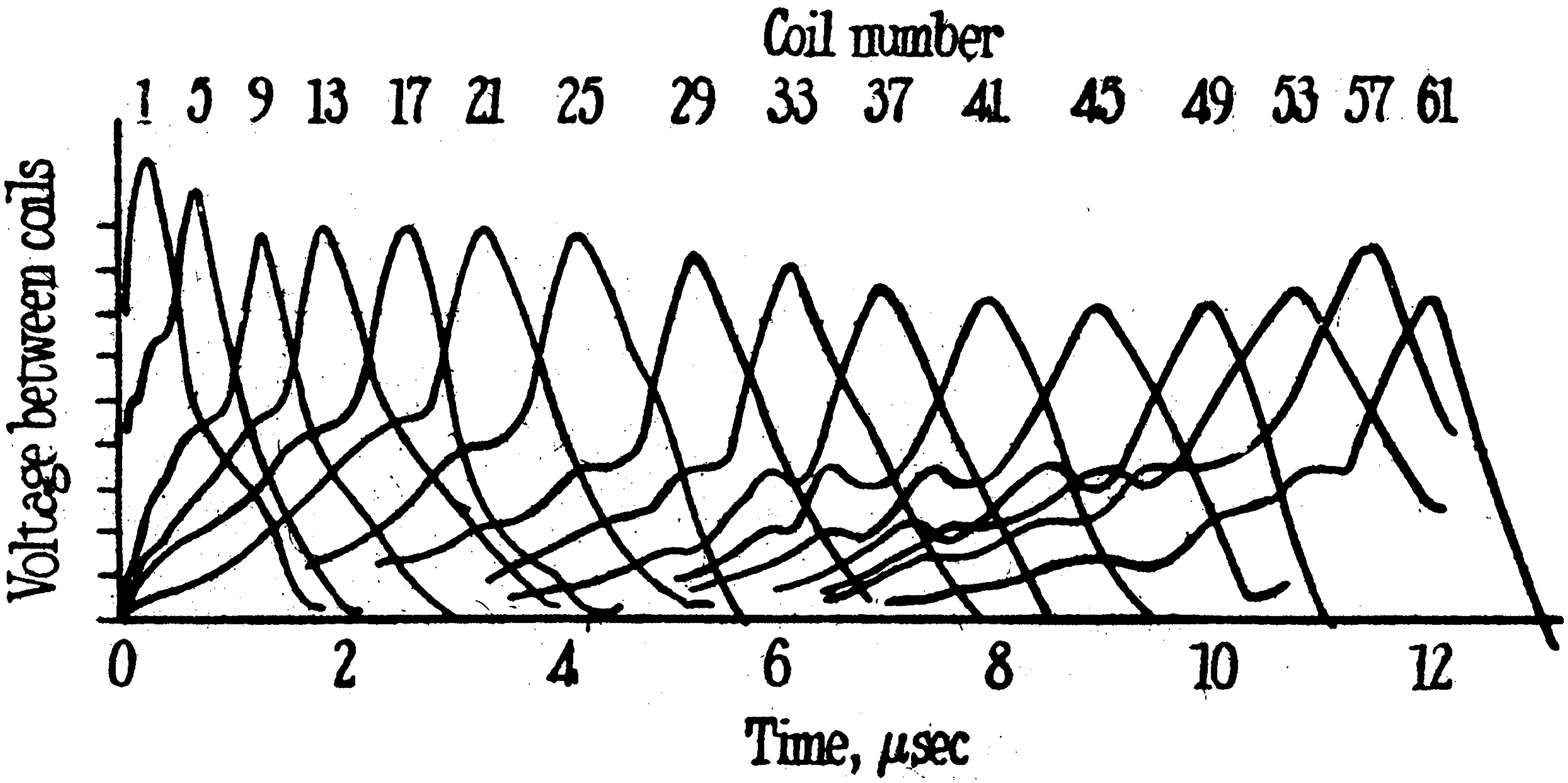


Fig. 5

—Propagation of inter-coil stress through a transformer winding.

1.3 Currents flowing at the Terminals and to the Tank.

Fault detection during the impulse testing of transformers requires a thorough knowledge of the various currents resulting from the discharge of the impulse generator. For the purposes of clarification and standardisation these currents are now defined* (see also Fig. 6(a)):

(a) Line Current (I_L): the total current supplied from the impulse generator to the transformer under test.

(b) Neutral Current (I_{NC}): the current flowing out of the earthed end (s) of the winding (s) under test.

(c) Tank Current (I_T): the total current flowing to the tank, core and clamping rings etc. through the shunt capacitances of the winding. It normally includes the current flowing from the low voltage winding to the tank due to the latter's capacitive and magnetic coupling with the winding under test, except when this component is measured separately (see below).

(d) Low Voltage (or High Voltage) Capacitance Current I_{LV} or I_{HV}):

The current flowing from the low voltage winding to the tank due to the winding's capacitive and magnetic coupling with the winding under test.

Since the applied voltage waveshape and magnitude is always known it is convenient to derive the above currents in terms of the applied voltage and the equivalent ladder network parameters. The most direct solution results from consideration of the tank current.

* Throughout this section it is assumed that the high voltage winding is being tested.

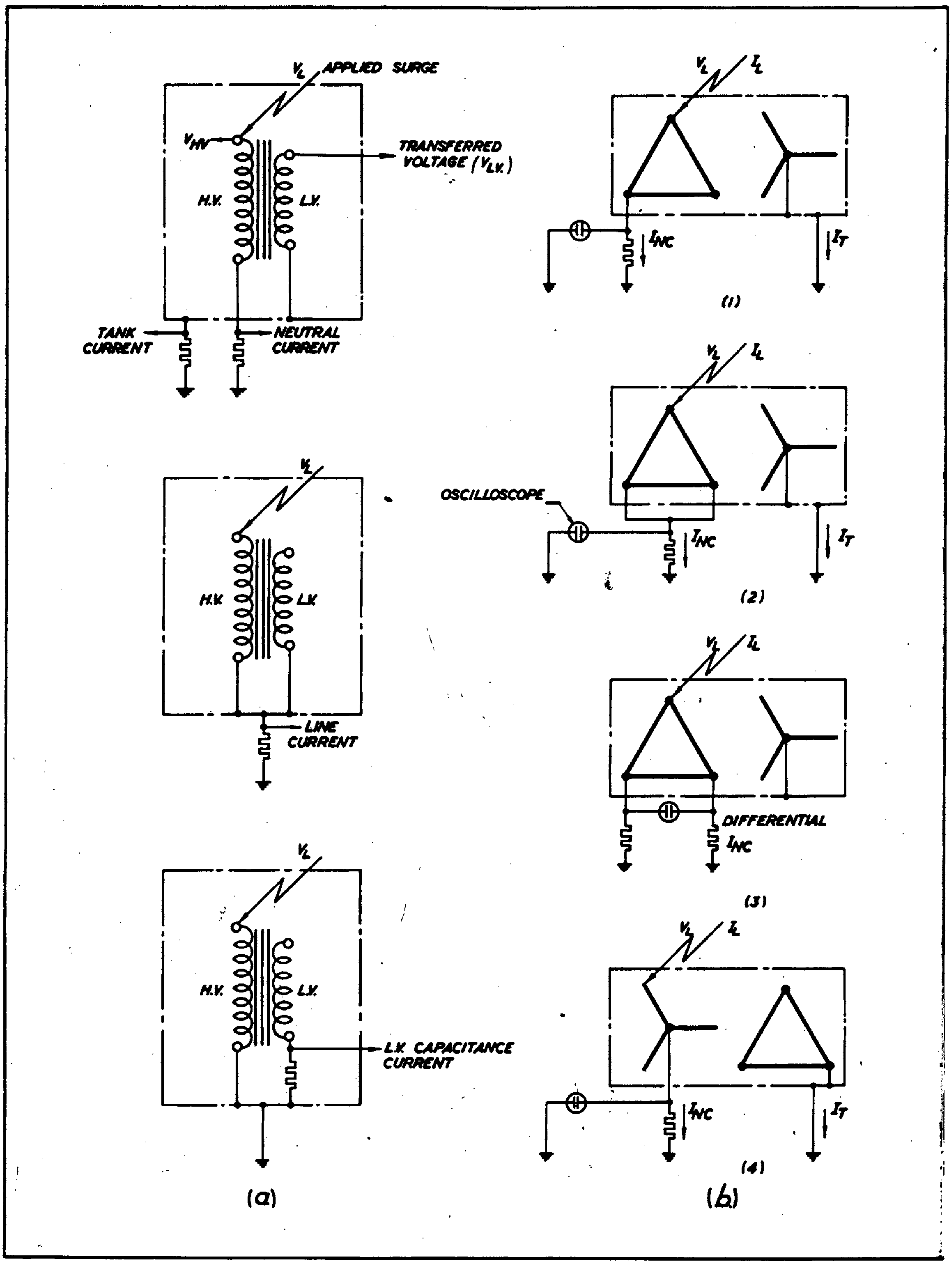


FIG 6 IMPULSE TEST CONNECTIONS AND RECORDING POINTS.

(a) Illustration of various recording points which can be used for fault detection during impulse testing

(b) Typical connections for test on a three phase delta - star transformer

The waveshape of the tank current can be confidently predicted if the voltage distribution relationships are known since this current is only dependent on the voltage variations throughout the windings and the shunt capacitances.

As shown previously the voltage at any point in a ladder type network representing a transformer winding with earthed neutral is given by:

$$v(mt) = 1 - \frac{m}{N} - \sum_{k=1}^{N} A_k \cos W_{ak} t$$

(see "1.2 - Voltage Distribution through the Windings").

Considering the equivalent ladder network shown in Fig. 1.(b) it can be seen that the tank current will be the sum of all the elementary currents through the shunt capacitances (Cge). Hence the instantaneous value of tank current can be expressed as:

$$i_t = \sum_{m=1}^{N-1} Cge \frac{dv(mt)}{dt} \quad \text{at any time } t.$$

The rate of change of voltage at any given point in the network is given by:

$$\frac{dv(mt)}{dt} = \sum_{k=1}^{N} A_k W_{ak} \sin W_{ak} t$$

Summation now gives:

$$I_t = \sum_{m=1}^{N-1} \sum_{k=1}^{N} Cge \; A_k W_{ak} \sin W_{ak} t.$$

This expression, which gives the tank current resulting from the application of unit function, does not yield the very high current peak which always occurs due to the initial charging of the capacitance...

1.3 Ctd.

network. The magnitude of this peak is inversely proportional to the duration of the wave front of the applied wave.

The initial peak tank current which results when a uniform single layer winding is subjected to an impulse voltage with a wave-front time equal to t_f, can be expressed as:

$$I_{T\ peak} = \frac{V_L\ Cge}{t_f} \int_{x=0}^{1.0} \frac{\sinh (1-X) \propto}{\sinh \propto}$$

(see "1.2 - Voltage Distributions through the Windings").

Fig. 7 illustrates the voltage distribution - tank current relationship derived above. The measured voltage distribution curves of a 30 kVA 7.6/0.445 kV three phase transformer of Australian manufacture, are shown in Fig. 7(a). The corresponding rate of charge of voltage curves are then plotted in Fig. 7(b). From the relationships set out above it will be seen that the incremental area under any one of the latter curves represents:

$$\frac{dv}{dt} \cdot dx .$$

Multiplying this expression by the total shunt capacitance, it becomes an element of tank current. By integrating under each curve in Fig. 7(b) in turn and plotting the results to a suitable scale against time, one obtains the tank current wave-form shown in Fig. 7(c). It is shown later that this waveform has the same basic shape as actual oscillographic records obtained during experiments on distribution transformers.

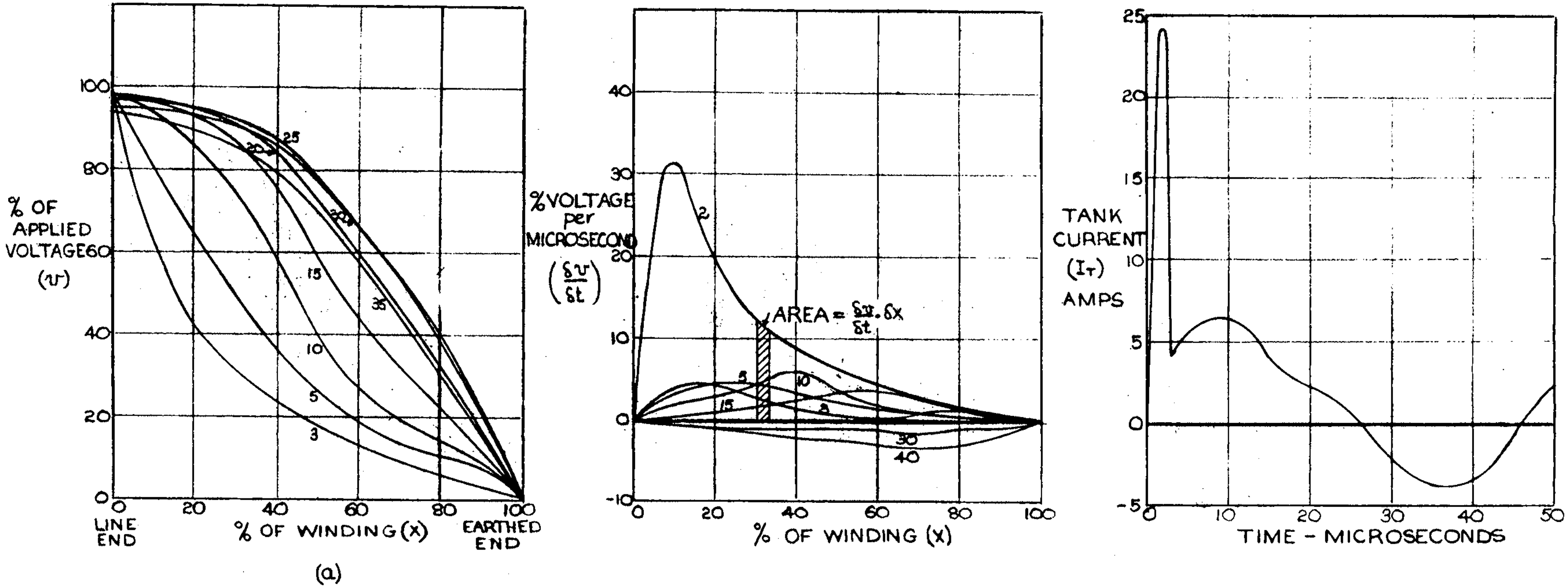


FIG 7 - ILLUSTRATION OF THE VOLTAGE DISTRIBUTION - TANK CURRENT RELATIONSHIP

DERIVATION OF THE TANK CURRENT OF A 30KVA 7·6/0·445 KV THREE PHASE TRANSFORMER

NOTE: 1. NUMBERS ON GRAPHS INDICATE TIMES IN MICROSECONDS
2. CURRENT SCALE (AMPS) FOR 100 KV, 1×50 APPLIED SURGE WITH A WINDING CAPACITY TO EARTH PER PHASE = 1,100 $\mu\mu F$

1.3 Ctd.

The derivation of the neutral current equation for a ladder network of the type shown in Fig. 1(b) is more difficult. Lewis (Ref. 9) gives the following transform equations for voltage and current when the neutral is earthed:

$$V(mp) = \sinh (N - m) W/p.\sinh Nw.$$

$$I(mp) = \cosh (N - m) W/p.Z \sinh Nw$$

$$\text{where } \cosh W = 1 + L_e C_{ge} p^2/2(1+L_e C_{se} p^2)$$

$$\text{and } Z = \frac{\sinh W}{p\, Cge}$$

The voltage expression for v(mt) given in Section 1.2 results from the standing wave solution of the above transform voltage equation (Ref. 9). No corresponding current solution is given, although Lewis (Ref. 9) states that a similar form of solution is possible.

However, the form of the neutral current can be predicted empirically in two ways:

(a) By assuming that the equivalent ladder network approximates a transmission line, that is, mutual coupling and the series capacitance elements are neglected, one can examine the currents produced by the application of unit function voltage.

(b) From fundamental experiments, described later, the neutral current is found to follow a basic pattern. This pattern is analysed to provide a sound theory.

The theory resulting from (a) is due to Ganger (Ref. 27) whereas (b) results from original work and correlation with recent developments concerning the derivation of the equivalent network. Both approaches have their merits when considered from a fault detection viewpoint, in fact they may be considered complementary. The theory based on transmission line reasoning is considered first.

An initial peak is always present in the neutral current waveform due to the charging of the series capacitances (C_{se}). This peak is much smaller than that which appears in the tank current and may even be negligable compared with the subsequent neutral current. This peak is shown in Fig. 8 where the neutral current, tank current and line current are derived from transmission line principles.

If the series capacitance elements (C_{se} in Fig. 1(b)) are neglected one can consider the equivalent ladder network as approximating a transmission line. The application of unit function voltage at one end with the other end connected to earth produces a voltage impulse and a current impulse (I) which travel at a constant velocity of propagation towards the earthed end. It is shown later that in oil immersed transformers, this velocity of propagation is approximately equal to 500 feet per microsecond.

During the first fundamental time then, only the initial charging peak appears. However when the impulse of voltage reaches the earthed end it reverses direction and polarity. This causes the neutral current to pass instantaneously from zero to 2xI. Actually the current impulse supplied by the generator reaches the earth connection at a value I and at the same time the shunt capacitances (Cge in Fig. 1 (b)), which have been charged by the first passage of the voltage impulse start discharging and increase the neutral current to 2xI (Fig. 8(a)).

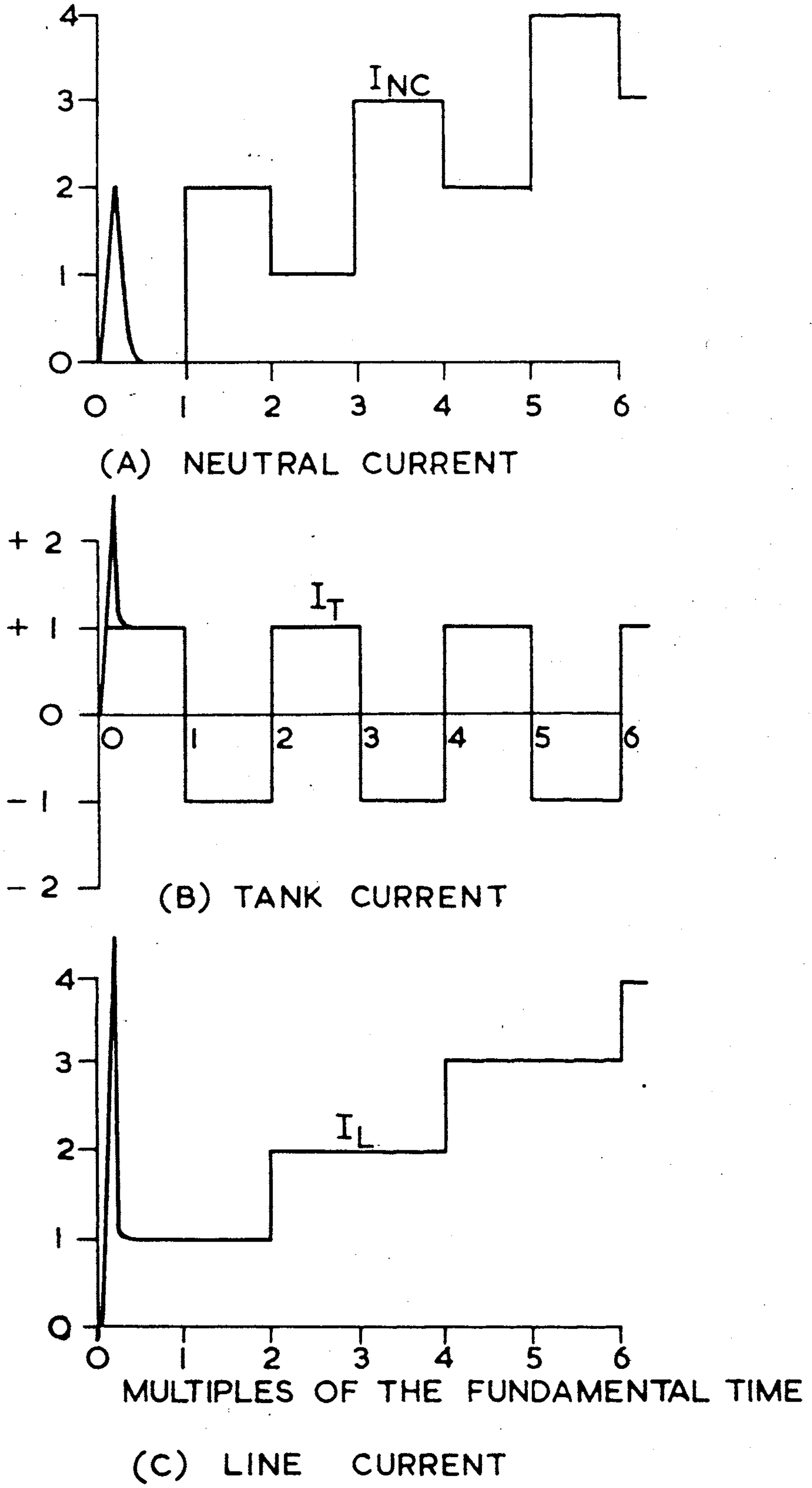


FIG 8 CURRENT WAVEFORMS DERIVED FROM TRANSMISSION LINE PRINCIPLES

1.3 Ctd.

At this instant (i.e. after the first fundamental time) the tank current, which up till now has been of the same polarity as the applied voltage, reverses whilst keeping its amplitude I (Fig. 8 (b)). This continues during the second fundamental time as the network reverts to earth potential and the energy stored in the shunt capacitances (Cge) disappears.

After twice the fundamental time has elapsed the reflected voltage impulse reaches the beginning of the winding. At this instant the charge on the latter has completely disappeared. Then the original value of the current impulse (I) is all that flows to the end of the winding (Fig. 8(a)). At this time the beginning of the winding learns for the first time of the unmatched conditions at the neutral end (see Fig. 8(c)).

The infinite source supplying the unit function voltage continues to charge the network and tends to maintain it under voltage. Consequently positive voltage and current waves again travel through the winding, charging the shunt capacitances. This immediately produces a change in the tank current from -I to +I (see Fig. 8(b)). At three times the fundamental time the neutral current which has been steady at +I increases instantaneously to 3I due to the arrival of the second current impulse (I) and the discharge current (I) which now commences due to the reflection and reversal of the voltage impulse. This discharge now causes a change in the tank current from +I to -I. Continuation of this step by step process gives the basic shape of the neutral current and tank current waveforms. The neutral current, due

1.3 Ctd.

to the fact that the winding is earthed and the long duration of the unit function voltage, reaches high value.

The line current is obtained by superposition of the neutral and tank currents. This fact proves important later when considering the relative merits of the various current records for fault detection purposes.

One would not expect abrupt steps in the actual neutral and tank current waveforms due to the effect of the neglected series capacitance and the mutual coupling between sections of the winding. The series capacitance elements would give a gradual increase in the neutral current of the same polarity as the approaching current impulse. However in accordance with Lenz's law of induction the neutral current increment due to the mutual coupling will be of opposite polarity to the approaching current impulse.

Due to the fact that it is based on experimental results described later, the second theory is developed in detail in Section 2.3 - "Fundamental Behaviour of Transformer Winding Currents During Impulse Tests". However for the sake of completeness it is summarised below.

The initial peak in the neutral current waveform is due to the charging of the series capacitance elements. This peak occurs in the first few microseconds after the application of the impulse test voltage.

During the first 50-100 microseconds of the test (assuming a standard 1x50 wave) oscillations occur in the neutral current which are closely related to the tank current although 180° out of phase with the latter. Actually these oscillations are superimposed on an electromagnetic component of the neutral current which becomes influential after

1.3 Ctd.

50-100 microseconds. At this time the higher frequency oscillations are diminishing and the leakage field is approaching that prevailing under power frequency conditions. Also, under lower frequency conditions, the series and the shunt capacitances become less significant than the total inductance (NLe) of the winding.

Consequently the current flowing is mainly the electromagnetic or exponential component related to the applied voltage by:

$$\text{Applied Voltage} = NLe \cdot \frac{di}{dt}$$

Since the tail of the applied wave is usually of exponential shape, the electromagnetic component of the neutral current also is of this shape. Although the applied voltage has usually decreased to a very low value after 150 microseconds, the electromagnetic energy stored in the winding can cause the electromagnetic component of the neutral current to persist for hundreds of microseconds.

Summarising, it can be stated that the currents during the test period pass through three stages, namely:

(a) the initial stage during which the capacitance elements are being charged.

(b) an intermediate stage during which the capacitance and inductive elements interchange energy with associated current oscillations but an appreciable electromagnetic current is not yet flowing.

(c) a final stage during which an influential current, predominantly the electromagnetic, or exponential, component, is flowing through the winding.

1.3 Ctd.

The major currents can be regarded as comprising:

Neutral Current - An inrush peak and an exponential component on which is superimposed a higher frequency component related to the tank current.

Tank Current - An inrush peak and an oscillatory component dependent on the transient voltage behaviour of the winding.

Line Current - The resultant sum of the neutral and tank currents. It is the total current supplied by the impulse generator.

The theoretical basis established above enables the major effects of faults occurring during impulse tests to be predicted. These faults can be grouped under three classifications and the general effects analysed under that classification.

Line Terminal Faults.

These faults result from dielectric failure at the terminals, at the lead to the winding or from any electrostatic winding shields connected to the line terminal.

A major fault such as this will chop the applied voltage (Line Voltage - V_L) wave almost to zero, and will increase the tank current to a very high value.

Depending on the time elapsing between the application of the test voltage and the failure, the neutral current will tend to be zero. The longer the failure is delayed, the greater will be the energy stored in the windings and the greater the neutral current oscillations during the dissipation of that energy. Normally this type of failure occurs before any electromagnetic component of the neutral current develops.

Winding to Earth Faults.

Such a fault effectively short-circuits the portion of winding between the point of failure and the earthed neutral. This has the effect of reducing the number of sections in the equivalent ladder network and reducing the inductance parameters, both factors causing an increase in the magnitude and the frequency of the oscillations of the line current. These in turn affect the applied voltage depending on the impedance of the impulse generator.

The tank current will increase immediately the fault to earth occurs and should provide an excellent indication.

The neutral current could be expected to diminish and even reverse polarity due to the inductive effect of the current flowing to earth through the winding portion between the line terminal and the point of failure. As shown in Fig. 9 the neutral current is now really the current circulating in the portion short-circuited by the fault to earth. Due to the laws of induction this current will be in opposition to the normal direction of current flow during the test. The effect would be primarily associated with the electromagnetic component and would persist until the energy stored in the windings was dissipated.

Interwinding Faults.

These faults can vary from interturn short-circuits to extensive flash-overs down the axial length of the windings. Consequently it is almost impossible to predict effects except for major faults.

A major fault would increase the load on the impulse generator due to reduction of the number of sections in the equivalent ladder network and reduction of inductance parameters. Depending on the generator's impedance this will produce an indication in the waveform of the applied voltage.

The shorting of sections by a major interwinding fault will also affect the voltage distribution over the winding. This in turn will produce changes in the tank current waveform. If any high frequency oscillations occur due to the insulation breakdown one would expect the tank current to show these due to the shunt capacitance coupling.

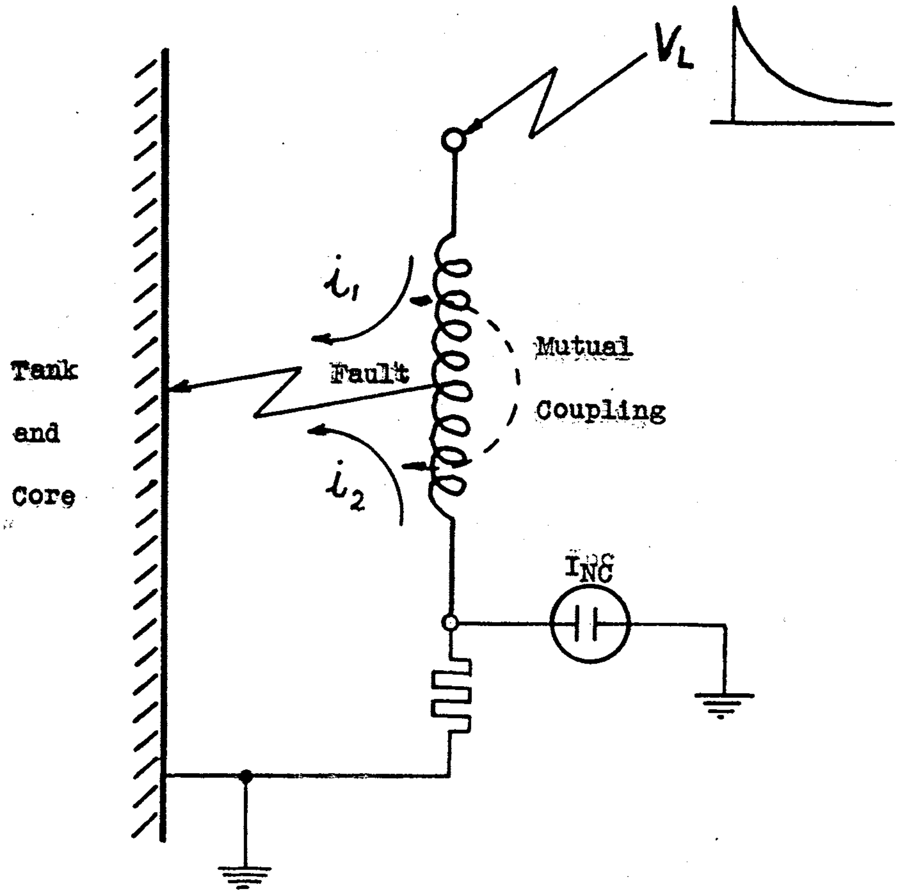


Fig.9 - Illustration of the inductive effect producing a reversal in the Neutral Current when a winding to earth fault occurs.

The oscillations in the neutral current would be expected to show similar changes to those in the tank current. However, the main effect would be in the electromagnetic component since short-circuiting of portion of the winding will decrease the total inductance and cause an increase in this component. The decrease in inductance will be due not only to a reduction in the number of sections in the equivalent ladder network but also to mutual inductance effects between the short-circuited portion and the rest of the winding.

A mathematical analysis of the effects of short circuits between turns has been made by Heller, Hlavka and Veverka (Ref. 40). Unfortunately the English translation in the CIGRE proceedings is not very good. The mathematical analysis, which is based on the expressions for leakage flux and flux linkages derived originally by Blume and Boyajian (Ref. 3), shows that the fundamental frequency of the winding increases due to a short-circuit between turns and the amount of increase depends on the position of the short-circuit.

Heller etc. measure this variation at the end of windings tested with their neutral insulated or use a special connection when testing a winding with earthed neutral. Very careful interpretation is required since the variation in frequency can be quite small, in fact a condenser shunt may have to be used to accentuate it.

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PART 2: FAULT DETECTION AND LOCATION EXPERIMENTS.

2.1: INITIAL OBJECTIVES.

The main theme of this work, the clarification and exposition of the theoretical and practical aspects of fault detection during the impulse testing of transformers, guided the experiments towards the achievement of several specific objectives.

From the viewpoint of a test engineer these objectives are closely related and the achievement of each is necessary for him to proceed confidently.

The first objective was to carry out experiments which will support and clarify theories already developed. From the results of these experiments it was hoped to examine in detail the fundamental behaviour of transformer winding currents during an impulse test.

Secondly, the preferred test connections had to be determined after consideration of service conditions and other limiting factors such as the effect of the test connections on the fault detection sensitivity.

Having standardised the test connections, the third objective was to carry out fault detection and fault location experiments on transformers ranging in size from voltage transformers to power transformers rated above 10,000 KVA. The effects of winding construction and connection are then to be studied from the results of these experiments. It is hoped that these results can be displayed in oscillographic form so that they will serve as a useful guide during the commercial impulse testing of transformers.

The fourth and last objective was to examine recent overseas experiments concerning:

(a) Fault Detection during chopped Wave Testing.

(b) Fault Detection from physical phenomena occurring during the impulse test.

2.2 EXPERIMENTAL EQUIPMENT.

To carry out the experimental work necessary for the achievement of the objectives described above, it was necessary to obtain either access to a full scale impulse testing laboratory or to employ a portable recurrent surge generator.

In 1953 neither of these facilities was available in Sydney, New South Wales, Australia. However the author had previously carried out work of a similar nature in the Transformer Works of the British Thomson-Houston Company, Rugby, England. This work provided a sound basis for the experimental programme and some of the results of this work are given later.

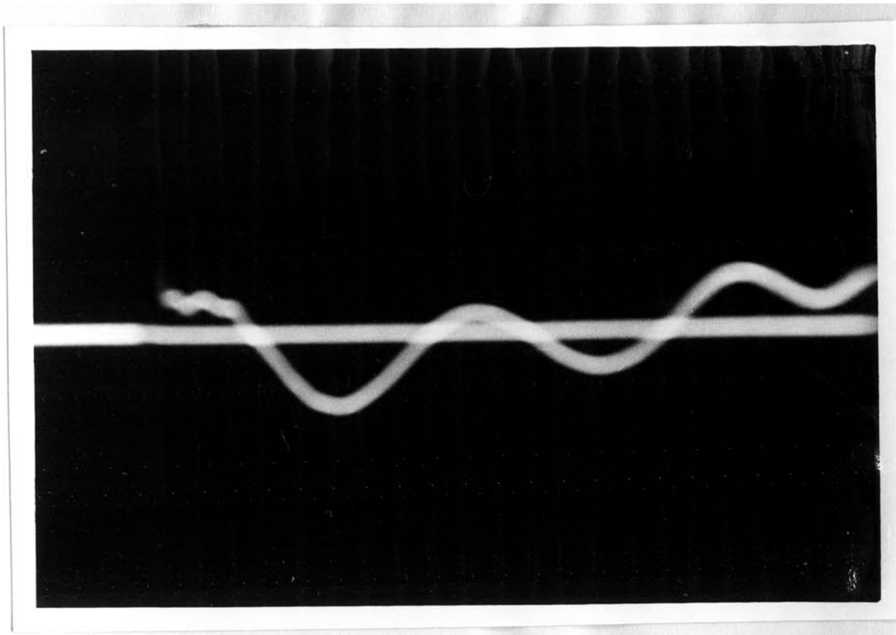
In this earlier work the author used a 2 KV Recurrent Surge Generator, the design of which has been described by Wilkinson (Ref.41). A 1200kV impulse generator, with a rating of 12 Kilowatt-seconds, was also employed. Records were made during full scale impulse tests using a pumped cathode ray oscillograph.

In order that the experimental programme could commence the author designed and built a 1000 volt recurrent surge generator on an experimental basis. This unit is referred to hereafter as the experimental R.S.G. to distinguish it from the final design, which was developed and built by the staff of the N.S.W. University of Technology.

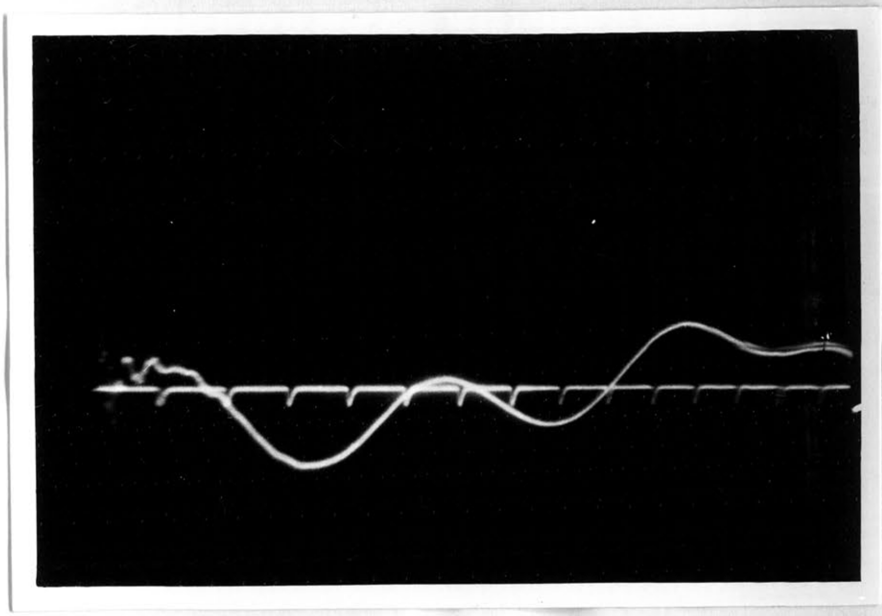
The experimental R.S.G. was of orthodox design, the surge output being generated by the discharge of a one microfarad condenser through a Mullard Type 4C35 Hydrogen Thyratron into a wave shaping unit. The condenser charging was from a 2 KV D.C. Power Supply Unit, ex-RAAF Type A20. Since the Hydrogen Thyratron was at high voltage the triggering circuit presented difficulties.

The triggering circuit employed a B.T.H. BT5 mercury thyratron to initiate a pulse through the primary of a specially insulated coupling transformer, the output of which supplied the grid of the 4C35. The pulse transformer, which fired the BT5 at mains frequency repetition rate, was also used to trigger the sweep circuit of a Cossor 1035 Cathode Ray oscilloscope. Although the experimental recurrent surge generator was cumbersome to transport and suffered from instability problems in the trigger circuit, it did yield valuable experience which assisted in the final design. Many experiments conducted with it are described later. One such experiment, however, is of interest here, since it showed the faithful nature of the R.S.G. records.

Experiments were made on a 200 KVA 3 phase 33/11KV Delta-Star transformer at the Tyree Works prior to acceptance Impulse Tests being carried out at Queensland University. The Neutral current record shown in Fig. 10 (a) was obtained using the 1000 volt experimental recurrent surge generator with Test Connection No. 2 (see Fig. 6(b)). This record was obtained from the voltage appearing across a 50 ohm non-inductive resistance shunt.



(a) Neutral Current record obtained during an experiment with a 1000 volt Recurrent Surge Generator(Tyree Works)



(b) Neutral Current record obtained during a fuhl scale (150Kv Impulse Test (University of Queensland H.V. Laboratory)

Fig. 10 Oscillograms showing the correlation between Recurrent Surge and Full Scale Impulse Test results on a 200 KVA 33/11 KV transformer.(Test Connection No.2 in Fig.6(b)).

Fig. 10(b) shows the neutral current record obtained using identical test connections at the Queensland University's Impulse Testing Laboratory. In this case however a single 1 x 50 impulse of 150 KV peak was applied to the 33 KV Delta-connected winding. It can be seen that, except for some high frequency oscillations, the records are practically identical. This experiment demonstrates the validity of treating a transformer winding as practically a linear circuit for periods up to a few hundred microseconds (Ref. 4).

It is also interesting to note that the neutral current records obtained in this experiment are very similar to that obtained by Rippon and Hickling at Parsons Works, England, on a 400 KVA, 10/0.4 KV, Delta-Star transformer (Ref. 5).

The final design for a Recurrent Surge Generator was based on a Specification drawn up by the author (see Appendix 4.3). The design is due to Dewsnap (Ref. 34 and 42) who also supervised the construction of the 2 KV Recurrent Surge Generator by the Electronics Workshop staff of the N.S.W. University of Technology.

The fundamental difference between the Specification and the final unit is that the latter does not include a display unit. It is arranged to operate with a Cossor 1035 Cathode Ray Oscilloscope as the display unit. This oscilloscope has to be slightly modified so that pulse brightening is achieved from the trigger pulse which synchronises the display unit with the Recurrent Surge Generator.

Fig. 11 shows the circuit of the R.S.G. developed by Mr. Dewsnap. A multivibrator circuit provides the synchronising

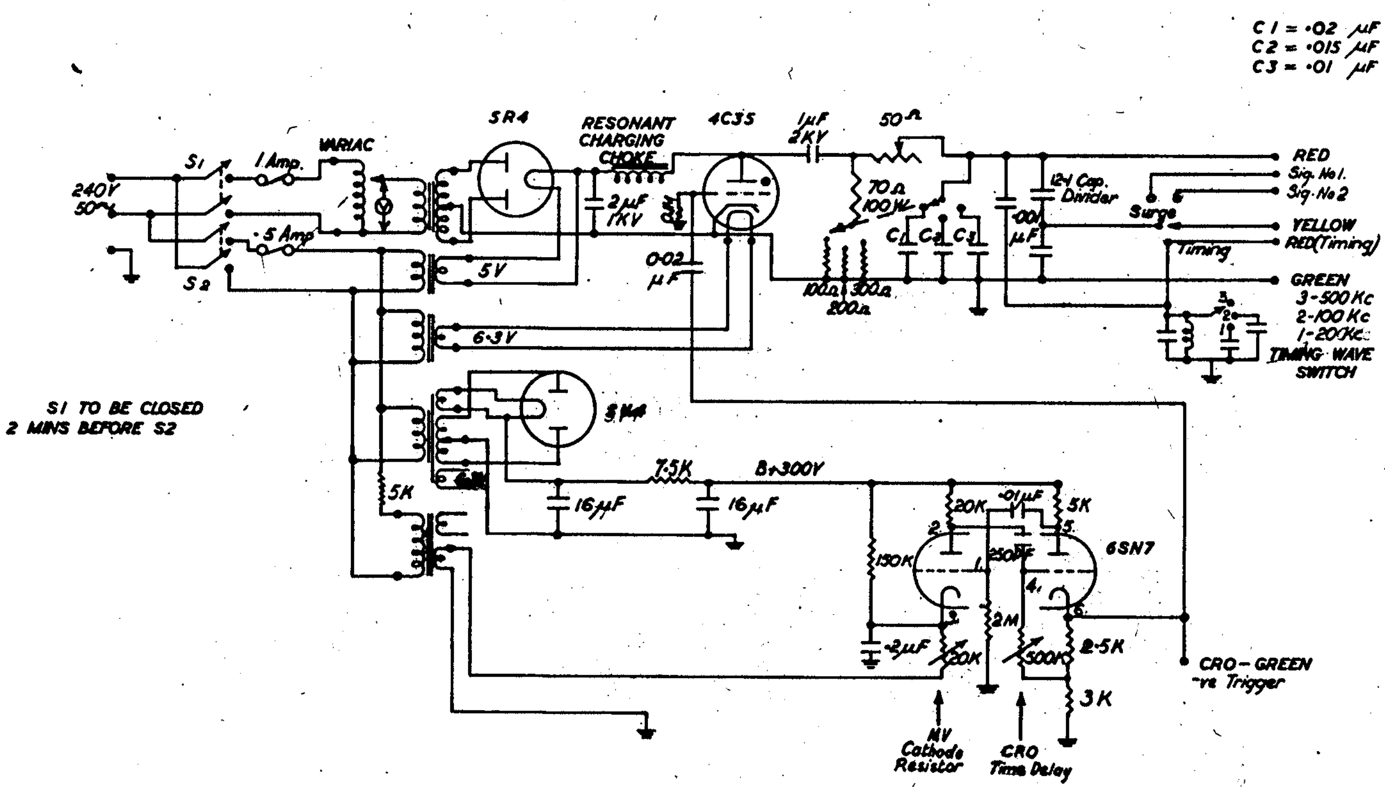


Fig. 11

DEPARTMENT OF TECHNICAL EDUCATION	Scale	Date	22·5·57	D	4558
N.S.W. UNIVERSITY OF TECHNOLOGY	Passed	Drawn			
RECURRENT SURGE GENERATOR		Traced	J.M.		
SCHOOL OF ELECTRICAL ENGINEERING		Check'd			

trigger signal.* The synchronising signal is composed of an initial negative polarity pulse followed by a positive pulse. The time between the negative and positive pulses can be varied up to 40 microseconds. The negative pulse triggers the C.R.O. sweep and the positive pulse brightens the trace and fires the thyratron in the generator to produce the surge output.

The recurrent surge generator design finally evolved and shown in Fig. 11 is notable for the resonant charging circuit and the simplified triggering of the 4C35 hydrogen thyratron, made possible by earthing the thyratron cathode.

The recurrent surge generator has a low output impedance, maintaining a good output waveform even when connected to the 33kV winding of a 13.5 MVA transformer. This low impedance output has enabled fault detection techniques to be developed with a substantially constant applied surge, even when faults involving a considerable winding section are present. These techniques are therefore more suitable for standardisation and instructional purposes than those which depend on variations in the output of a high impedance surge generator. These variations will naturally be different at different impulse testing laboratories.

The peak value of the output surge can be smoothly varied by a regulating transformer. The voltage being supplied to the

* This circuit was developed under the guidance of Mr. J.K. Reavley, Testing Branch, Sydney County Council.

charging circuit is shown on an integrally mounted voltmeter. A reading of 200 volts on this voltmeter corresponds to a peak output of approximately 1350 volts.

A 12 to 1 capacitance divider is used to monitor the output surge (see Fig. 11). The output of this divider is applied directly to the plates of the Cossor Oscilloscope to avoid distortion through the oscilloscope amplifiers. The high voltage output of this generator enables direct connection to the deflection plates in most cases thus reducing possible sources of error particularly in the recording of high frequency components. It has been observed that the output of the R.S.G. contains a parasitic oscillation of approximately 5-10 megacycles. However this only appears at the front of the wave and was of too high a frequency to affect the experimental results described herein. During the building of a similar unit at the University of Adelaide, a similar parasitic oscillation was observed in the output. Extensive shielding and earth connection rearrangement was found necessary to obviate the difficulty.

Another advantage of using a relatively high voltage generator output is that "sparking" or intermittent faults can be produced in windings under examination by the use of cold cathode discharge tubes. The sudden ignition of such a tube produces effects similar to those to be expected by a dielectric failure under actual test conditions.

The unit has proved very reliable and convenient during two years use for experimental work in many different locations. Fig. 12 shows the unit being employed for a demonstration of fundamental phenomena before the Institution of Engineers, Sydney Division, on 26th March 1958.

Current measurements were made using non-inductive resistance shunts.

Voltage measurement on windings under impulse test conditions is most difficult due to the deleterious effect of the connection of even small capacitances. Since this work was not vitally concerned with voltage distribution measurements the problem did not arise. However for the purposes of illustrating some theoretical aspects, approximate measurements were occassionally made by using a low capacitance connection to the vertical deflection plates of the oscilloscope. The output voltage of the recurrent surge generator was reduced to a suitable value to enable this direct measurement to be made.

The transformers, on which experiments were made, are grouped into three categories:

(a) Voltage transformers and distribution transformers up to 50 KVA.

(b) Distribution transformers to 1000 KVA.

(c) Power transformers.

Through the co-operation of manufacturers and supply authorities, the design particulars of most of the transformers used in the experimental work are available. These particulars are not included in this thesis. However relevant basic design features such as length of winding conductor, type of winding construction, are described where this information assists in the interpretation of the experimental results. The author will submit a comprehensive file of original results in support of this thesis.

It will be appreciated that practical difficulties such as lifting of the core and windings, access to tapping switches under oil, and so on, were encountered throughout this work. The time available for the experiment was sometimes limited. In order to obtain the maximum information under such conditions, the individual experiments were conducted using similar techniques and test connections. It is felt that this feature of the experiments is valuable because it reveals the effects of the transformers design features. For the same reason non-inductive resistance shunts were employed. Complex shunts would have introduced another factor into experiments which already involved many uncontrollable variables.

During investigation of the fundamental behaviour of transformer windings under impulse testing conditions it was found necessary to build an experimental winding stack, which could be fitted with an earth screen to simulate the normal shunt capacitance network of a transformer. A removable core made of stalloy laminations was also inserted in the experimental winding stack as required.

The details of these experimental winding components are given below:

WINDING: Twelve (12) bobbin type coils from the high voltage winding of a 200 KVA 10000/415 volt transformer were assembled in a wooden frame with the normal axial spacing.

The turns per coil average 354.

Total Turns = 4239

Conductor size = 15 S.W.G.

O.D. of coils = 10.9 inches.

I.D. of coils = 8.5 inches.

Length of conductor = 1070 feet (3270 metres)

Total resistance = 19.3 ohms.

Height of coil stack = $35\frac{1}{2}$ inches.

The shunt capacitance to earth without earth screen or core = 170 micromicrofarads.

Total inductance without earth screen or core = 1.0 henry

Inductance of 50% winding without earth screen or core = 0.44 henry

" " 25% " " " " = 0.17 henry

Note: Inductance and capacitance values were measured at 1000 cycles per second with a GR Bridge.

EARTH SCREEN: A cylinder made of sheet insulation was metallised to form an internal earth surface of 7.5 inches diameter. The insulation was overlapped so that a short-circuited turn was not provided.

Total shunt capacitance to earth with earth screen fitted = 800 micromicrofarads.

Inductance unchanged.

STALLOY CORE: Three packets of Stalloy were made up in leather wallets so that the centre of the winding stack could be completely filled when required. It was found that in most cases one packet was sufficient.

Total inductance with one of the packets inserted = 7.4 henries

50% winding inductance with one of the packets inserted = 3.0 henries

25% winding inductance with one of the packets inserted = 1.1 henries

Capacitances unchanged.

Figure 12 is a photograph of this equipment set up for a recurrent surge demonstration of fundamental phenomena, and Fig. 14 shows a simplified schematic diagram of the experimental equipment and its connections.

2.3 FUNDAMENTAL BEHAVIOUR OF A TRANSFORMER WINDING DURING IMPULSE TESTS.

The behaviour of a transformer winding subjected to an impulse test has been analysed theoretically in Part 1. The experimental results which clarify and support this theoretical study fall naturally into three groups:

(a) the effects of winding parameters.

(b) the currents which flow.

(c) the voltage conditions created.

These aspects are considered separately for each of the two main test conditions, namely Full Wave Tests and Chopped Wave Tests.

2.3 1 Behaviour under Full Wave Test Conditions.

By using the experimental winding stack described in Section 2.2, fundamental experiments can be made in a logical sequence, starting first with the winding standing alone. The winding in this condition, that is to say, without a core or a tank, is referred to later as a "free standing winding".

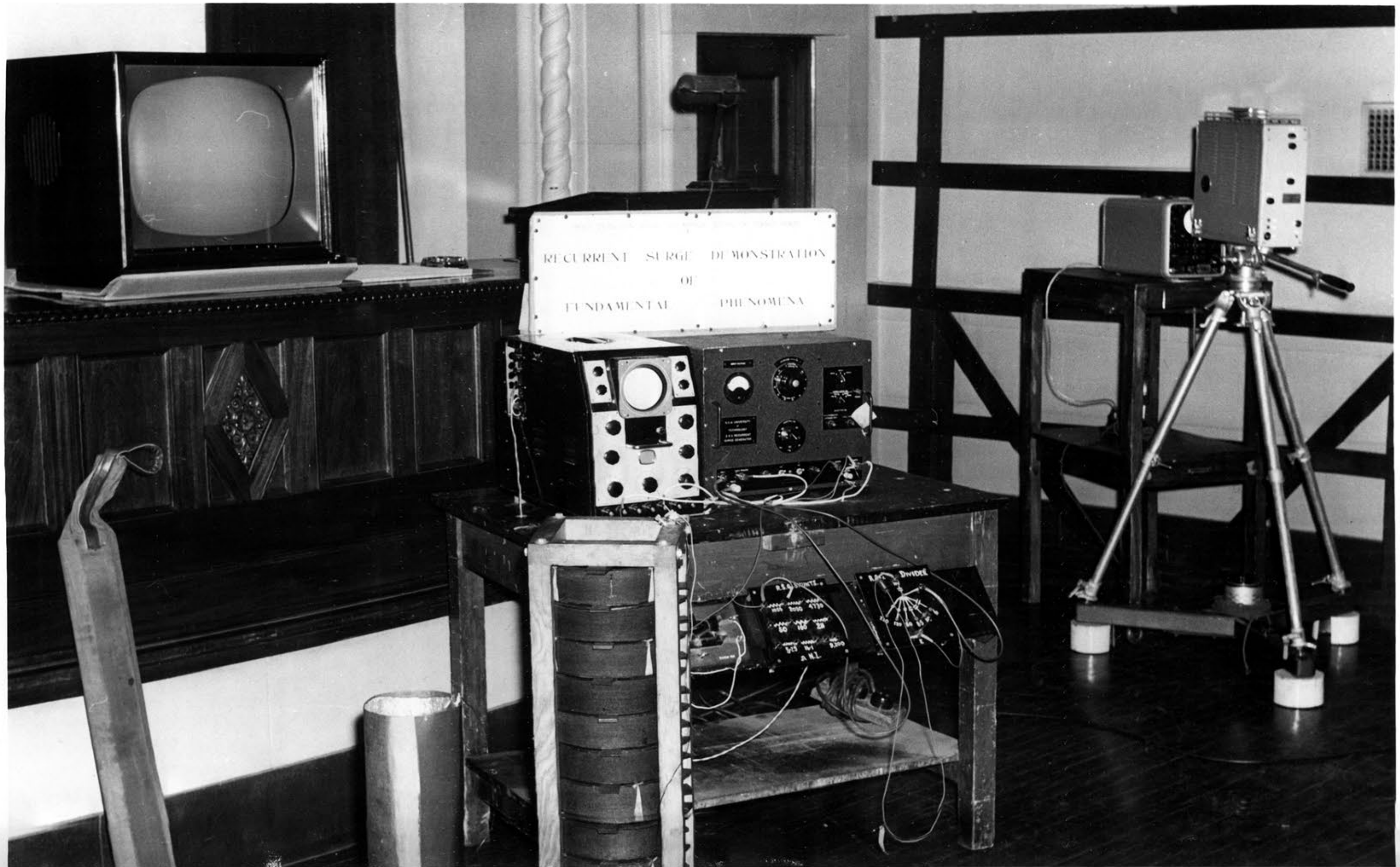


Fig.12 - Recurrent Surge Equipment arranged for a Demonstration with the Experimental Winding Stack.

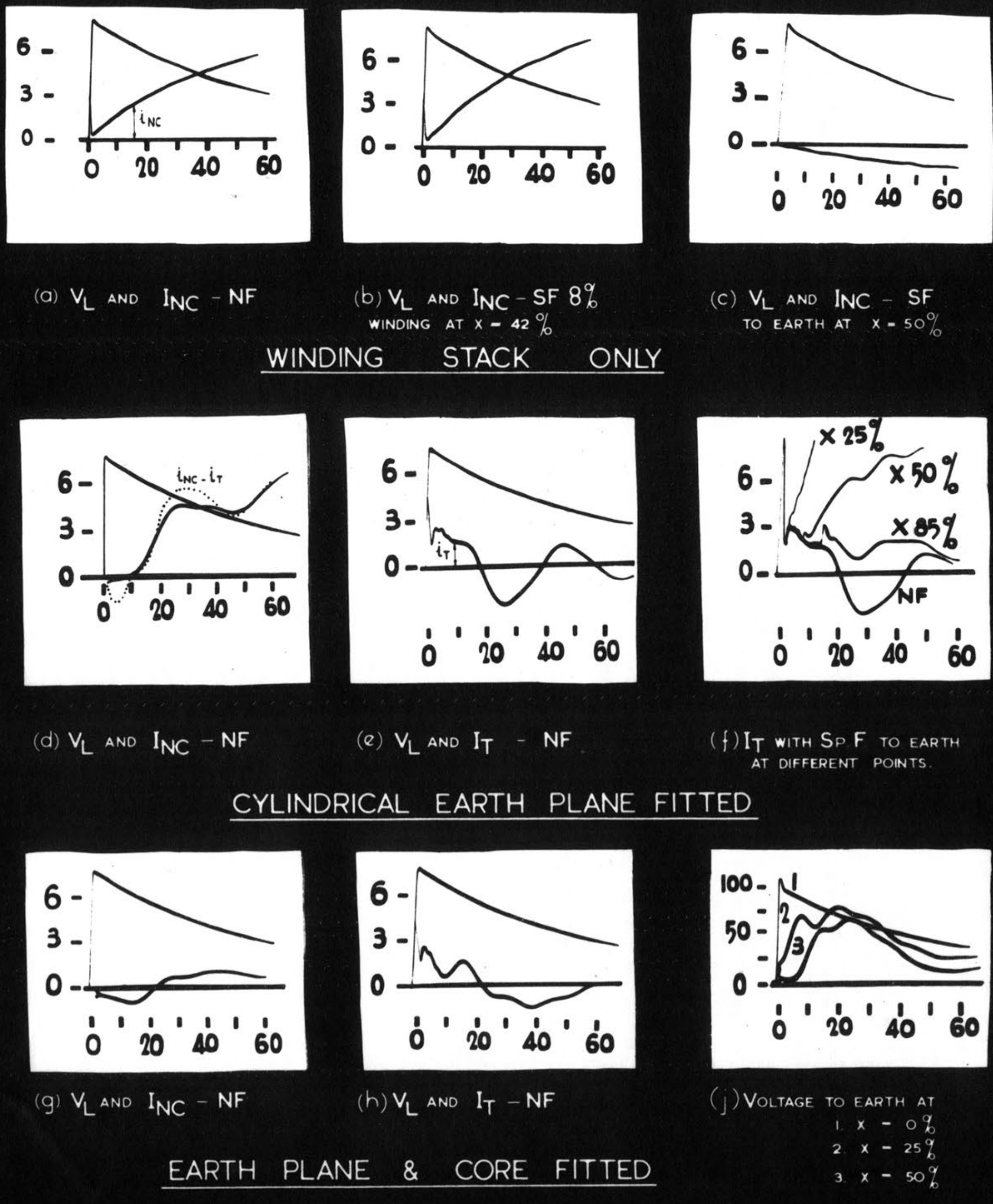


FIG. 1[illegible] OSCILLOGRAMS FROM TESTS ON A FREE STANDING EXPERIMENTAL WINDING CONSISTING OF TWELVE BOBBIN TYPE COILS.

THE CYLINDRICAL EARTH PLANE AND THE IRON CORE WERE PLACED THROUGH THE CENTRE OF THE STACK

CURRENT SCALES ARE FOR A 100 KV, 1 X 50 APPLIED SURGE.

TIME IN MICROSECONDS.

The experimental stack standing alone is practically a plain inductance, the values of shunt capacitance to earth (Cge in Fig. 1) being small and non-uniform. Under these conditions the total measured shunt capacitance of the winding to earth is 170 micromicrofarads. Inductance measurements were made on this free standing winding and the results are given in Section 2.2. These results can be considered in the light of the empirical relationship used by Abetti and Maginnis (Ref. 13, 35). The ratios of percent inductance to percent winding are:

$$50\%\ \text{Winding} \quad - \quad \frac{0.44}{1.0} = 0.44$$

$$25\%\ \text{Winding} \quad - \quad \frac{0.17}{1.0} = 0.17$$

Note: These parameters were measured with a 1000 cycles per second inductance bridge.

From Fig. 3, it can be seen that these ratios correspond to the inductance function of an air-cored, uniform, single-layer helical winding with a ratio of coil length to coil diameter equal to 3.0. This indicates that the mutual coupling between winding sections (M^1 in Fig. 1) is not very great.

The next experiment with this free standing winding involved recurrent surge tests. A recurrent surge with a peak value of 1280 volts was applied from the generator described in Section 2.2 (final design). Current measurements were made using a 1000 ohm non-inductive shunt. The oscillographic results of this experiment are shown in Fig. 13 (a), (b) and (c). For the sake of uniformity the current

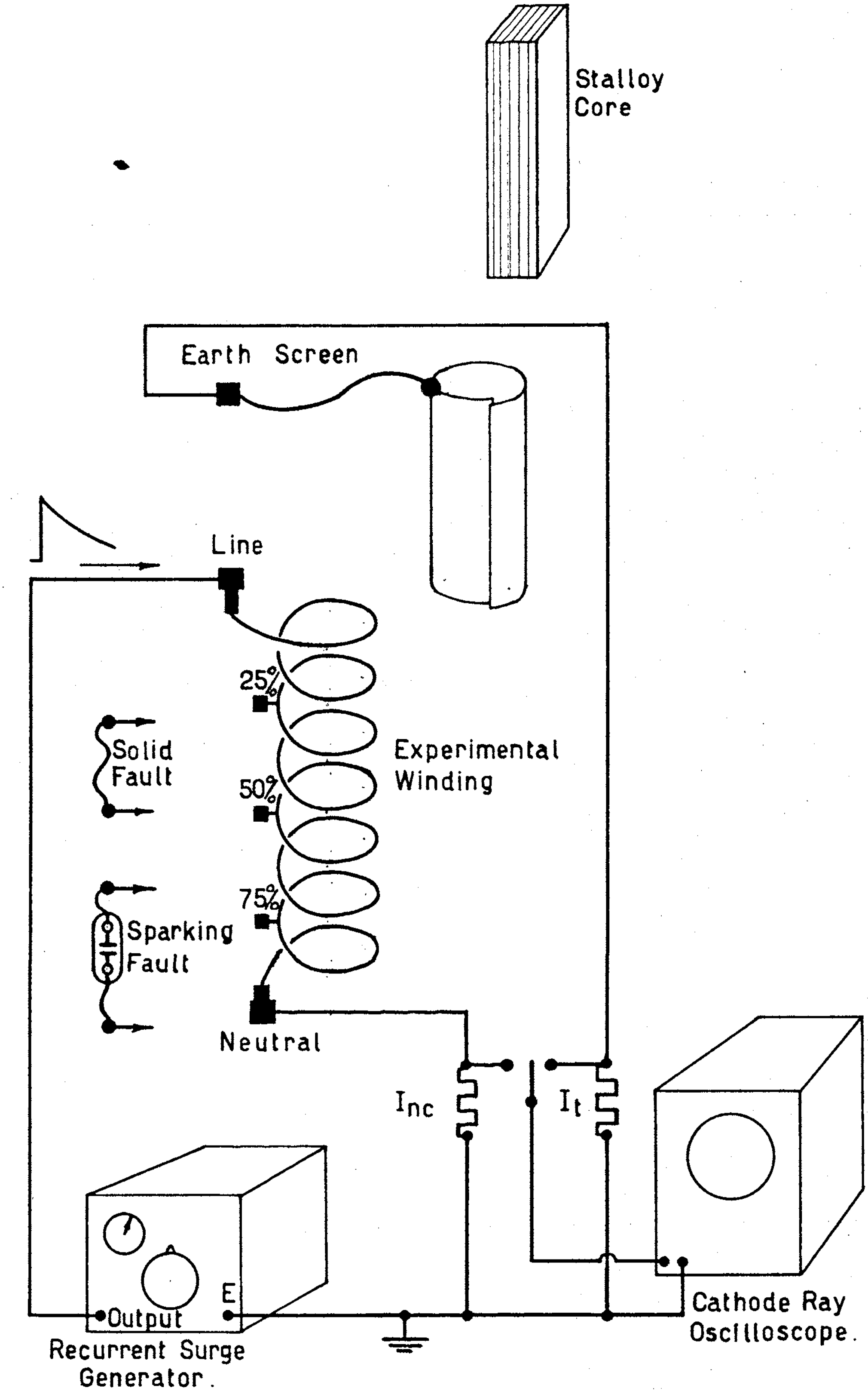


FIG. 14 Schematic Diagram of the Experimental Equipment and Associated Equipment.

scale has been referred to a 100 KV peak applied wave. This procedure is followed wherever possible so that the setting up of measuring equipment for corresponding full scale tests will be facilitated. The arrangement used for the experiment is shown schematically in Fig. 14.

The neutral current (Fig. 13(a)) has an initial peak which coincides with the front of the applied 1/50 microsecond voltage wave. This is the charging current of the series capacitance elements (Cse in Fig. 1). With the initial voltage distribution established by virtue of the winding's capacitance network, current now flows through the winding conductor to the neutral end. The slowly rising current is of an exponential form, related to the exponential decay of the applied voltage by the relationship,

$$i = \frac{1}{NL_e}\int v.dt,$$

This current is referred to as the electromagnetic component and is the basis for many fault detection methods.

It is interesting to note, at this stage, that the electromagnetic component persists for some time after the applied voltage has fallen to a negligible value. This phenomenon is due to the storage of electromagnetic energy in the winding during the first 50-100 microseconds of the test. It is important for three reasons:

(a) The sweep times for recording neutral and line currents may have to be longer than that required to measure the applied voltage.

(b) Under chopped wave test conditions the stored energy represents an important factor in fault detection.

(c) The amount of energy stored in the magnetic circuit will have a bearing on the physical damage produced by any fault dissipating all or portion of that energy.

Faults were now applied to the experimental free standing winding to determine their effect of the neutral current. The first fault was a short-circuit across 8% of the winding at 42% winding from the line end. This fault produced a reduction in the total inductance of the winding and the electromagnetic component of the neutral current increased by approximately 10%.

The second fault was a "solid fault" to earth at 50% winding from the line end. This fault produced the characteristic reversal of the neutral current which was predicted in Section 1.4 due to mutual coupling. Fig. 9 shows the equivalent circuit for this fault condition.

A cylindrical earth screen was now fitted inside the experimental winding stack. This increased the total shunt capacitance of the winding to earth from 170 micromicroseconds to 800 micromicrofarads. This shunt capacitance would now be fairly evenly distributed along the winding stack, so that each of the twelve bobbin coils would have a shunt capacitance (Cge) of approximately 70 micromicrofarads.

The inductance of the winding was unchanged since the earth screen is made so that it does not provide a short-circuited turn.

Fig. 13(d), (e) and (f) show the oscillographic results for this part of the experiment. The neutral current under no fault conditions is shown in Fig. 13(d). It can be seen that the increase in the shunt capacitances of the winding section has produced a substantial change in the waveform. Before considering the reason for this change, the tank current under no fault conditions should be examined.

The waveform of the tank current, that is, the current flowing through the shunt capacitances to the earth screen and thence to earth through a 1000 ohm measuring shunt, is shown in Fig. 13(e). The initial peak is due to the charging of the shunt capacitances (Cge in Fig. 1) during the wave front of the applied surge. The remainder of the wave is of an oscillatory nature with numerous irregularities. The basic wave shape was predicted in Section 1.3 - "Currents flowing to the Terminals and to the Tank", when the close relationship between tank current and voltage distributions through the winding is described in detail.

The tank current waveform shown in Fig. 13(e) also confirms the modified transmission line theory due to Ganger (Ref. 27) and fully described in Section 1.3. During the first fundamental time, the initial charging of the shunt capacitance elements takes place and the first positive half-cycle of the tank current occurs. At the end of this time the voltage wave reaches the earthed end and it reverses direction and polarity. This causes the tank current to become negative.

In Fig. 13(e) it can be seen that this occurs at approximately 20 microseconds after the application of the test voltage at the line terminal. Since the total conductor length of the experimental winding stack is 1070 feet (3270 metres) this corresponds to a velocity of propagation of 540 feet per microsecond (164 metres per microsecond).

Although this experiment was conducted with the winding in air, the propagation constant compares favourably with the values established by Elsnar (Ref. 14) and Ganger (Ref. 27) of 146 metres/ microsecond and 150 metres/microsecond respectively for oil-immersed units.

Having ascertained the nature of the tank current it is now profitable to examine its relationship to the neutral current. In Fig. 13 (d) a dotted waveform has been superimposed on the recorded oscillograms of applied voltage and neutral current. This waveform was obtained by subtracting the instantaneous values of tank current (i_T in Fig. 13(e)) from the corresponding instantaneous value of the electromagnetic component derived previously (i_{NC} in Fig. 13 (a)). The electromagnetic component must remain the same when the earth screen is inserted into the experimental winding, since the total inductance of the winding is unaltered.

It can be seen that the waveform of $i_{NC} - i_T$ follows fairly closely the neutral current waveform recorded in Fig. 13(d). The reason for this important relationship is not immediately apparent, However by using the basic transformer impulse test circuit shown in

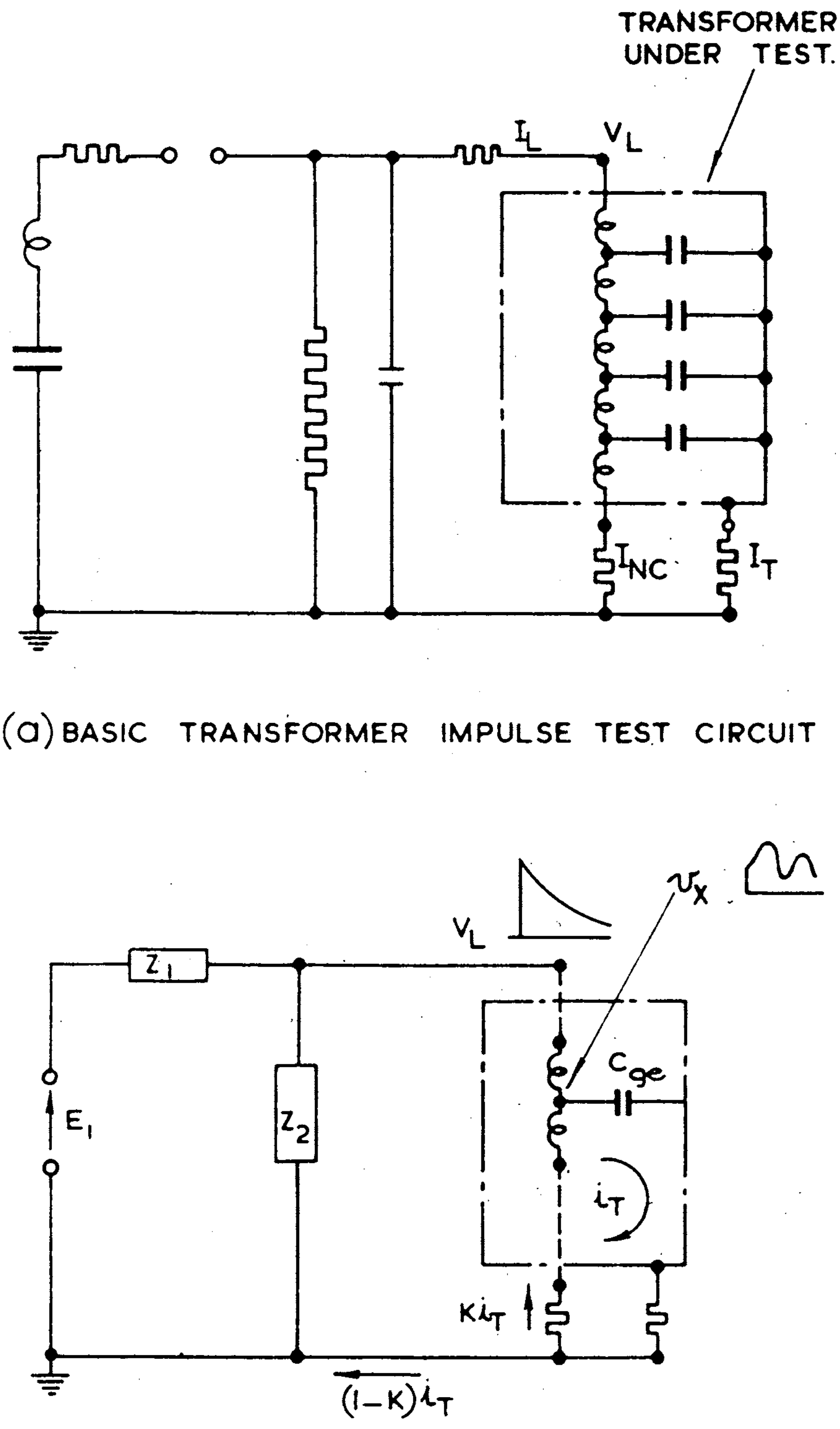
Fig. 15 as a starting point, one can produce an equivalent network which demonstrates the reason. In Fig. 15 (b) the test circuit has been reduced to its fundamentals and only one element of the ladder network shown. An oscillatory circuit is formed by the parallel connection of the inductive series element and the shunt capacitive element of the equivalent transformer network. The impulse generator presents an alternative path to that through the neutral end of the winding so that not all of the current through the shunt capacitances (Cge) appears in the neutral current shunt. The proportion is represented by the factor K in Figure 15(b).

The fact of this relationship between the tank current and the oscillatory component of neutral current enables neutral current records to be more readily analysed. As shown in Section 1.3, the tank current under "No Fault" conditions is dependent entirely on the voltage behaviour of the winding and the value of the shunt capacitance elements.

Conversely, records of the tank current, and of the neutral current, obtained using non-inductive resistive shunts provide an indication of the voltage behaviour during an impulse test. This fact is utilised in a later experiment.

A comparison between the tank current waveform and the derived tank current waveform shown in Fig. 7 confirms this hypothesis.

These relationships do not appear to have received sufficient emphasis in previous literature. It is the author's opinion that they are very important foundations on which to build a satisfactory understanding of the subject.



(a) BASIC TRANSFORMER IMPULSE TEST CIRCUIT

(b) EQUIVALENT NETWORK WITH DRIVING VOLTAGE E_I.
(ONLY ONE SECTION OF TRANSFORMER NETWORK SHOWN)

FIG. 15 DIAGRAM ILLUSTRATING HOW A COMPONENT OF TANK CURRENT (I_T) CIRCULATES IN THE EARTHED END OF THE WINDING UNDER TEST.

At this stage, that is, with a cylindrical earth screen inserted into the winding stack without any core, an experiment was conducted to investigate the effects of the propagation of the major voltage stress through the winding.

The progress through the winding of the peak voltage stress both to earth and between winding sections, has been described in Section 1.2. Considering that most transformers subjected for impulse test will have had some preliminary works tests at power frequency, it is unlikely that a low resistance fault between winding and earth, or between winding sections, will be present at the start of the impulse test. Any fault which does develop, will probably require several hundred volts to produce rupture of the dielectric at that point. This is particularly true for winding to earth faults.

Added to this is the fact that the transformer will have been subjected to a 75% calibration test, normally without failure. It can be seen that breakdown at a given point in a winding is unlikely to occur until the voltage stress at that point approaches its first peak value. This behaviour has been noted by Elsnar (Ref. 14) and (——) (Ref.43) under full scale impulse test conditions. (See also Section 1.2).

The oscillograms shown in Fig. 13 (j) show how the voltage at say, 50% from the line end does not reach a significant value until approximately 12 microseconds after the application of the test voltage. However at 25% from the line end the same voltage is reached in approximately 4 microseconds. Assuming the same dielectric strength at both points it follows that a failure at 50% from the line end will occur later than an identical failure at 25% from the line end.

The tank current records shown in Fig. 13(f) were obtained with the earth screen fitted inside the experimental winding stack and under the following conditions.

(a) No fault on the winding.

(b) A "Sparking" fault to earth at 85% from the line end.

(c) " " " " " " 50% " " " "

(d) " " " " " " 25% " " " "

The "Sparking" fault was made by a neon tube which was connected between each point in turn, and the earth screen. This simulated a flashover to the tank under actual fault conditions. Comment on the oscillograms is given below:

(a) Since conditions are the same, the "No fault" oscillogram is the same as that shown in Fig. 13 (e).

(b) With the fault at 85% from the line end the tank current record is identical to the "No Fault" oscillogram until approximately 17 microseconds have elapsed. At this instant a discontinuity occurs due to breakdown of the neon tube similating an insulation failure at a point 85% from the line end. After this instant the tank current has a D.C. component which is a portion of the electro-magnetic component which now flows direct to the tank instead of through the neutral end of the winding.

(c) The waveform under these conditions again follows the "No fault" waveform but only for about 10 microseconds.

Then the "sparking" fault occurs and an electromagnetic component flows. This component is appreciably greater than that which flowed under condition (b).

(d) The behaviour here is similar but only 5 microseconds elapse before the voltage stress at 25% from the line end, reaches the flashover values. The electromagnetic component is now very large and the oscillogram trace leaves the recording film at a high vertical rate.

From this experiment it can be seen that a linear relationship between time to breakdown and distance to the fault exists. Graphs for faults of this type to earth and between windings have been published by Elsner (Ref. 14) and (-) (Ref. 43) respectively.

The graphs, which show the linear relationsiip, were derived from full scale impulse tests. Naturally this relationship is of great importance for fault location.

The differences between the electromagnetic components for different fault locations provide a further indication of the fault position.

The electromagnetic component is a function of the applied voltage (v) and the total inductance (NLe) - see Section 1.3. Hence if the impulse generator maintains a fairly constant output voltage under the various fault conditions, the electromagnetic component will increase as the total inductance is reduced by the fault to earth occurring nearer the line end. Whilst a definite relationship cannot be established due to the variations of generator impedance encountered in practice, it is felt that the technique represents a valuable check on the elapsed time method of fault location. Although the latter method has been well described in the literature (Ref. 14 and Ref. 43), the observations made concerning the magnitude of the electromagnetic component appear to represent original work.

The last experiment using the experimental winding stack involves insertion of a stalloy core through the centre of the winding. The earth screen is left inside the winding so that no change in the equivalent capacitive network occurs, only in the inductive parameters.

The main result of this alteration to the composite winding arrangement is to reduce the electromagnetic component to a very low value. This is remarkable because many authorities stress that the flux penetration into the iron core is almost negligible. Ganger, for instance, calculates that the magnetic flux penetration at 500 Kilocycles per second is 0.0178 millimetre (Ref. 27). Also Waldvogel and Rouxel (Ref. 37) used only a cylindrical sheet of transformer steel to represent the core in their experimental winding. The latter used a 16,000 cycles per second supply for direct measurement of the experimental winding parameters. Above this frequency they found that the inductance of the winding elements (Le in Fig. 1 (b)) remained substantially constant as the frequency was increased, indicating that the maximum skin effect is present at 16,000 cycles per second.

The findings mentioned above are applicable to calculations of the voltage behaviour during the first 20-30 microseconds, when the frequencies involved are relatively high. However lower frequencies also have to be considered in fault detection problems and the author considers that the results of this last experiment show that the core plays a very important part.

At this stage artificial winding faults applied to the experimental winding showed that the percentage change of the neutral current for a short-circuit across a given portion of the winding was greater with the core inserted than without it. This is due to the increase in the mutual coupling between winding sections (M' and M" in Fig. 1(a)) due to the presence of the core. This increase was previously demonstrated by the 1000 cycle per second measurements described in Section 2.2.

A further demonstration of the effect of frequency and the presence of the core on the mutual coupling was obtained from an experiment carried out at power frequency. A 200 kVA 50 c.p.s., 11000/415 volt Type ON Three-phase transformer was energised from a 100 cycle per second supply and the effect of a single turn fault determined.

The transformer connections were delta-star and the tapping position was "Normal". The impedance of this transformer was 5.16%. The windings are:

H.V. - Bobbin type, 8 off, round wire.

L.V. - Single layer, multi-strand.

The test connections were as shown in Fig. 6(b) (2). A single phase 100 c.p.s. supply was connected to the H.V. winding in place of the impulse voltage shown in Fig. 6(b) (2), i.e. between B phase H.V. terminals and A and C connected together. Under no fault conditions with 1000 volts RMS applied, the magnetising current flowing was 0.0105 amp.

A single-turn fault was then simulated by wrapping a shorted turn around the centre of the B phase stack. The current taken with 1000 volts applied increased to 0.042 amp, i.e. a 400% increase. As is shown by a later experiment, the increase in the electromagnetic neutral current component of a bobbin type 500 KVA 10000/415 volt transformer under impulse test conditions with a one turn fault, is almost negligible.

Thus it can be seen that mutual coupling and frequency have an important bearing on fault detection sensitivity for interwinding faults.

Fig. 13(h) shows the tank current waveform with the core inserted into the experimental winding. Since the capacitance network is unaltered the substantial differences between Fig. 13(e) and Fig. 13 (h) must be due to changes in the voltage behaviour of the winding. Once again attention is drawn to the greater discrepancies occurring as the lower frequencies become prominent, i.e. after the first 10 microseconds.

The relationship between tank current and the oscillatory component of the neutral current is still evident, although the increase in inductance causes a greater proportion of the high frequency component to circulate through the impulse generator rather than the neutral end of the winding.

Although the study of voltage distributions in transformer windings is a complex subject outside the scope of this thesis, records were made at this stage, using the fully assembled experimental winding, for the purpose of illustration. The resulting oscillograms, shown in Fig. 13 (j), were obtained using special care that the minimum of capacitance to earth was connected in parallel at the measuring point. The applied surge voltage is measured by a 12:1 capacitance voltage divider fitted in the Recurrent Surge Generator. To avoid using this divider to measure the voltage at 25% and 50% from the line end, the magnitude of the applied surge was reduced so that the voltages at each point in turn could be connected directly to the plates of the cathode ray tube.

It can be seen that the voltages to earth at 25% and 50% from the line end conform to the standing wave solution given in Section 1.2. The progression through the winding of the maximum voltage stress is also illustrated.

The physical nature of various types of faults is considered later in Section 2.8. However it must be mentioned here that the possibility of transient flash-overs occurring during full wave testing must not be overlooked. In such a case two main problems present themselves:

(a) Interpretation of the oscillographic evidence using interpolation between established "NO FAULT" and "SOLID" or "SPARKING" fault records. A "SPARKING" fault is defined as that type of fault which occurs during the test and persists until the end.

(b) Determination of whether or not the fault has affected the service life of the transformer under test.

The duration of a transient fault will depend on the voltage occurring at the fault, the characteristics of the damaged dielectric and the amount of ionised material present at the fault. The latter factor is related to the energy released by the occurrence of the fault.

Attention is drawn to the fact that a low output impedance generator will enhance the possibility of maintaining a fault of this type for the duration of the test.

In the following section the fundamental behaviour under Chopped Wave Tests is considered and similar aspects of transient and sparking faults have to be considered.

2.3 2 Behaviour under Chopped Wave Test Conditions.

The Chopped Wave Test is intended to simulate the service condition where a flashover occurs externally at the transformer terminal a few microseconds after the arrival of the surge voltage.

The waveform of the impulse voltage to be used for Full Wave Tests is practically standardised internationally by B.S.923-1940, A.S. C57.12 - 1949, C57.22 - 1948 and a recent IEC Technical Committee No. 42 Draft Specification on High Voltage Testing Techniques. However due to lack of international agreement, the impulse voltage waveform for chopped wave tests is not standardised. British practice, however, is to specify an applied wave of the same shape as the standard full wave but with a peak value 15% greater than the specified full wave peak value. This applied wave is to be chopped by a rod-gap or other means connected between the transformer terminal and earth (Ref. 44). The time to chop is generally accepted as approximately three microseconds. The earth connection of the chopping gap is made direct so that the gap current does not flow through the tank or neutral current shunts (Fig. 6).

The time to chop when using a rod-gap is not consistent and sphere gaps are being used to overcome this irregular behaviour since a consistent time to chop is essential for fault detection using oscillographic records (see later). The best way to achieve this object appears to be the use of a trigatron type chopping gap. In this arrangement a small voltage appearing in the test circuit on application of the surge is used to fire a trigger electrode which initiates the main chopping gap and ensures its consistent firing.

An appreciation of the voltage behaviour of transformer windings under chopped wave test conditions is necessary before considering fault detection under these conditions. Fig. 16 shows that, by employing the principle of superposition, a chopped wave can be considered as the result of two full waves. The first wave is the normal full wave with its peak value increased to 115% and the second wave is of opposite polarity and with a very steep wave front depending on the chopping time, usually less than 0.25 microsecond. The chopped wave form is the sum of these components.

Up to the time of the chop the voltage behaviour of the winding will be identical with that occurring under full wave test conditions, except that the voltages to earth and between winding sections is increased by 15%. It should be noted that this fact increases the possibility of a failure during the first three microseconds of the chopped wave test.

Thomas (Ref. 10) has shown experimentally that the chopping of the applied wave can produce a substantial increase in the intercoil stresses. One of Thomas' oscillograms demonstrating this is reproduced in Fig. 16. The reason for the increase is shown by consideration of the effect of the hypothetical full wave voltage, of opposite polarity to the applied wave, which is assumed to be superimposed at the instant of chopping. Since the chop time is very small, usually less than 0.25 microseconds, the front of this component wave is very steep. This produces a more severe initial

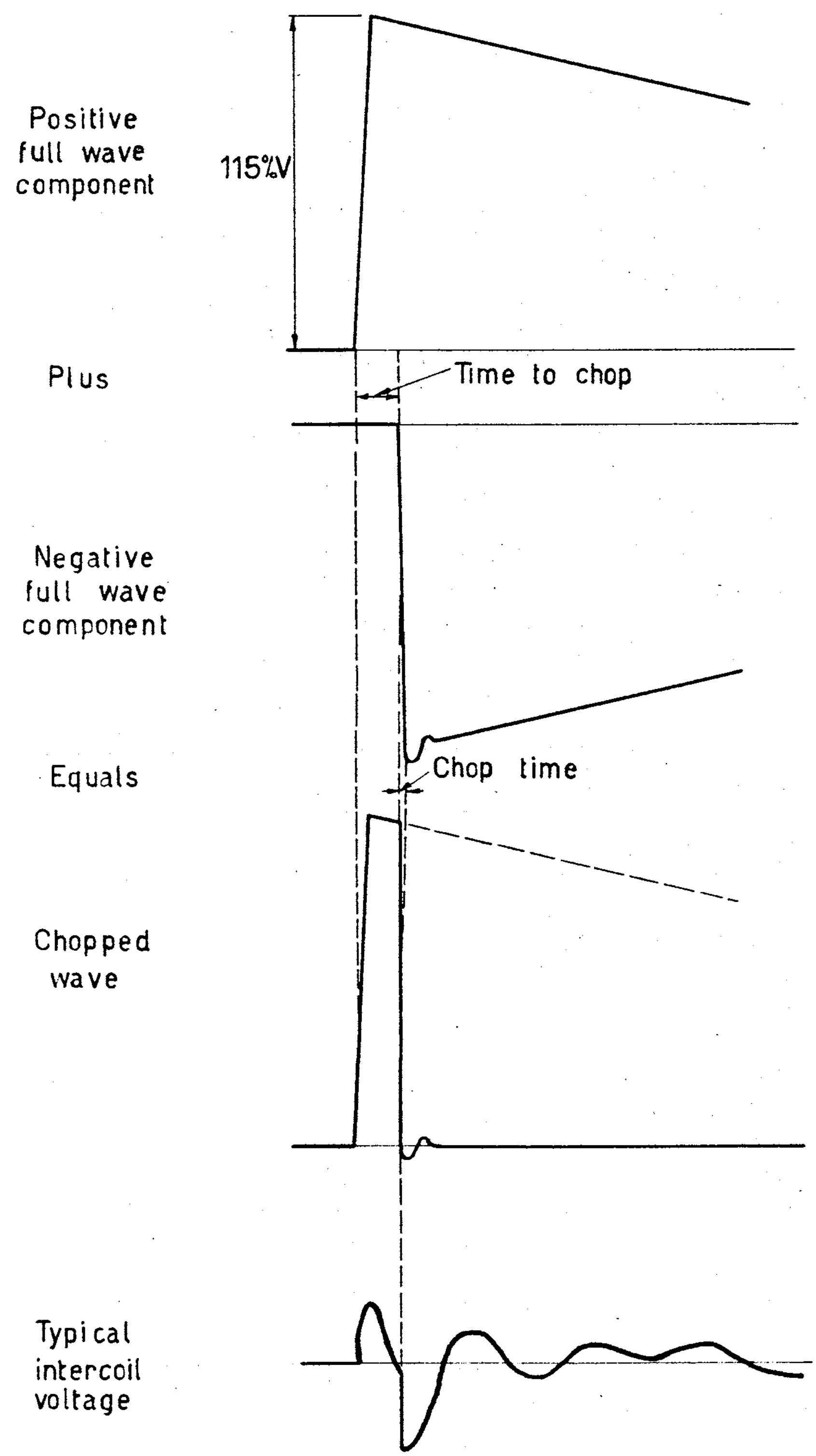


FIG: 16 Synthesis of a chopped wave form using the Superposition Principle and illustrating the increase in intercoil voltage.

NOTE: V is the peak value of the corresponding full wave test voltage.

voltage distribution and subsequent oscillations with consequent increases in the intercoil voltage stresses.

It will be seen that the chop produces oscillatory intercoil voltages generally similar to those produced by the full wave, but in the inverse sense and superimposed on the latter. If the chop occurs at the instant when the intercoil voltage is at a maximum negative amplitude, the resultant peak is liable to be greater than the initial peak. Design experiments by an Australian manufacturer has confirmed these observations.

Except for the more severe voltages to earth which occur during the first three microseconds due to the 15% increase in the peak value of the applied voltage, the voltage stresses to earth do not present any problem. The chop shorts the line end of the winding to earth and the only voltages to earth which can now occur are those due to internal oscillations which occur as the stored energy of the winding is dissipated.

The energy which is stored in the winding prior to the chop is mainly electrostatic since insufficient time has elapsed for any substantial magnetisation of the core by the electromagnetic component of current through the winding. Rippon and Hickling (Ref.5) refer to the failure of the neutral current method, if based on changes in the electromagnetic component, under chopped wave test conditions due to the fact that $\int Edt$ is zero after the chop occurs. (See Section 1.3). It follows that the electromagnetic component is zero after the instant of chopping.

Considerable electrostatic energy is stored in the transformer winding however, mainly in the shunt capacitance elements (Cge in Fig. 1) and this energy takes some tens of microseconds to dissipate. Provoost (Ref. 15) shows that the duration of a short-circuit across portion of the winding caused by a flashover under impulse test conditions is considerable. The ionised path created by the fault current persisted and the duration of the short-circuit was obtained experimentally for two sizes of transformer:

(a) 15 KVA 8300/267 volts Star-Star transformer
Time to chop = 2 microseconds
Winding involved = 2.4%
Duration of Short-circuit = 15-20 microseconds.

(b) 1000 KVA 50/10 Kilovolts Star-Star Transformer
Time to chop = 2 microseconds
Winding involved = 0.9%
Duration of Short-Circuit = 80-100 microseconds.

Provoost shows that as the time to chop is increased so does the duration of the fault. This is due to the increase in the amount of stored energy which has to be dissipated after the chop occurs. These results prove to be of considerable importance in the problem of fault detection under impulse test conditions.

The fault detection possibilities during a chopped wave impulse test can be summarised as:

(1) An indication from the high frequency oscillations which are recorded in current or voltage oscillograms (i.e. the tank current, neutral current, transferred voltage, line current or L.V. capacitance current records).

(2) Application of a supplementary impulse or power frequency voltage in such a way that any fault current, produced

by the chopped wave test, is kept flowing whilst oscillographic records are made.

(3) Detection of a physical disturbance due to a fault within the transformer by observations of noise flame or smoke.

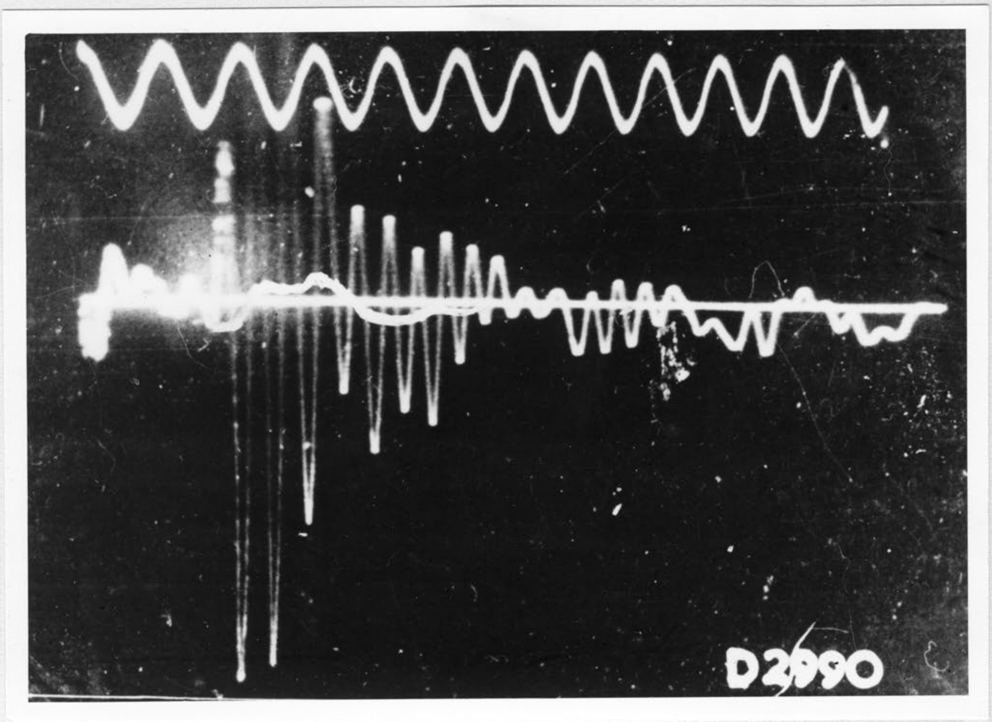
An analysis of some experimental results concerning the first two methods is now made but method (3) above is considered later (Section 2.8 - Physical Phenomena and their Detection). The experimental results were not obtained by the author but were taken from overseas experiments to illustrate the methods.

The first set of results examined were supplied by Mr. E.C. Rippon (Ref. 5) They relate to a chopped wave test at 250 KV on the 132 KV winding of a 75 MVA transformer. The oscillograms were recorded under No Fault Conditions.

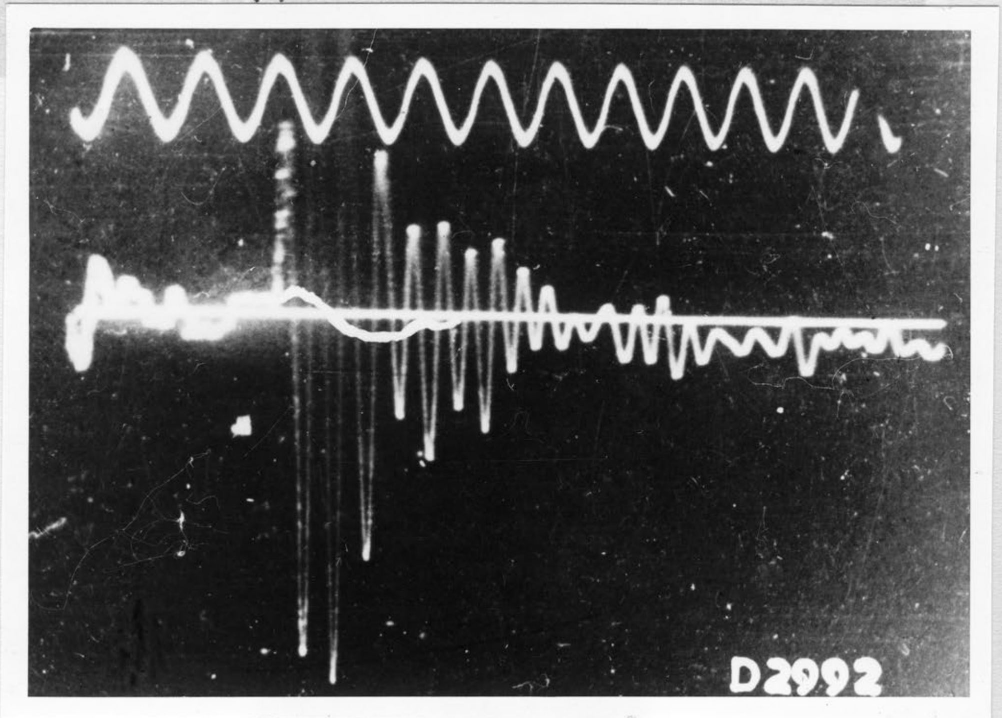
The first oscillogram (Fig. 17(a)) shows the neutral current waveform obtained when the applied wave is chopped after 3.5 microseconds. The normal full wave neutral current is sketched in for times after 3.5 microseconds for comparison purposes. It can be seen that large oscillations occur in the neutral current and that, as mentioned above, there is no electromagnetic component.

When the time to chop was increased from 3.5 to 5.5 microseconds the neutral current waveform shown in Fig. 17 (b) resulted. Once again the No Fault full wave neutral current is sketched on the oscillogram after the instant of chopping.

Comparison between Fig. 17(a) and 17(b) shows that a different wave-shape resulted when the time to chop was increased to 5.5 microseconds. Such variations would nullify the value of

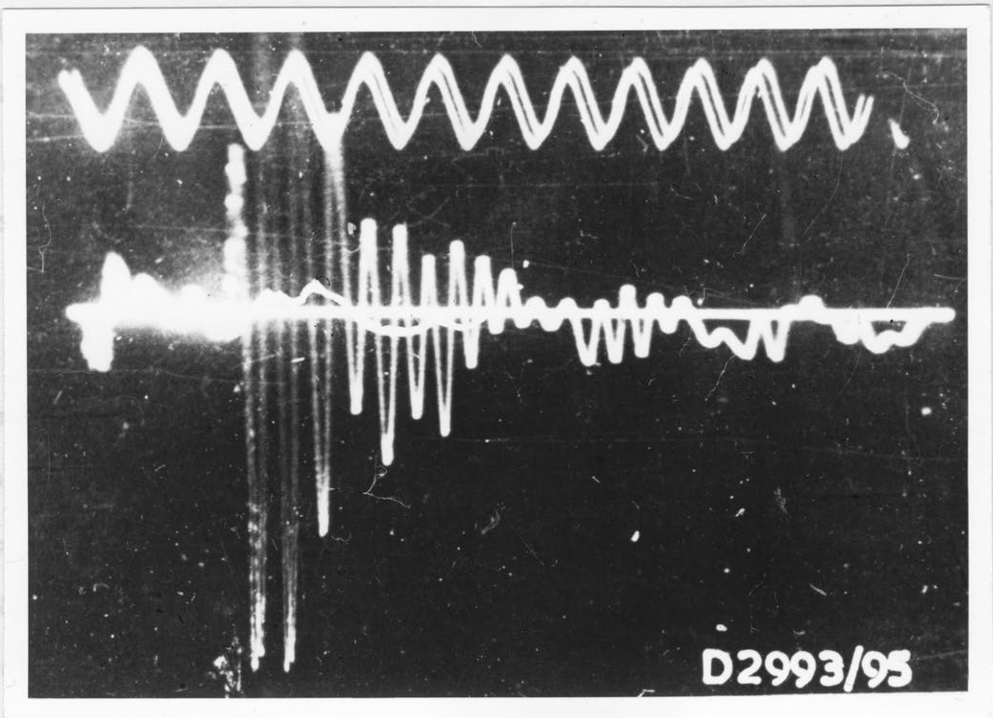


(a)



(b)

Fig. 17 : Neutral Current Oscillograms taken during a 250KV(40% Test Level) Chopped Wave Test on the 132KV winding of a 75MVA transformer. See next page for(c). 500Kc Timing wave.



(c)

Fig. 17 continued.

a neutral current oscillogram for fault detection during a chopped wave test. Consequently, as stated at the beginning of this sub-section, special measures must be adopted to ensure that the time to chop is consistent.

In Fig. 17 (c) two neutral current oscillograms of two separate tests under the same conditions as above and with the same time to chop for each test (3.5 microseconds) are superimposed. It can be seen that there is good agreement. This consistency and other experience has led Rippon and some other authorities (including those in the USSR - see Ref. 43) to base their fault detection methods on the neutral current, tank current or transferred voltage records. Elsner (Ref. 14) is particularly optimistic but his experimental results are not completely convincing. From the records shown in Fig. 17 it can be seen that interpretation is more difficult than for full wave tests. Considerable experience of full scale chopped wave impulse testing would be necessary to determine whether such a method is satisfactory.

Provoost (Ref. 15) points out the inherent difficulties of the high frequency method (No. 1 above) as:

(a) The necessity to develop a special chopping device to ensure that waves are chopped after an absolutely constant time interval.

(b) When testing a large transformer with a one microsecond wave front, the discharge currents from the generator to the transformer are so high that sparking in the earth circuit is practically inevitable. This leads to high frequency disturbances in the oscillograms.

(c) The possibility that the chopping gap may not break down with the same mechanism in every respect at different voltages (i.e. at the calibration level and at the test level, say). This may result in high frequency changes even though no fault has occurred.

(d) The effect of corona will be different at different voltage levels.

As a means of overcoming the above difficulties and producing more definite oscillographic evidence of failure Provoost has recommended two approaches to Method No. 2 (see Fig. 18):

(a) Simultaneous application of the chopped wave test voltage to the winding under test and an auxiliary power frequency voltage to the untested winding (Fig. 18 (a)). The loading resistance (R_L) across the HV winding allows a power frequency load current to flow in the winding under test. The impulse test voltage is synchronised with the auxiliary power frequency voltage so that it is of the same polarity as the load current flowing at that instant. Short-circuit of a section of the winding by a fault during the test would cause an increase in the power frequency current flowing and this would be detected by the electromagnetic oscillograph in the excitation circuit.

(b) Simultaneous application of the chopped wave test to the winding under test and an auxiliary reduced magnitude full

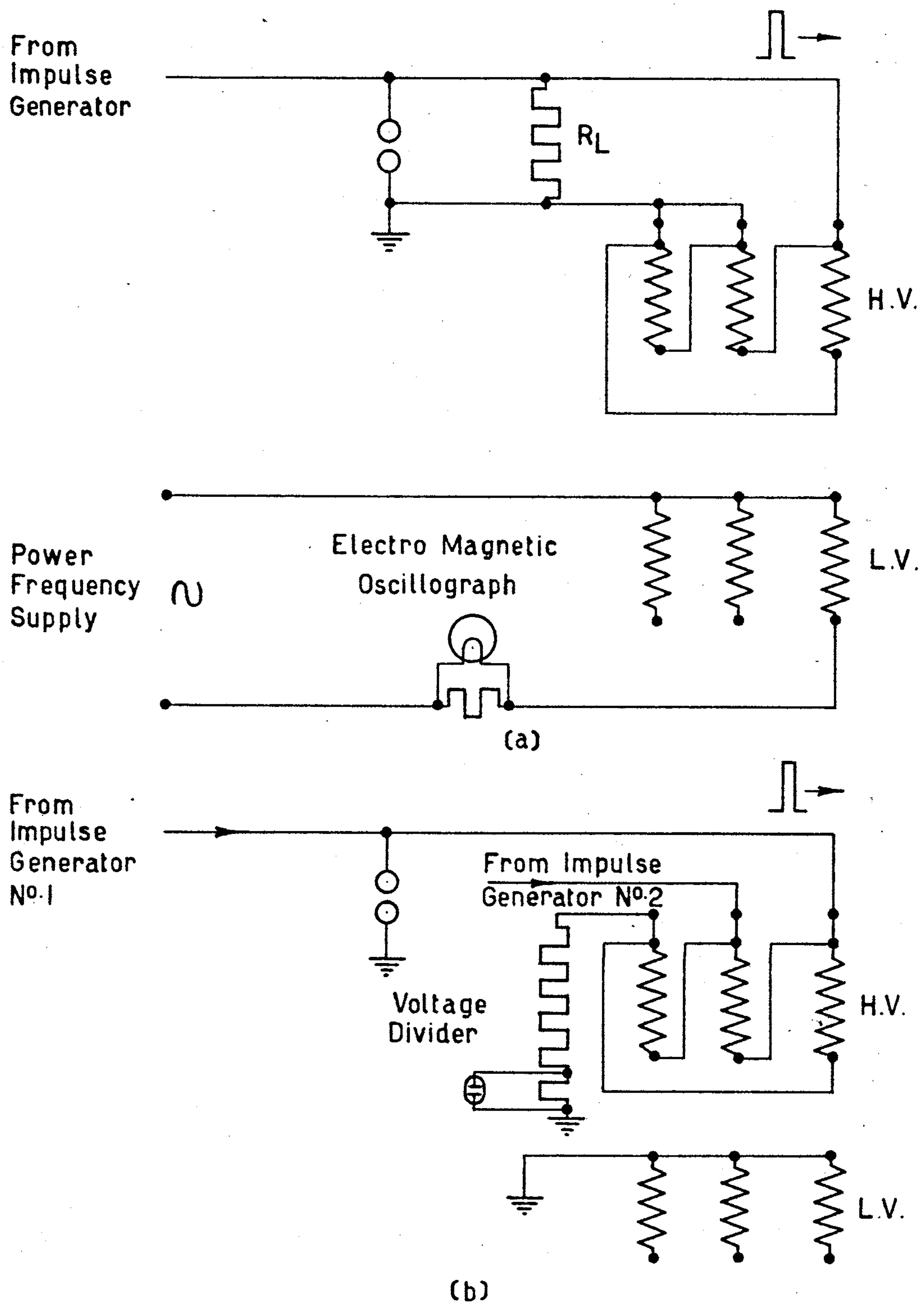


Fig. 18 : Recommendations by Provoost for Fault Detection During Chopped Wave Impulse Tests.

wave impulse voltage to an adjacent phase.

The auxiliary wave is of such a polarity that it will maintain the current flowing through the fault path, thus enabling full wave fault detection methods to be used. Provoost has developed the method primarily for tests with other line terminals unearthed, in which case fault detection is based on transferred voltage records. It appears that the principle could be applied to the test connections recommended herein (see Section 2.4).

In view of the length of time the short-circuit persists at the point of failure, a more satisfactory variation of Provoost's proposal (b) above suggests itself. This would be the application of the auxiliary reduced magnitude full wave at the terminals under test a few microseconds after the chop has occurred.

These results of experiments carried out overseas emphasise the difficulties of fault detection under chopped wave conditions without revealing any simple solution.

However consideration of the service conditions on which impulse testing procedures are based show that the position is not as serious as it appears at first. When a chopped wave appears at the terminals of a transformer in service it normally means that an external flashover has occurred. This flashover will produce a power frequency fault which will operate the protection and thus remove the possibility of any power frequency fault current flowing in the transformer itself.

The normal impulse testing procedure in Britain and the

U.S.A. is to carry out a full wave test after the chopped wave tests. If any permanent damage which would affect the service operation of the transformer has been done during the chopped wave test, then the subsequent full wave test will detect it. If however no fault or only a transient fault of short duration occurred during the chopped wave test then the transformer will pass the full wave test. This would show that under service conditions the transformer would be in a fit state to withstand any surges impressed on it (within its Basic Impulse Level) after a chopped wave had appeared at its terminals.

2.4 Test Connections.

At the present time no other commercial high voltage test applicable to transformers is so closely related to service conditions as the impulse test. The Basic Impulse Level required for the transformer determines the impulse test voltage and the co-ordination of associated system equipment such as lighting arresters, switchgear, insulators etc.

Although a 25% reduction in power frequency test voltage is permitted for tests made after a transformer has been installed on site, no such reduction can be envisaged for the impulse test voltage. This close relationship between the actual impulse test and service conditions has a major bearing on the test connections.

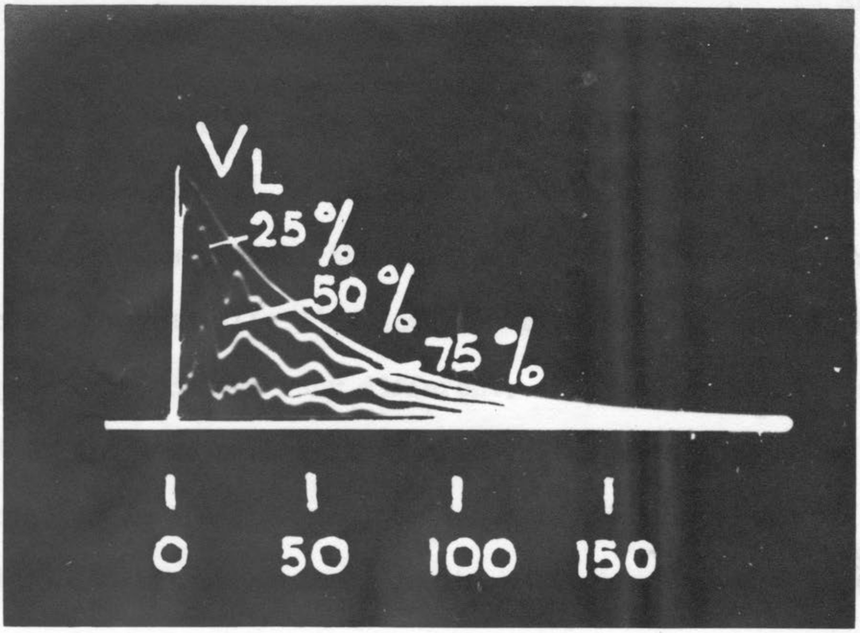
The optimum test connection depends on two main considerations:

(a) The winding under test - whether to earth the remote terminal(s).

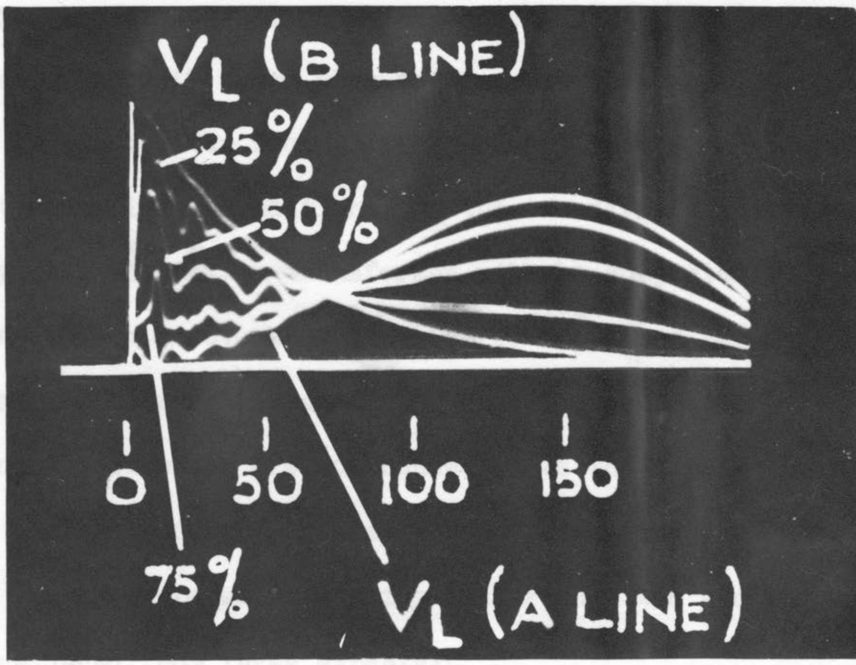
(b) The windings not under test - transferred voltages and the effects of short-circuiting these windings.

The earthing of remote terminal(s) of the winding under test is now examined. Fig. 19 shows the effect, on the voltage conditions, of not earthing the remote terminals of the delta-connected high voltage winding of a 200 KVA, 10,000/415 volt transformer, when the surge is applied to B line terminal. The experiment was conducted using the 2 KV recurrent surge generator. The high voltage delta-connected winding comprises eight (8) bobbin type coils per phase.

The oscillograms of the voltages appearing at the line terminal (B phase) being tested, and at three points through the winding



(a) Normal test connection with A & C line terminals earthed



(b) A & C line terminals unearthed.

FIG. 19: VOLTAGE DISTRIBUTION OSCILLOGRAMS SHOWING THE EFFECT OF NOT EARTHING THE REMOTE END OF THE WINDING.

Notes: Experiment made on H.V. winding of 200kVA 10,000/415V delta-star transformer. Basic test connection diagram No. 2 in Fig. 6(b). ("M")

(X = 25%, 50% and 75% respectively), have been superimposed so that intercoil voltages as well as voltages to earth can be readily ascertained.

It can be seen that the voltage behaviour over the first 20 microseconds is practically identical for each condition. Subsequently the voltage conditions are very different. The normal test connection with A and C line terminals earthed, and the impulse applied to B line terminal results in the intercoil voltages being maintained for periods of approximately 100 microseconds. In the case where A and C line terminals are left unearthed, however, the intercoil voltages become zero at approximately 70 microseconds. The subsequent low frequency oscillation of the voltages imposes severe stresses to earth but these are no greater in magnitude than will occur when the impulse is applied to A line terminal.

It can be seen from this experiment that a considerable difference exists between voltage conditions for the two different test connections. It is very unlikely that a transformer will be subjected to a surge unless it is connected to an overhead line (surge impedance 500 ohms) or an underground cable (surge impedance 50 ohms). Hence the terminals of the winding under test which are not connected to the impulse generator output, should be earthed through a resistance not exceeding 500 ohms.

The part played by windings other than the winding under test can be considered from three aspects:

(a) Insulation stresses produced by voltages transferred to these windings.

(b) The effect of shorting these windings on the voltage distribution in the winding under test.

(c) The effect of shorting these windings on the fault detection sensitivity.

Voltage is transferred to windings other than the winding under test by capacitive or magnetic coupling (see Fig. 1(a)). Relatively low impedance windings such as the 415 volt winding of a distribution transformer quickly dissipates any capacitance transfer and the magnetically transferred component predominates. This component is dependent on the turns ratio of the windings. However the relationship between the Basic Impulse Level and rated voltage does not decrease linearly. This means that for tests on the higher voltage winding the lower voltage winding is not overstressed. For the same reason tests on the low voltage winding normally produce excessive voltages in the high voltage winding. Table 2 below summarises the transferred voltages measured during experiments on several transformers. The details of these experiments are given subsequently in Sections 2.5, 2.6 and 2.7. Transferred voltages (peak values) are expressed as a percentage of the peak value of the voltage applied to the winding under test.

Table 2 - Voltages transferred to Windings other than the winding under test.

Transformer	Description	Transferred Voltages	
		HV to LV	LV to HV
B	Voltage Transformer	3%	-
P	500 KVA 10/0.415 KV	2%	-
O	400 KVA 10/0.415 KV	1%	-
Q	500 KVA 10/0.415 KV	2%	-
N	200 KVA 33/11KV	25%	320%
W	13,500 KVA 33/5.35 KV	14%	-

The above results cannot be regarded as a comprehensive guide since due to different winding constructions and voltage ratings considerable variations are possible. However it does appear that for the majority of voltage and distribution transformers, a reliable estimate of the transferred voltage can be based on the transformation ratio. In most cases it will be found that there is no need to shunt the lower voltage winding when the high voltage winding is tested.

Before carrying out an impulse test, recurrent surge measurements should be made to ensure that other windings will not be overstressed. If necessary high voltage resistances should be connected across the untested windings to reduce the transferred voltages appearing at the terminals. Two points which suggest the need for further investigation are:

(a) The shunt across the terminals of untested windings may not sufficiently reduce intercoil voltages at the centre of those windings.

(b) If severe transferred voltages appear under test conditions should not the possibility of them appearing under service conditions be considered? The Basic Impulse Level of a high voltage winding of a power transformer, for example, may have to be related to the turns ratio and the BIL of the lower voltage winding.

Holcomb (Ref. 12) has investigated this problem, as it relates to tests on distribution transformers. He recommends a 25 KV impulse, with a duration of 1-2 microseconds, for the testing of the low voltage windings of distribution transformers. He claims that this -

(a) simulates service conditions

(b) does not produce excessive voltages in the higher voltage winding.

Whilst (b) can be readily conceded, point (a) requires further investigation particularly since the impulse strength of insulation is related to the duration of the stress applied.

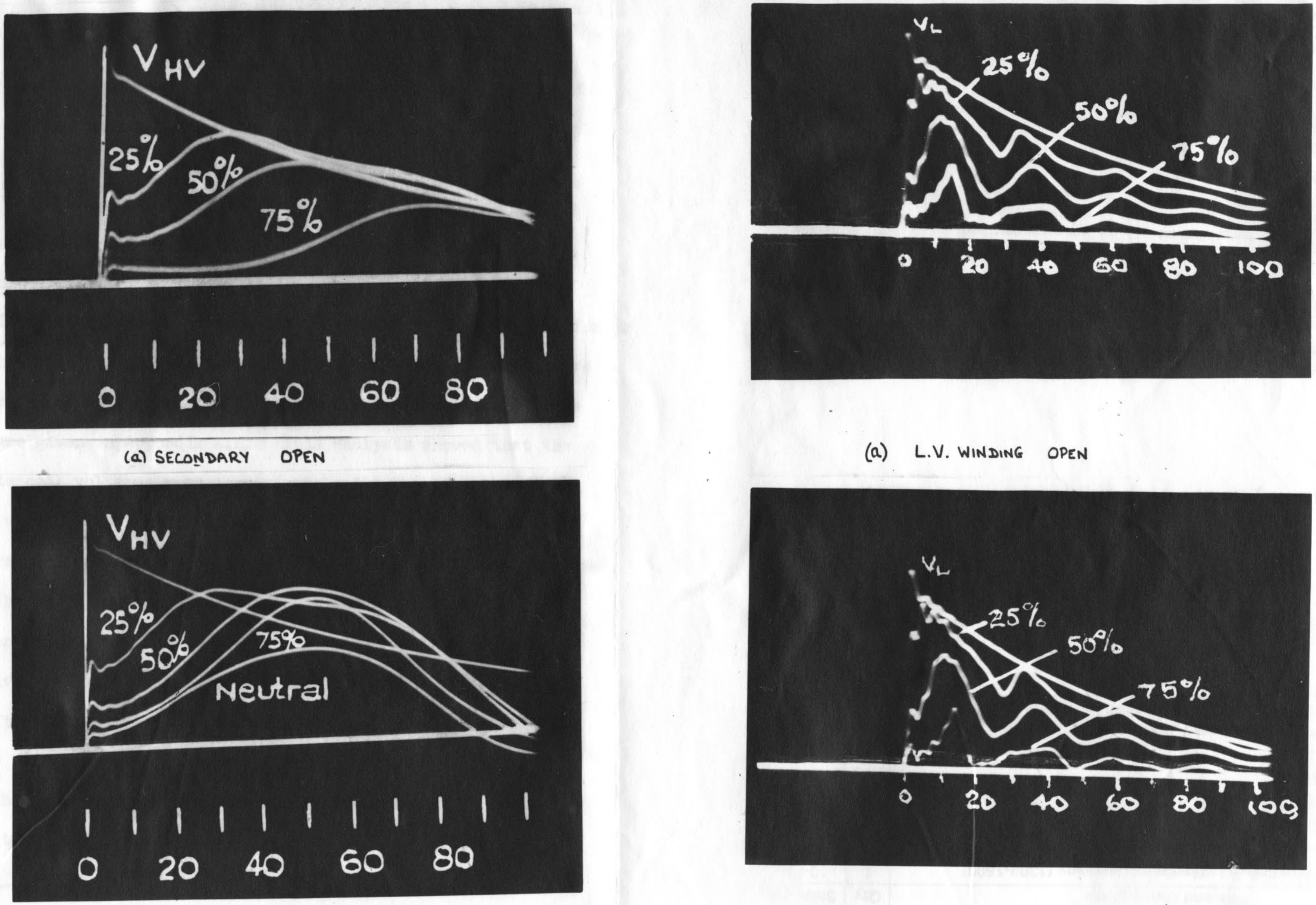
The effect on the voltage distributions of short-circuiting the other windings cannot be overlooked since, although this is not a service condition (Ref. 46), the other windings may have to be shorted or connected to loading resistances to reduce the transferred voltages described above. Two experiments have been conducted using the 2 kV recurrent surge generator to ascertain the effect on:

(a) an 11000/110 volts, 50 VA voltage transformer (Transformer B) star-star connected.

(b) a 200 KVA, 10000/415 volt distribution transformer (Transformer M). Delta-star connected.

A recurrent 1/50 wave was applied to each unit in turn using Test Connection No. 2 (see Fig. 6). A low capacitance lead direct to the vertical deflection plates of an oscilloscope was used to measure the voltage at the input terminal (V_L) and at points through the winding. The resulting oscillograms are shown in Fig. 20. The core and coils of each unit were standing in air for each experiment. Since the measurements were only intended for a first-order comparison, this necessary condition was accepted.

Transformer B had a star H.V. winding with insulated neutral. Each phase comprised a winding stack of four bobbin coils, each coil



(a) SECONDARY OPEN

(b) SECONDARY SHORTED

11000/110 VOLT VOLTAGE TRANSFORMER, STAR-STAR.

(a) L.V. WINDING OPEN

(b) L.V. WINDING SHORTED.

250 KVA, 10,000/415 VOLT, DELTA-STAR.

NOTE: SURGE APPLIED TO ONE LINE TERMINAL OF THE H.V. WINDING IN EACH CASE WITH THE OTHER TERMINALS EARTHED.

FIG. 20: OSCILLOGRAMS SHOWING HOW VOLTAGE CONDITIONS IN THE WINDING UNDER TEST ARE CHANGED BY THE SHORT-CIRCUITING OF OTHER WINDINGS.

comprising 2500 turns, layer wound. The voltages measured by direct connection to the intercoil junctions at X = 25%, X = 50% and X = 75% and at the neutral, are shown superimposed in composite oscillograms (Fig. 20). The upper oscillogram (a) shows these voltages when the LV windings were open-circuited. The voltage at the neutral was almost zero with respect to earth, in this case.

These oscillograms of the voltage conditions in this transformer (b) with the secondary winding open-circuited and short-circuited were analysed to determine the intercoil voltages. The resulting voltage waveforms are given in Appendix 4.4. This analysis showed that the maximum intercoil voltages were approximately the same for the first 25% of the winding but that the intercoil voltages further down the winding were much more severe when the LV winding is left open-circuited.

The experiment on the 250 KVA transformer (M) was conducted in a similar fashion and the resulting voltage to earth oscillograms are also given in Fig. 20. When these results were analysed it was found that the intercoil voltages were again more severe when the LV winding was left open-circuited.

The intercoil voltages, expressed as a percentage of the peak applied voltage, are given below:

<u>Voltage Transformer</u> (B)	LV Open	LV S/C
1st Bobbin coil	62	61
2nd " "	37	26
3rd " "	42	13
4th " "	31	22

200 KVA Transformer (M)

Line B to X = 25%	25	23
X = 25% to X = 50%	46	47
X = 50% to X = 75%	42	33
X = 75% to Line A	37	33

During the discussion on the paper by Rippon and Hickling in 1949 (Ref. 5), manufacturers' test engineers expressed strong opposition to test connections which did not enable windings other than the winding under test to be short-circuited and earthed. It would appear that this point of view has prevailed in Great Britain since Hickling, in his recent comment on the author's joint paper with G.C. Dewsnap (Ref. 42) states that all untested terminals are usually earthed solidly except on small wire wound units or on very large transformers where resistance earthing of secondary windings becomes necessary to obtain specified wave durations. He also states that short-circuiting of windings not under test gives maximum intercoil voltage stresses (See Appendix 4.1). The latter statement is contrary to the results of experiments on Transformers B and M described above.

From a theoretical view-point it seems that any reduction in the inductance parameters of the equivalent ladder network (Fig. 1) would damp the voltage oscillations and improve the voltage conditions after the first fundamental time. Admittedly the voltage conditions in transformer M did not change as much as would have been expected (see Fig. 20). Also Dr. Ganger found no change in the tank current waveform as he shunted the other winding of a 9 MVA 170/7KV single phase transformer with resistances ranging from 500 ohms to zero ohms. This can only be possible if the voltage conditions had remained the same (Ref. 27). In view of the above it appears that a large number of voltage distribution experiments would be necessary to draw a general conclusion as to the comparative severity of the voltage conditions.

Provoost, another authority on impulse testing expresses opposition to Hickling's viewpoint (Ref. 46) and states that "in actual service no winding is short-circuited". He considers that only when transferred voltages are excessive should the other windings be shunted and then only by the necessary resistances. The economic advantages to transformer manufacturers who do not use this procedure and who short-circuit the other windings for all tests, can be summarised as:

(a) No recurrent surge measurements of transferred voltage need be made, thus reducing testing time.

(b) There is no need to provide high-voltage resistors.

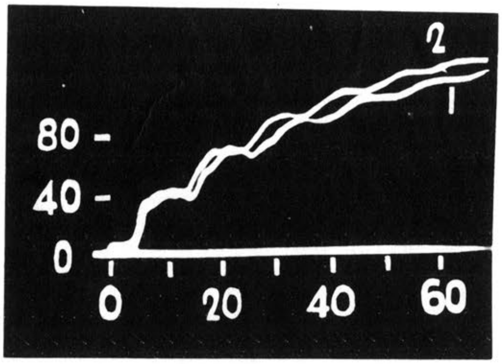
(c) The possibility of failure of windings other than the winding under test is reduced to a minimum.

It is considered that these factors should not be allowed to jeopardise the value of the impulse test as the high voltage test most related to service conditions. An example of the inherent danger of the practice of indiscriminate short-circuiting of other windings is given in Section 2.7.

The connection of windings other than the winding under test can also affect the fault detection sensitivity. Fig. 21 (a) shows the reduction in fault detection sensitivity which occurs when the low voltage winding of a 500 KVA, 10000/415 volt transformer (disc type winding) is short-circuited. The short-circuit across the low voltage winding reduces the inductance parameters of the high voltage winding by mutual coupling. This in turn increases the electromagnetic component of the neutral current (NOTE: different current scales for the two oscillograms of Fig. 21(a)) to such an extent that any further reduction caused by a fault between turns is difficult to detect.

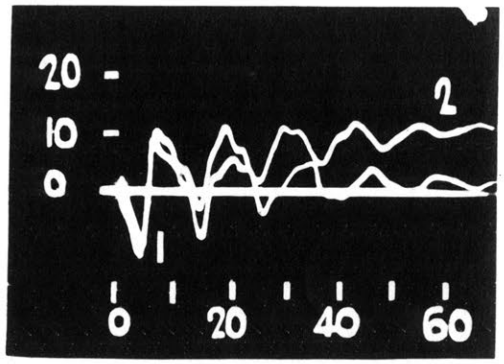
The neutral current oscillograms in Fig. 21(a) which were recorded with the low voltage winding not shorted, other conditions remaining the same, show that the percentage increase in the electromagnetic component is now considerably greater. Hence for fault detection methods based on an electromagnetic indication it is important that other windings are not short-circuited.

It is often convenient to carry out recurrent surge measurements to check the effects of other windings with the core and windings out of oil. Fig. 21 (b) shows that the electromagnetic indication is the same as for oil immersion but the electrostatic indication is altered. As would be expected from the theoretical treatment in Section 1.3 the magnitude of the oscillatory components are reduced due to the reduction in the shunt capacitance values when out of oil. The reduction in the series and the shunt capacitance parameters also increases the frequency of oscillation of the electrostatic component and introduces minor changes in waveform. It can be seen that certain comparitive recurrent surge measurements can be made with the windings out of oil provided that due allowance is made for the factors mentioned above.



I_{NC} – L.V. WINDING SHORT – CIRCUITED

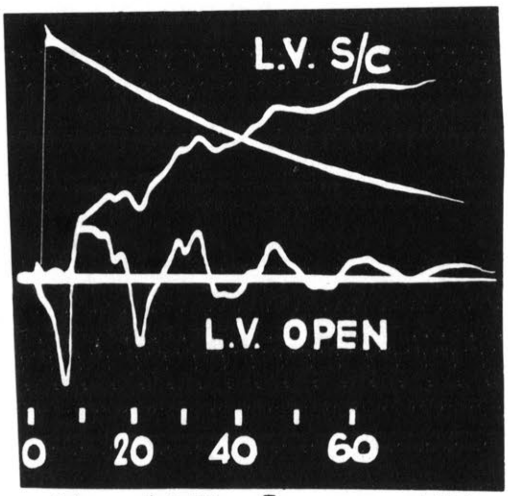
1. NF
2. SF – ONE TURN AT X = 5%



I_{NC} – L.V. WINDING NOT SHORTED

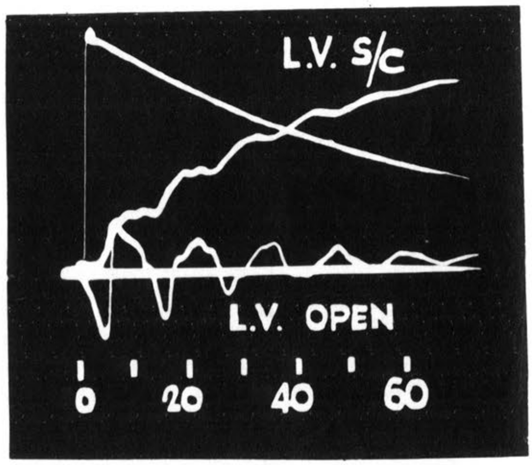
1. NF
2. SF – ONE TURN AT X = 5%

(a)



V_L AND I_{NC} – NF

CORE AND WINDINGS IN OIL



V_L AND I_{NC} – NF

CORE AND WINDINGS IN AIR

(b)

FIG. 21: RECURRENT SURGE OSCILLOGRAMS OF A 500 K.V.A. 10000/415 VOLT TRANSFORMER WITH DISC TYPE DELTA CONNECTED H.V. WINDING
TEST CONNECTION (2) IN FIG. CURRENT SCALE (AMPS) IS FOR A
100 K.V. 1 X 50 μSEC. APPLIED WAVE. TIME SCALE IN MICROSECONDS.

(a) EFFECT ON THE NEUTRAL CURRENT METHOD OF A SHORT CIRCUITED LOW VOLTAGE WINDING.

(b) EFFECT OF OIL IMMERSION.

Summary.

The results of this experimental investigation of the optimum test connections can be summarised thus:

Winding under Test:

Terminals remote from that to which the surge is applied must be earthed through resistances not greater than 500 ohms. This ensures the most severe intercoil voltages.

Other Windings.

Windings other than the winding under test must be considered as disconnected from any load or line shunt impedances since this may often be the case under service conditions. However, investigation of factors such as transferred voltages, voltage distribution in the winding under test and fault detection sensitivity under test conditions reveal that:

(a) Transferred voltages - When the higher voltage winding is being tested it is usually satisfactory to leave the lower voltage winding open. The reverse is the case when testing the lower voltage winding and it will usually be necessary to shunt the higher voltage winding with a high voltage resistance. Internal winding voltages may be severe even with this shunt connected.

(b) Voltage distribution in the winding under test - It appears that the optimum connection based on service conditions, i.e. with other windings open-circuited, produces the most severe intercoil voltage stresses in the winding under test. This

question however, requires further investigation particularly with respect to power transformers. In some designs the change in voltage conditions due to the short-circuiting of other windings may be insignificant.

(c) <u>Fault Detection Sensitivity</u> - Fault detection sensitivities of neutral current methods, using the electromagnetic component for indication, can be greatly reduced by the shunting of other windings. Neutral current methods based on the electrostatic indication, and tank current methods in general, should not be seriously affected.

2.5 VOLTAGE TRANSFORMERS AND DISTRIBUTION TRANSFORMERS TO 50 KVA.

The literature does not provide very many results of experiments and tests on this size of transformer. The experiments carried out by the author and described here deal only with voltage transformers since no opportunity presented itself to work o n small distribution transformers. However, due to similarities in winding design the results obtained can be related to distribution transformers up to 50 KVA.

Full design details of each unit were obtained whenever possible but since these are normally confidential they are not published here except as necessary to clarify the oscillographic results. For the same reason transformers are given a Code Identification Letter starting from the letter "B" for transformers in this range. The experiments are summerised in Table 3. Details of the experiments are given in Appendix 4. 5.

Table 3 - Experiments made on Voltage and Distribution Transformers up to 50 KVA.

Transformer	Description	Type of Winding	Nature of Experiment
B	11000/110 volt voltage transformer. Three phase 50 VA star-star.	Bobbin - HV Layer - LV	Voltage distribution. Fault detection Full Scale Tests
C	220KV/110 volt voltage transformer. Single phase.	Not known. Two LV windings Core insulated from earth and connected to midpoint of HV winding.	Fault Detection. Full Scale Test.

TRANSFORMER B

The experiments and tests on transformer B were carried out by the author in his capacity as a Test Engineer of The Sydney County Council Electricity Undertaking. The transformer formed part of a prototype outdoor 11 kV metering unit intended for direct connection to overhead 11 kV feeders. The unit had to be tested to prove general compliance with the Council's impulse testing specification for type tests, namely:

"Clause 9(g) - Impulse Voltage Test (S.C.C. Specification No. 2196)

It is desired that one transformer covered by each item of the contract should be submitted to impulse voltage tests consisting of:

(i) An application of a reduced full impulse voltage wave of between 50 and 75 per cent of the value of the full wave referred to in (iii) below.

(ii) Two applications of a chopped impulse voltage wave. The impulse wave shall have a crest voltage of 110 kV with time to flash over gap of 3 microseconds: the wave shall be chopped by an air gap.

(iii) Two applications of a full impulse voltage wave. The wave shall have a crest value of 95 kV and no failure or flashover shall occur.

The above tests shall be applied to the high voltage winding. Neutral current and/or line current records which will detect any failure affecting the service life of the transformer shall be taken.

The tests shall be applied to the high voltage terminals one at a time with the other terminals of the same winding earthed through whatever shunts are required to satisfy the abovementioned requirements. The low voltage winding neutral shall be earthed but other low voltage terminals must not be earthed. They must be protected by a gap having a 1/50 breakdown value of at least 25% below the impulse strength of the winding.

A nominal 1.0 x 50 microsecond positive wave shall be used for the impulse test and it shall otherwise conform to the requirements of BSS 923 - 1940 or later issues thereof."

This clause was drafted in its present form in 1957, to embody recommendations made by the author. These recommendations arose out of the work described herein.

The corresponding power frequency type tests specified are:

(a) Tests from a single-phase supply of sine wave-form for one minute at the following voltages:

Between higher voltage winding and lower voltage winding connected to frame -------- 23 kV

Between lower voltage winding and frame ------ 2 kV

(b) A three-phase induced voltage test, at a suitable frequency, of twice the rated voltage.

Before transformer "B" was placed in the metering unit tank, the voltage conditions in the HV winding were checked using the recurrent surge generator. The HV winding details are as follows:

3 phase, star connected, insulated neutral. Fully insulated.

Each phase consists of four (4) bobbin coils in series, Each bobbin coil comprises 2498 turns, layer wound, of 35 SWG.

Total turns per phase = 9992. Length of conductor per phase = 12,900 feet (3940 metres).

The voltage conditions in the winding (core and windings in air) are shown in Fig. 20 (a) and Appendix 4.4. The LV winding was earthed at the neutral and was on open-circuit for this experiment. The surge was applied to B phase HV line terminal with A&C terminals earthed.

On the basis of a 95 kV full wave test, the maximum voltages occurring in the windings are:

Voltage to earth at	X = 0	X = 25%	X = 50%	X = 75%	Neutral
KV (peak)	95	61	48	30	0
Voltage across	1st Bobbin	2nd Bobbin	3rd Bobbin	4th Bobbin	-
KV (peak)	59	34	40	30	-

Examination of the oscillograms shows that these maxima occur later in time as distance from the line terminal increases. This confirms Norris' results (Fig. 5) and the results obtained with the experimental winding when investigating the location of faults from tank current records (Section 2.3.1).

As a result of these voltage distribution measurements, a rearrangement of winding leads and connections was made to reduce the possibility of flashovers across the first bobbin coil. It was considered that due to the winding construction the voltage conditions in this transformer would not be seriously changed by oil immersion.

<u>Fault Detection Experiments</u>.

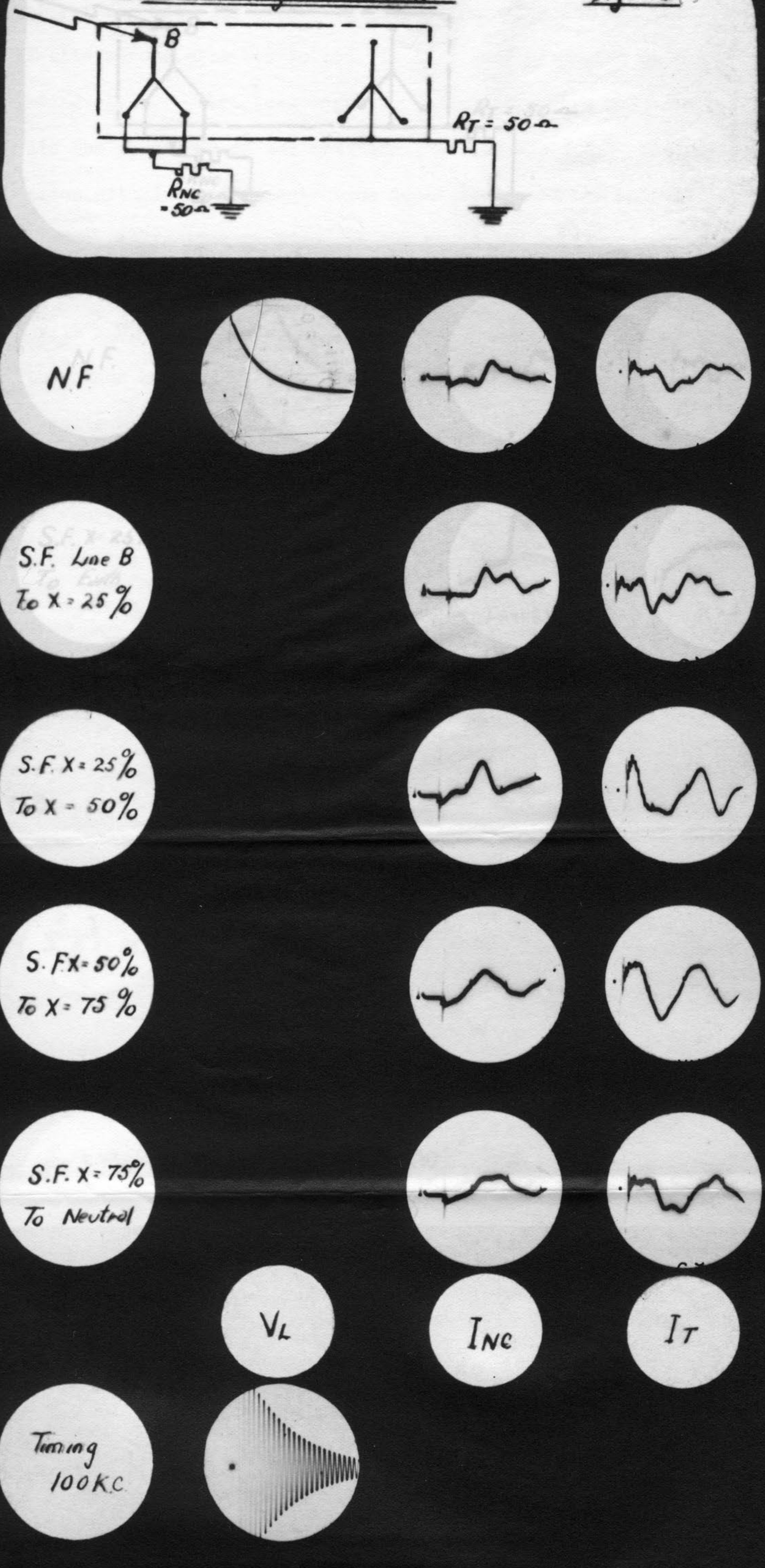
Fault detection experiments were then made with the windings and core in air. Test Connection No. 2 (see Fig. 6) was used and line voltage (V_L) neutral current (I_{NC}) and tank current (I_T) oscillograms were recorded using the recurrent surge generator, a commercial oscilloscope and camera. The oscillographic results are given in Fig. 22 (a) and (b).

The neutral current and the tank current waveforms under "no fault" conditions show that the fundamental time is approximately 63 microseconds. Since the HV winding is star-connected with an insulated neutral, this means that the propagation constant is equal to $\frac{2 \times 3940}{63}$ = 125 metres per microsecond. This differs from the normal figure of 150 metres per microsecond. The difference may be important for fault location purposes and is probably due to the bobbin type construction. The layers of each bobbin coil were thoroughly impregnated with varnish as the coils were wound. The different S.I.C. of the varnish may also have affected the propagation constant.

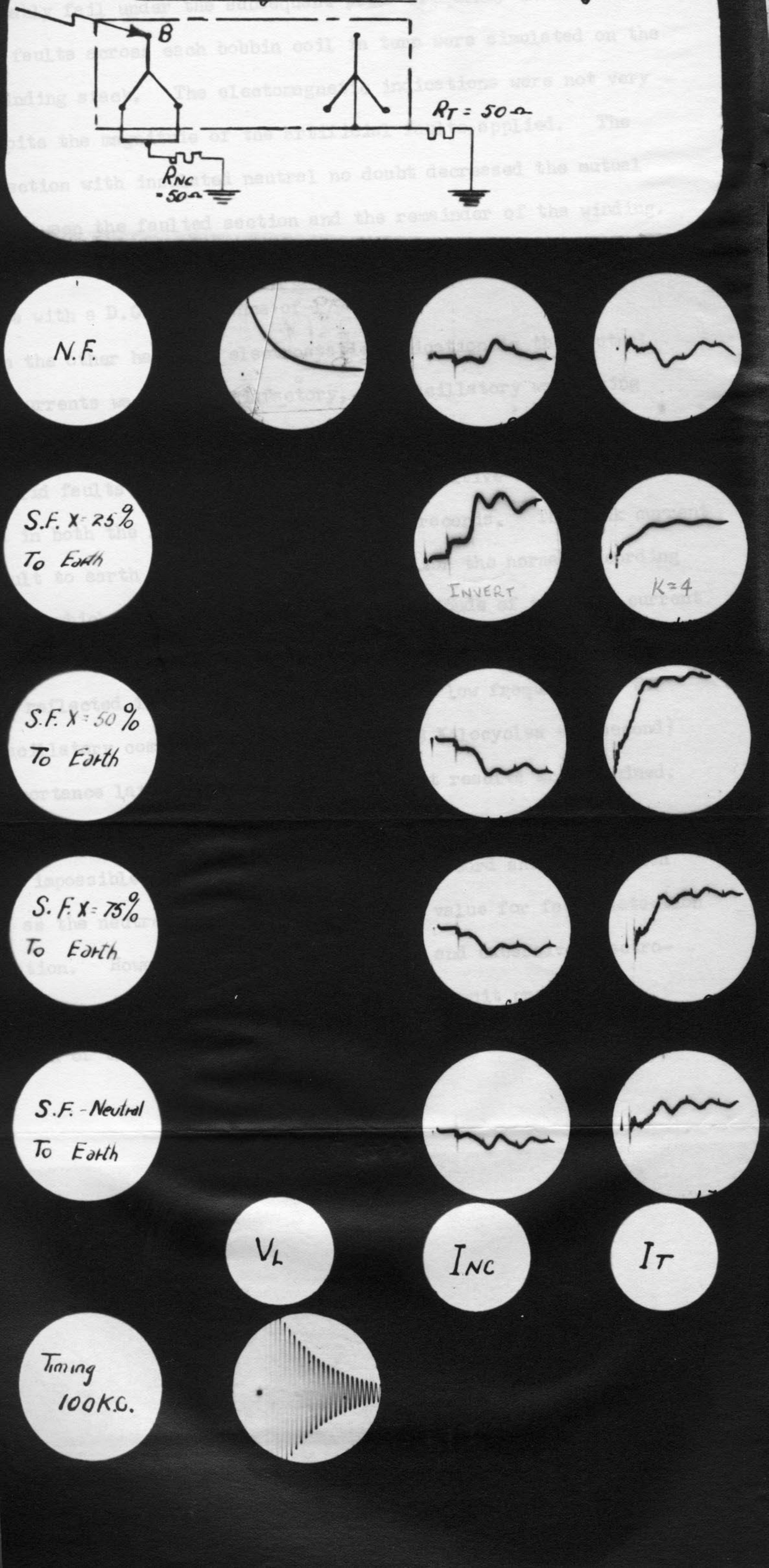
There is good correlation between the electrostatic or oscillatory component of the tank current and the neutral current and, as usual, they are of opposite phase. This confirms previous theoretical and experimental derivations of the neutral current - tank current relationship.

It was not possible to introduce small interturn faults of one or two turns since the transformer was ready for the full scale tests. It was considered that such faults would have to occur through the enamel and varnish interturn insulation and that the carbon track so formed

S.C.C. Voltage Transformer — Fig 21(a)



S.C.C. Voltage Transformer — Fig 21 (b)



would probably fail under the subsequent power frequency induced test. Flashover faults across each bobbin coil in turn were simulated on the B phase winding stack. The electomagnetic indications were not very great despite the magnitude of the artificial faults applied. The star connection with insulated neutral no doubt decreased the mutual coupling between the faulted section and the remainder of the winding. Also the large number of turns per phase (9992) constituted a formidable inductance with a D.C. resistance of 1790 ohms.

On the other hand the electrostatic indication in the neutral and tank currents was most satisfactory, the oscillatory wave being different for each location of the intercoil faults.

Solid faults to earth were applied and positive indications appeared in both the neutral and tank current records. The tank current for a fault to earth at X = 25% was too great for the normal recording sensitivity which had to be reduced. The magnitude of the tank current gave a good indication of the location of the fault to earth. This was also reflected in the neutral current. The low frequency of the major oscillatory component (approximately 7.3 Kilocycles per second) is of importance later when the full scale test results are examined.

It was realised that the detection of faults of one or two turns would be impossible and that the tank current record should be taken as well as the neutral current in view of its value for fault detection and location. However equipment limitations and excessive electrostatic pick-up in the tank current recording circuit prevented realisation of the latter. The fault detection risk was accepted so that any major design defects could be checked by the full scale tests. It was also anticipated that faults of a few turns would cause puncture through enamel and varnish, not oil, and hence would be detected by subsequent power frequency induced voltage tests. At this stage the transformer was subjected to and passed a 100 cycle per second induced voltage test of 27.5 KV line to line for one minute.

Full Scale Tests.

Full scale tests were carried out using the Sydney County Council's single-stage 120 KV impulse generator, at Waverley Substation. The transformer was complete in the metering unit, which was filled with "50KV No Puncture" oil. The transformer had to withstand a chopped wave voltage with a peak value of 110KV and a full wave voltage of 1/50 microsecond shape with a peak value of 95 KV. The lid of the metering unit was removed for observations.

The nameplate details of the transformer are:

SYDNEY COUNTY COUNCIL.

VOLTAGE TRANSFORMER SERIAL NO. 102.

Class A Burden 50 VA Volts 11000 Freq. 50

Ratio 11000/110 Phases 3 Star-star

At the 48% test level tests were made on "A" phase to recheck the fault detection sensitivity. A negative polarity voltage was applied to "A" line terminal using the test connections shown in Fig. 23 (d). The oscillographic results are shown in Fig. 23 (a). The relevent neutral current records are -

MU71 - No Fault.

MU73 - Solid fault - "A" phase of LV winding short-circuited ("a" to "n" and earth).

MU77 - Solid fault - LV winding short-circuited completely ("a", "b" and "c" to neutral and earth)

The time scale for the oscillograms in Fig. 23 is 100 microseconds equals 5.2 millimetres.

Unfortunately these records could not be directly compared with the recurrent surge oscillograms due to -

(a) the slower sweep speed used for the full scale records

(b) pick-up in the I_{NC} recording circuit during the first 60 microseconds masked that portion of the record.

However oscillogram MU73 shows an increase in the oscillatory component of the neutral current similar to that evident in the recurrent surge oscillogram for a solid fault from X = 50% to X = 75%. The frequency of the oscillation in MU73 is approximately 5.2 Kilocycles per second, a considerable decrease due either to oil immersion or the greater extent of the artificial fault. Oscillogram MU77 produces a large electromagnetic indication, much greater in fact than can be expected from any anticipated intercoil failure.

Before proceeding with the 100% test level shots the voltage transformer leads were disconnected from the HV fuse holders, metering current transformers and HV connections inside the metering unit. The latter components were then tested together with the voltage transformer disconnected. Each phase successfully withstood five (5) applications of a negative 95 KV peak 1.7 x 60 microsecond impulse voltage to each phase in turn with the other phases earthed to the tank. Fault detection was by measurement of tank current (I_T) and observations with the tank lid adjusted so that the phase being tested was visible under the oil. After these tests the voltage transformer was reconnected.

A negative 1 x 60 microsecond wave (MU69 in Fig. 23(a)) was applied to each phase using test connection No. 2 (see Fig. 6). Due to equipment limitations only one quantity could be recorded during each shot. It was decided to measure neutral current for each full wave test, line voltage (V_L) being checked at intervals during the test programme. A 0.0023 microfarad shunt capacitance load was connected in parallel with the test object for all tests so that waveform checks could be made with the test object disconnected for the check. Also the wavefront time could be adjusted by calculation since the recording equipment was inadequate for any oscillographic measurements of this time.

The tests on transformer "B" are summarised in Table 4 below.

Table 4 - Summary of Full Scale Tests on Transformer B - 12-14th August,1958.

Phase	Test Level	Oscillograms	No. of shots	Remarks
	62%	MU79, 81, 83, 85 and 87	5	F.W. No apparent failure.
A	113%	No oscillograms	2	Chopped Wave. No apparent failure.
	100%	MU89 and 91	2	F.W. No apparent failure.

Phase	Test Level	Oscillograms	No. of Shots	Remarks
B	55%	MU93 and 95	2	F.W. No apparent failure
	113%	No oscillograms	5	Chopped Wave. Sphere gaps failed to flash over on all shots except No. 4. Small bubbles were noticed on surface of oil above "B" phase after each shot. Suspected failure.
	100%	MU97, MU99 and 101	3	F.W. No indication of further failure
C	55%	MU109 and 111	2	F.W. No apparent failure.
	113%	No oscillograms	2	C.W. No apparent failure.
	100%	MU113 and 115	3	F.W. MU115 shows an indication of an intercoil failure.

The most important oscillographic results are shown in Fig. 23.

The "A" phase calibration and fault detection sensitivity results are given in Fig. 23 (a) - oscillograms MU69, MU71, MU73, and MU77. The neutral current record at 74% test level (MU85) does not show any significant difference from oscillograms MU71, the 48% test level record.

The chopped wave tests on A phase were made without oscillographic recording. Due to equipment limitations and pick-up in the recording circuits not even the line voltage waveform (V_L) could be recorded.

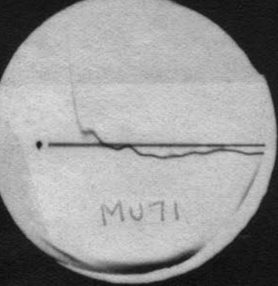
The three 100% full wave shots on A phase were monitored by neutral current (I_{NC}) records, one of which, MU89, is shown in Fig. 23(a). The other two neutral current records (MU89 and MU91) were identical and the only difference between the three 100% test level records and the 74% test level record (MU85) seems to be due to a slower sweep speed which was inadvertantly used.

The tests on B phase were marred by instability in the liquid tail resistor which was not detected until it was too late. Oscillogram MU93 shows the shortened tail of the applied wave (V_L) which resulted from this instability. However the chopped wave test, which would be virtually unaffected by this defect, produced failure of the major insulation between the B phase HV winding and the LV winding. A fault was suspected since the gaps failed to chop when the first 113% test level wave was applied. It appears that the fault was intermittent at this stage since the gaps subsequently did chop during shot No. 4. Small bubbles were found on the surface of the oil over B phase winding stack.

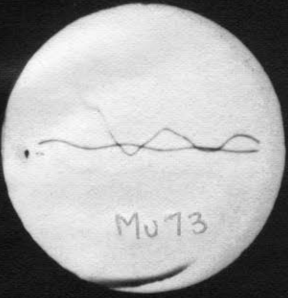
The full wave shots at 100% test level were then applied but no evidence of further failure was detected.

C phase was tested last and by this time improvements in the tail resistor of the impulse generator had been made. There was no evidence of failure until the last 100% full wave shot (see oscillograms MU115). This oscillogram showed definite evidence of a change in the electrostatic component of the neutral current and a slight increase in

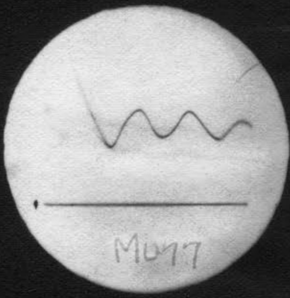
N.F.
48 % Test Level
A = 1



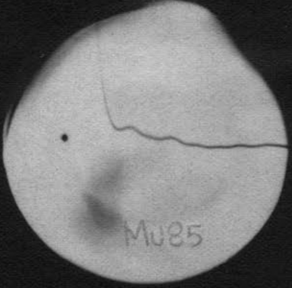
S.F
L.V. winding:
one phase short-circuited
(a to neutral
48%



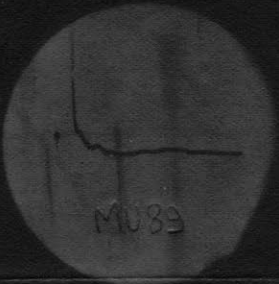
S.F
L.V. winding: all
phases short-circuited
48%



74% Test Level
Shot No 3



100% Test Level
Shot No 1

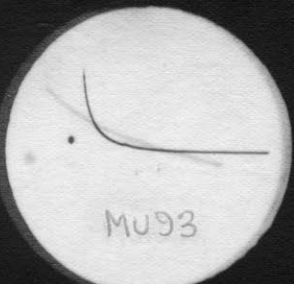


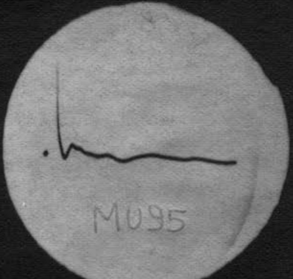
V_L $\quad$ I_{NC}

Time Scale. 0 50 100 150 200

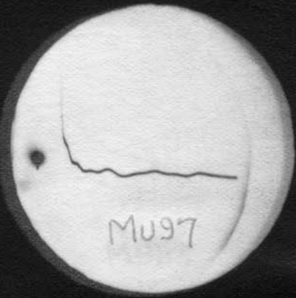
Fig 23(a) 11000/110 Volt Voltage Transformer SCC No
"A" Phase Oscillogram Record of Full Wave Tests
100 % Test Level = 95 K.V. Peak
A = C.R.O. Amplifier Constant

N.F.
55 % Test Level
A = 1

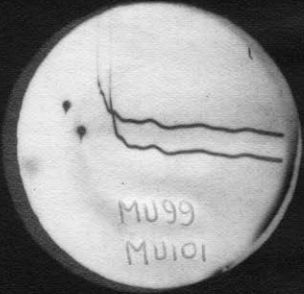




100 % Test Level
(Nominal Choppal Wave)
A 0·75



100 % Test Level
Shots No 1 & 2.
A = 0·75



V_L I_{NC}

Time Scale.
0 50 100 150 200

Fig 24 (b) 11000/110 Volt Voltage Transformer S.C.C. No

'B' Phase Oscillogram Record of Full Wave Tests

100 % Test Level = 95 Kv. Peak

A = C.R.O. Amplifier Constant

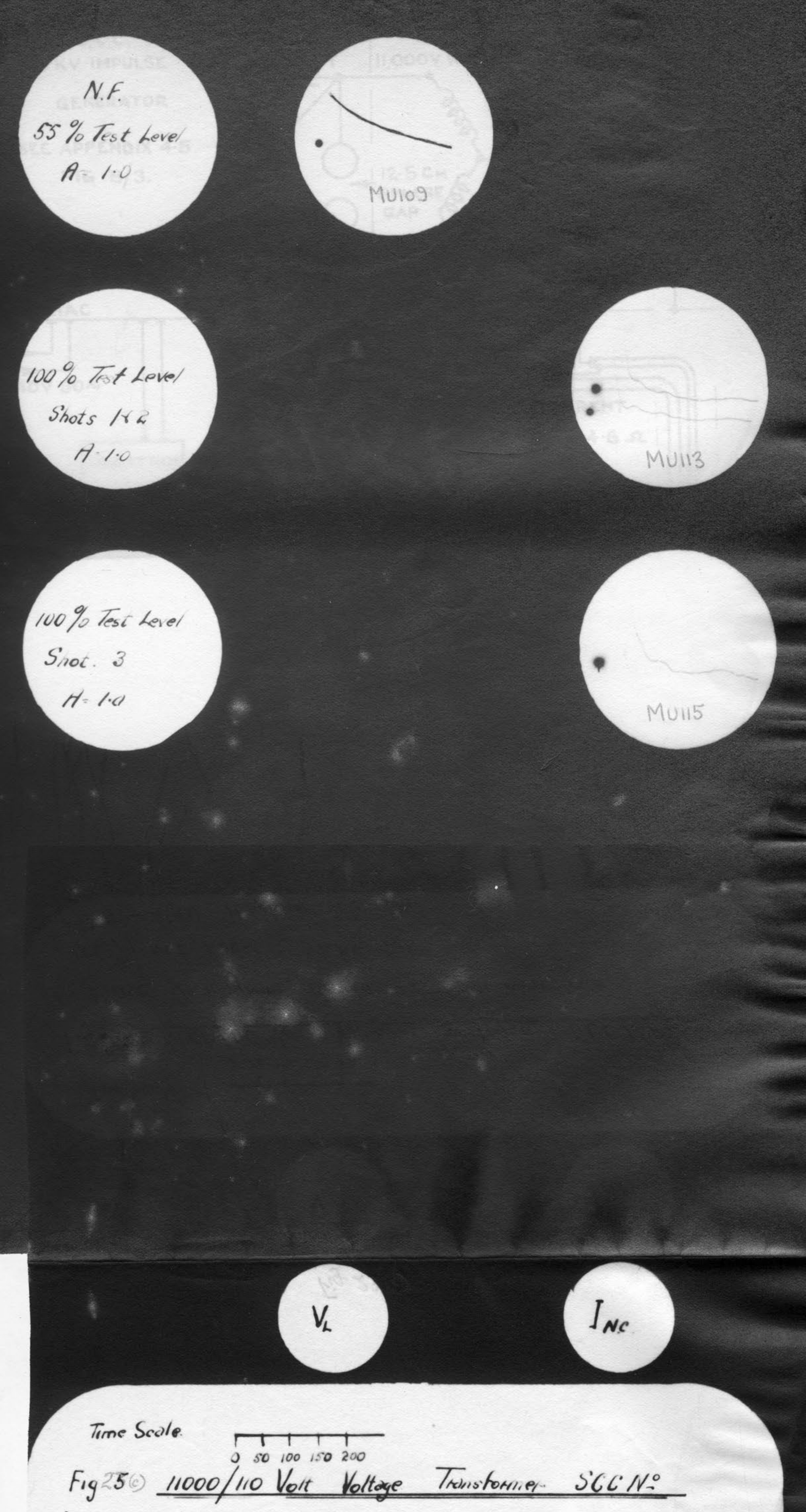


Fig 25(c) 11000/110 Volt Voltage Transformer SCC No.
"C" Phase Oscillogram Records of Full Wave tests
100% Test Level = 95 Kv Peak
A = CRO Amplifier Constant

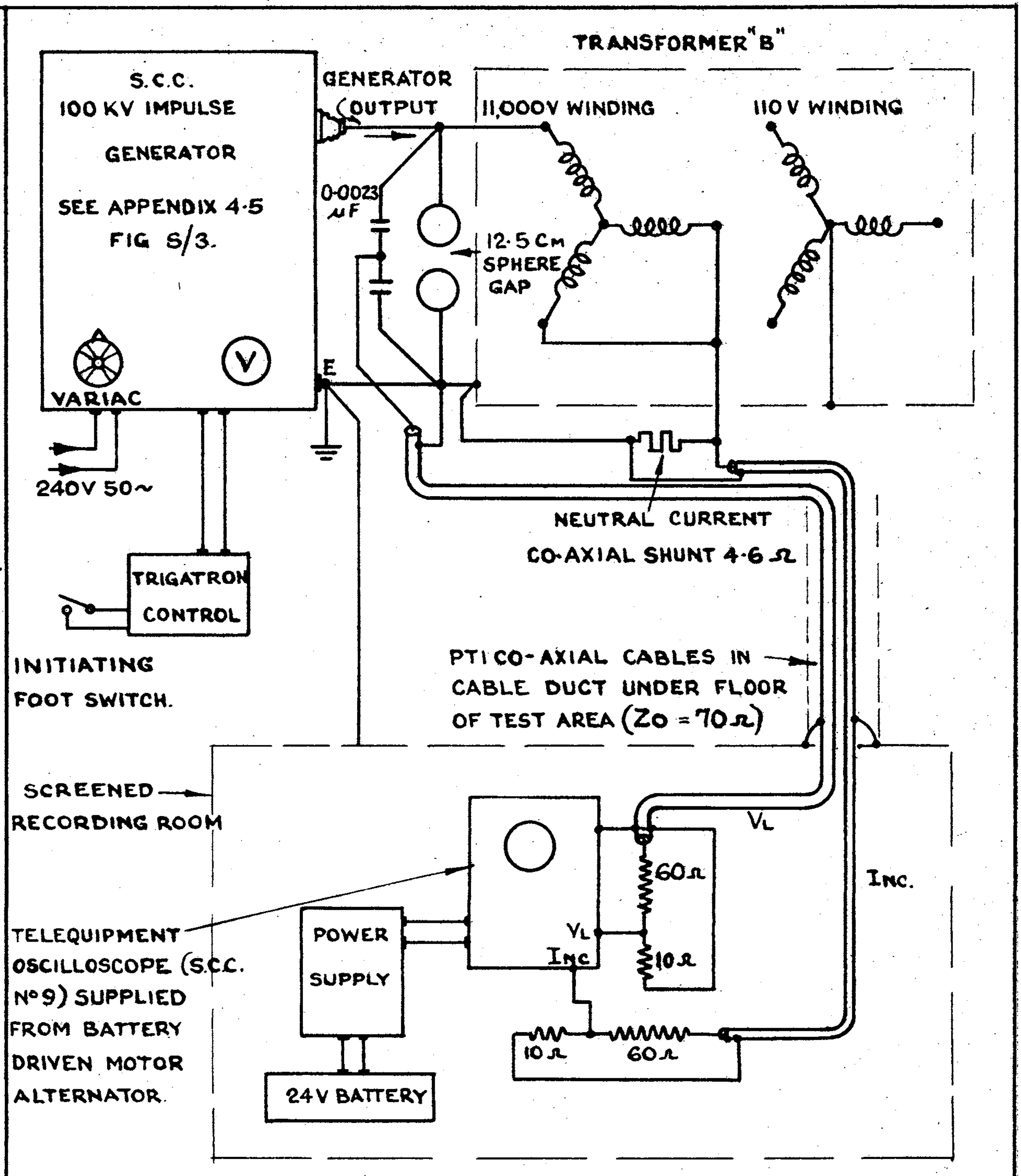


FIG. 23(d.) FULL SCALE IMPULSE TESTS ON TRANSFORMER "B"
—DIAGRAM OF CONNECTIONS—

the electromagnetic component which provide evidence of an interturn fault.

As soon as the tests on C phase were completed, the metering unit was moved to a power frequency testing laboratory and the following tests applied:

Insulation Resistance - 2500 volt Megger (oil temperature 19°C)

HV - frame 6000 megohms HV - LV 5000 megohms

LV - frame 100 + megohms (1000V Megger).

Induced Power Frequency High Voltage Tests.

Test A: A 100 cycles per second, 3 phase supply was applied to the LV winding with the HV winding isolated from earth. The line to line supply voltage was raised to 275 volts (i.e. equivalent to 27.5 KV line to line on the HV side). After 50 seconds there was a slight discharge in the tank. After a further 60 seconds there were no further discharges in the tank and the three phase current were:

		Previous Test
a	1.50 amperes	1.50 amperes
b	1.50 amperes	1,250 amperes
c	1.75 amperes	1.50 amperes

These readings confirm that an interturn fault was produced in "C" phase during the impulse tests since the "C" phase current has increased from the original value by approximately 17%.

Test B: Test A was repeated but with C phase terminal of the HV winding earthed. At approximately 200 volts (20 KV line to line on HV side) smoke-filled bubbles rose to the surface above B phase stack. The star point was broken and the following insulation resistance readings taken:

A–e	10,000 megohms	A – LV	10,000 megohms
B–e	3,000 megohms	B – LV	less than 10,000 ohms
C–e	10,000 megohms	C – LV	10,000 megohms.

The B phase high voltage winding was then stripped and a definite puncture found through the main interwinding cylinder which comprised six (6) layers of 0.010 inch leatheroid. Fig. 24 shows the puncture and the damage at the line end of the first bobbin coil of B phase stack.

The puncture occurred close to the line lead which entered the first bobbin coil on this stack at the inside layer. The stripping and location of the fault in C phase winding stack had not been carried out when these results were recorded.

The full scale test results can be summarised as follows:

"The voltage transformer failed to pass impulse tests generally in accordance with the requirements of Sydney County Council Specification No. 2196, Clause 9(g) although it successfully withstood full wave negative impulse voltages with a peak value of 70 KV. The failures detected during the 95 KV (nominal) tests were:

(a) B phase HV winding punctured to the LV winding during the chopped wave (113% peak) test.

(b) C phase HV winding developed an interturn fault during the 100% full wave tests."

The full scale tests and the recurrent surge tests on transformer "B" have been fully described here even though equipment limitations did not allow the use of the optimum technique and also reduced the standard of the results. This complete description is felt to be of value because:

(a) These tests are the first transformer impulse tests conducted by The Sydney County Council and provided the author and other testing staff with valuable experience.

(b) The tests show the important part that recurrent surge measurements can play in checking a transformer's transient response before subjecting it to any high voltages.

(c) The results of the full scale tests demonstrate the difficulty of inductive interference with recording circuits and describe two actual impulse test faults.

TRANSFORMER "C".

The experiments on the 220 KV single phase voltage transformer (transformer "C") were conducted whilst the author was working in the Transformer Engineering Department of the British Thomson - Houston Company Limited, Rugby, England. The author was assisting Mr. D. Wadland, the engineer responsible for transformer impulse testing. The oscillographic results are not given here, only a summary of the findings.

The initial experiments were made using a 1000 volt recurrent surge oscilloscope. Complete records of line voltage (V_L) and transferred voltage (V_{LV}) were made under the following conditions.

(a) No Fault - LV windings open

(b) Intercoil fault - simulated by short-circuiting one LV winding.

The applied voltage records (V_L) showed no indication suitable for fault detection purposes, at any stage in the experiment.

The transferred voltages appearing across the terminals of each LV winding were practically identical. Each voltage waveform was mainly composed of oscillatory components, the fundamental being approximately 30 kilocycles per second. No significant unidirectional electromagnetic component could be observed in the transferred voltage records.

The "no fault" transferred voltage records contained an initial 125 Kilocycle oscillation of large magnitude during the first fundamental time (approximately 18 microseconds). The application of an artificial fault by the short-circuiting of one of the low voltage windings, damped out the 125 kilocycle oscillation completely. However the 30 kilocycle component was practically unchanged and there was no significant electromagnetic indication.

The results of the experiments on transformers "B" and "C" show that the detection of small faults by an electromagnetic indication in the neutral current is extremely difficult. All the indications of any value were electrostatic and consequently related to the change in voltage conditions due to the fault. In view of this, it is recommended that the tank current fault detection methods be used for voltage transformers and distribution transformers up to 50 KVA, particularly if the number of turns between HV line terminals is 10,000 or greater.

The fundamental time of the HV windings of this range is usually quite long and relatively slow sweep speeds can be used ~~consistent~~ provided the requirements of fault location are met. The intercoil voltages of transformer "B" given in Appendix 4.4 illustrate this fact.

2.6 DISTRIBUTION TRANSFORMERS TO 1000 KVA.

The electricity supply undertaking with which the author was associated during this work, is particularly concerned with the impulse strength of distribution transformers. This fact led the author to conduct a considerable number of experiments on units within the range 50 KVA to 1000 KVA. It now appears that this bias has been beneficial for two reasons.

(a) Fault detection during impulse tests on small transformers with a low volts per turn ratio is more difficult than during tests on large power transformers.

(b) The economic provision of satisfactory impulse strength in distribution transformers is presenting a severe problem to the electrical supply industry as a whole.

The experiments conducted are summarised below. Details of the experiments are given in Appendix 4.5:

Design details of each unit were obtained wherever possible but since these are confidential they are not published here except as necessary to clarify the oscillographic results. For the same reason transformers are given a code identification letter starting from the letter "M" for transformers in the range 50 KVA to 1000 KVA.

TABLE 5 - EXPERIMENTS MADE ON DISTRIBUTION TRANSFORMERS

Transformer	Rating in kVA	Voltage Ratio in kV	Type of Winding	Nature of Experiment
M	200	10/0.415	Bobbin/ layer	Voltage Distribution. Effect of test connexions
N	200	33/11	Bobbin/ layer	Fault Detection
T	250	11/0.433	Layer/ layer	Fault Detection
O	400	10/0.415	Bobbin/ layer	Fault Detection
P	500	10/0.415	Bobbin/ layer	Fault Detection
Q	500	10/0.415	Disc/ Layer	Fault Detection
R	500	10/0.415	Disc/ layer	Fault Detection
S	500	10/0.415	Bobbin/ layer	Fault Detection

The details of all these experiments are contained in the author's Impulse Testing Oscillogram and Transformer Data files.

Transformer M - 200 kVA 10/0.415 kV, Delta-star, Bobbin/Layer

The voltage distribution experiments on transformer "M" were described in Section 2.4 - Test Connexions, and the oscillographic results analysed therein. It is interesting to note that the delta-connected H.V. windings of several transformers of the same design as transformer "M" have failed in service at approximately X = 25% from one line terminal. These transformers were operating in electrically-exposed areas at the time. From the intercoil voltage wave-forms given in Appendix 4.4 it can be seen that the voltage appearing across the first two of the eight bobbin coils in each H.V. winding stack, has a peak value of 25% of the applied surge. However, the maximum voltage across the succeeding two bobbin coils in that H.V. winding stack is 46% of the applied surge. This unusual distribution is probably due to the use of re-inforced end turns in the first two bobbin coils which would then have less turns per coil than the main winding coils. It may have been a factor in the numerous service failures of transformers of this design.

The maximum intercoil stress across the last 25% of the winding occurs 10.3 microseconds after the application of the surge and the maximum voltage to ground at X = 75% occurs after 14 microseconds have elapsed (See Appendix 4.4 and Fig.20). The length of conductor per phase of the H.V. winding of transformer "M" is 5170 feet (1570 metres). Therefore, the propagation constants for fault location purposes would be:-

(a) For major intercoil faults -

$$\frac{0.875 \times 5170}{10.5} = 430 \text{ feet/microsecond}$$
(13/metres/microsecond)

(b) For faults to earth -

$$\frac{0.75 \times 5170}{14} = 276 \text{ feet/microsecond}$$
(84 metres/microsecond)

These constants are for air immersion. Under oil it is expected that they would be less. They differ considerably from the 150 metres/microsecond which is the usual value used under full scale test conditions (Ref.14 and 43). However, the results illustrate how the constants can be different when locating a major intercoil fault or a fault to earth by an electrostatic indication in, say, the tank current oscillogram.

Transformer N - 200 kVA, 33/11 kV, Delta-star, Bobbin/layer.

The fault detection experiments on transformer "N" were most interesting since they were made just prior to it undergoing full scale acceptance and design tests at the University of Queensland. The experiments were conducted with the core and windings in the tank under oil.

The 33 kV bobbin type winding was the "winding under test" for the first series of experiments. The transferred voltage across one phase of the 11 kV winding was measured oscillographically when a recurrent surge was applied using test connexion No.2 in Fig.6. The peak value of the transferred voltage was 25% of the applied surge (i.e. 50 kV for 200 kV applied to the 33 kV winding). Since the impulse level of an 11 kV winding is 95 kV, resistance earthing of the 11 kV winding is not necessary.

Transferred voltage oscillograms were taken for the various artificial faults but the indications of failure were disappointing except for major faults. Also the transferred voltage oscillograms were very difficult to interpret because of the complex relationship between the transferred voltage and the applied surge. This relationship is complicated by the two winding ladder network required for its derivation (see Fig.1(a)) and, with the oscilloscope sweep speeds normally used, by the flux in the core.

The neutral current waveform under no fault conditions was shown previously in Fig.10, both under recurrent surge and full scale test conditions. Besides, proving good correlation between the oscillograms under the two conditions, the oscillograms of Fig.10 bear a close resemblance to the neutral current waveform obtained by Rippon and Hickling when testing a 400 kVA 10/0.4 kV delta/star transformer (Ref.5; Fig.15(b)).

The fault detection results of the recurrent surge experiments on the 33 kV winding are summarised below (Test connaxion No.2, Fig.6.)

Nature of Fault	Neutral Current Oscillogram (Sweep time = 100 microseconds)	Transferred Voltage Oscillogram (Sweep time =100 microseconds)
Single turn fault at x = 50% (0.02% winding)	Positive indication	No indication
Solid fault across 2.5% winding at x = 50%	Positive indication	Poor indication
Solid fault from tapping switch to earth	Positive indication	Positive indication
Solid fault from tapping switch to 11 kV line terminal.	Positive indication	Positive indication
Solid fault from 33 kV line terminal to tapping switch.	Positive indication	Fair indication

The experiments on the 11 kV layer winding were made using test connexion No.4 (Fig.6). The voltage transferred to the 33 kV winding had a peak value 3.2 times greater than that applied to the 11 kV winding (i.e. 300 kV when a 95 kV surge is applied to the 11 kV winding). This voltage exceeds the basic impulse level of 200 kV for the 33 kV windings and these windings must be shorted or shunted to reduce this excessive voltage.

The neutral current recorded with the 33 kV windings short-circuited contained a predominant electromagnetic component, with the electrostatic component practically damped out. The neutral current records showed no indication of an artificial one turn fault which was applied. This poor sensitivity of the electromagnetic component shows the need for use of the electrostatic component in such circumstances.(See Hickling's contribution to Ref.42 - Appendix 4.1)

The main points of interest arising from the full scale tests were:-

(a) There was good correlation between the recurrent surge oscillograms and those recorded under full scale test conditions.

(b) A major fault occurred in the 33 kV winding whilst undergoing design tests at 300 kV but the neutral current trace disappeared off the record so quickly that no indication of magnitude or polarity was obtained. Hence, it was not known if a fault to earth or across portion of the winding had occurred.

(c) Major faults occurred in the 33 kV and 11 kV windings at design test levels and were positively detected. However, these faults must have been flashovers in oil since subsequent tests, including power frequency tests, showed no signs of permanent damage.

<u>Transformer T - 250 kVA, 11/0.433 kV, Delta/star, Layer/layer</u>

The experiments conducted on the layer type H.V. winding are of particular interest since this winding construction is being more extensively used in distribution and power transformers. The increase in the use of the layer construction is due to its excellent impulse voltage response. The winding layers act as the concentric cylinders of a condenser bushing and the ratio of the series to shunt capacitances of the equivalent network is significantly increased with a consequent improvement in voltage distribution. In a star-connected winding with earthed neutral, as employed for extra high voltage power transformers, graded insulation economies are possible with the layer construction.

During the assembly of transformer "T" recurrent surge measurements of neutral current and tank current were made. The H.V. and L.V. windings were standing together as a unit assembly without the core and tank. The L.V. winding was used as the earth plane for the tank current measurement. Due to the winding construction it was found that

(a) the initial charging current peak appearing in the neutral current was much greater than that appearing in the tank current, confirming the increase in series to shunt capacitance ratio.

(b) The tank current had an oscillatory waveform but of small magnitude compared with the electrostatic component of the neutral current. After 8 microseconds the tank current had greatly diminished. Since the H.V. winding had a transit time of approximately

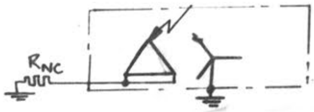
11 microseconds, it appeared that an electrostatic indication of a fault may not be observed in the tank current.

Due to (b) above, only neutral current records were taken during the recurrent surge experiments on the assembled transformer. The results of these experiments are shown in Fig.24.

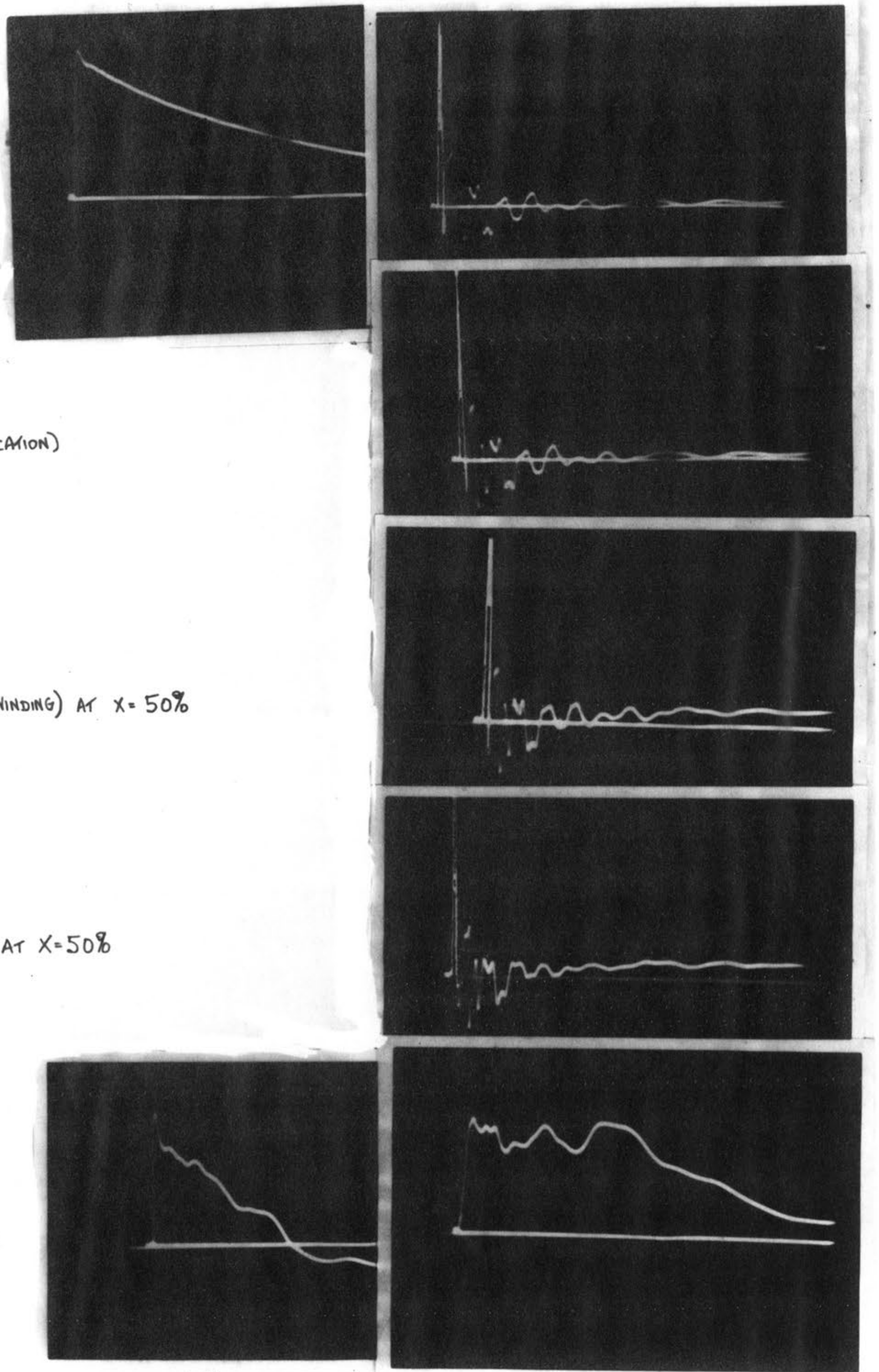
The "no fault" oscillograms of applied voltage and neutral current are shown at the top of Fig.24, under the diagram of test connexions. The very high series capacitance charging current peak is again evident in the neutral current record. The subsequent oscillatory electrostatic component has a more complex waveform than that normally associated with disc or bobbin type windings. The predominant frequency seems to be approximately 94 kC with a large but rapidly attenuated 300 kC component initially superimposed. The conductor length of the H.V. winding is 1660 metres, indicating a higher speed of propagation than the 150 metres per microsecond which is normally derived using Dr. Ganger's modified transmission line reasoning (See Fig.8). Later in the neutral current a lower frequency component of small magnitude is noticed.

The complexity of the waveform of the electrostatic component indicates that the voltage conditions in the layer type winding are also complex. The relationship between the voltage conditions and the electrostatic component

TEST CONNECTIONS



CORE & WINDINGS OUT OF OIL



N.F.

SF - 1 TURN AT X = 50% (NO APPRECIABLE INDICATION)

SF - 5 TURNS (0·3% WINDING) AT X = 50%

SF - 2·5% WINDING AT X = 50%

SF - LINE TO TAP 4 (ie. X = 50%)

V_L I_{NC}

TIME SCALE FOR ALL OSCILLOGRAMS 0 20 40 60 80 MICROSECONDS.

FIG. 24 : FAULT DETECTION EXPERIMENTS ON A 250 KVA 11000/433 VOLT TRANSFORMER WITH LAYER TYPE DELTA CONNECTED H.V. WINDING (TRANSFORMER T).

of the neutral current is not as direct as for a disc or bobbin type winding since the whole winding is closely coupled electrostatically by the series capacitances. It appears that any methematical solution of the behaviour of this type of winding would have to be fairly rigorous, with each layer being divided into several sections, each with equivalent mutual inductance and capacitance parameters. Only the ends of each layer would have shunt capacitances to earth. For the work described herein, an appreciation of the part played by the large interlayer capacitances has been found sufficient, but considerable scope exists for more detailed analyses.

A one turn solid fault, applied at x = 50%, produced only a very small electromagnetic indication, insufficient for reliable fault detection (Fig.24). However, a 5 turn short circuit (0.3% winding) at x = 50% gave a positive electrostatic and electromagnetic indication.

With a solid fault across 2.5% of the winding (44 turns) the electromagnetic indication is much the same as for the 0.3% short circuit. However, appreciable damping of the electrostatic component occurs.

The fault last applied was extremely severe. This simulated a flashover from the line lead to a tapping lead, in this case Tap 4. The applied voltage oscillogram gave a good indication whilst the electromagnetic component of the neutral current reached a high value.

The electromagnetic component does not possess the normal exponantial shape indicating that the total inductance has been reduced to a low value by very high mutual coupling between the shorted winding section and the remainder.

Transformer O - 400 kVA, 10/0.415, Delta-star, Bobbin/Layer

A limited number of experiments were conducted on this transformer using test connexion No.1 in Fig.6(b). The voltage trnasferred to the L.V. winding was only 0.7% of the applied voltage.

The neutral current under "no-fault" conditions had a similar waveform to that recorded for transformer "N" (Fig.10).

The tank current followed the conventional waveform expected from the previous study of the voltage conditions - tank current relationship (See Section 1.3)

During these experiments the misleading effect of inductance in the neutral current shunt was detected. A prominent 300 kC component disappeared when a non-inductive shunt was used to replace an inductive decade box used initially.

No artificial faults could be applied to this transformer since it was completely assembled in its tank under oil.

Transformer P - 500 kVA, 10/0.415 kV, delta-star, Bobbin/layer

Experiments on this transformer were conducted in 1954 when the experimental technique was being developed, using a 1 kV recurrent surge generator of temporary construction. Records of applied voltage, neutral current and transferred voltage were taken using test connexion No.2 in Fig.6(b).

The voltage transferred to the L.V. windings was only 2% of the applied wave so that resistance shunting of this winding was unnecessary. The waveform of the transferred voltage was similar to that of the applied voltage. Indications of quite severe faults were disappointing and did not discriminate between a fault across part of the winding or a fault to earth.

The neutral current under "no-fault" conditions was of conventional shape for a bobbin type winding (See Fig.10 and subsequent description of experiment on transformer "S"). Under "no-fault" conditions the electromagnetic component was very small, equivalent to approximately 0.1 amp. for an applied voltage of 100 kV peak. Superimposed on this unidirectional electromagnetic component was the electrostatic component with a definite frequency of 36 kC and a peak value equivalent to 1.0 amp. with a 100 kV surge applied.

It is very interesting to compare the frequency of this electrostatic component with that recorded on a 500 kVA transformer with a disc winding (Transformer Q). In the disc winding, the frequency was 72 kC for the major component with an H.V. winding length of 1300 metres. The transformers were subjected to the same test conditions using the same experimental equipment.

The winding length of transformer P could not be obtained but the available data indicates that it is unlikely that there would have been a 2:1 ratio of winding conductor lengths.

<u>Transformer P.</u> (Bobbin type H.V. winding)
10 bobbin coils per H.V. stack
1461 turns per H.V. stack
Winding length - unknown
L.V. winding - two layer, helical.
Fundamental frequency of electrostatic component of neutral current ≈ 36 kC.

<u>Transformer Q</u>. (Disc type H.V. winding)
50 disc sections
1168 turns
Winding length = 4260 feet (1300 metres)
L.V. winding - two layer, helical
Fundamental frequency of electrostatic component of neutral current = 72 kC.

The large difference in the "fundamental" frequencies, i.e. in the propagation constants, seems to be related to the different winding constructions since both transformers are 500 kVA units with the same voltage ratios. These results are very interesting since one of the objects of this work is to determine if such variations do occur due to differences in winding construction. The variation in propagation velocities could be very important for fault location purposes.

The surge was applied to B line terminal of the H.V. winding using test connexion No.2 (See Fig.6(b) and artificial faults were applied to B phase winding. At this stage in the experimental work a long time sweep (500 microseconds) was employed for the cathode ray oscillograms so that the electromagnetic indication was clearly recorded. The electrostatic indication was not very clear with such slow sweep speed but its general behaviour was recognisable.

The two artificial faults and their effects are summarised below. (Currents are equivalent values for a 100 kV surge).

<u>Solid Fault across 1.2% winding (18 turns)</u>.

Electromagnetic component : increased to +0.9 Amp.

Electrostatic component : 36 kC component still persists but attenuated to half magnitude.

<u>Solid Fault from B phase tapping switch (x = 50%) to Earth</u>.

Electromagnetic component : decreased to - 1.9 amp.

Electrostatic component : A 30 kC component still persisted superimposed on the electromagnetic component.

During the setting up for the above-mentioned experiments it was found that a high resistance contact in the tapping switch could be detected from the neutral current waveform. The fault in the tapping switch was corrected before carrying out the fault detection experiments described above.

Transformer Q - 500 kVA, 10/0.415 kV, delta-star, disc/layer.

The experiments on this transformer were conducted in 1954 using the recurrent surge generator, and applying the surge to B line terminal with test connexion No.2 (See Fig.6(b)).

A very comprehensive programme was carried out, the oscillograms taken being summarised below:-

Applied or line voltage (V_{HV})	- 7
Transferred voltage (V_{LV})	- 5
Neutral current (I_{NC})	- 13
Line current (I_L)	- 12

Once again, the sweep times were kept at about 200 to 400 microseconds to clarify the electromagnetic indication. The comprehensive nature of the experiments proved of great value to the author at the time but analyses of the results and further research revealed that the line current and transferred voltage oscillograms had limited value.

The results are analysed below. The current values given are equivalent to the application of a 100 kV surge.

Applied or Line Voltage (V_L) or (V_{HV}).

Very poor indication of failure except when the tail dropped on the application of major faults.

Transferred Voltage (V_{LV})

The transferred voltage was only 2 percent of the applied voltage in magnitude and had approximately the same waveform. Its behaviour during the application of artificial faults was almost identical to that of the applied voltage.

Neutral Current.

Under "no-fault" conditions the electromagnetic component was practically zero. An electrostatic component with a frequency of 72 kC was superimposed, resulting in the conventional waveform (See Fig.25 Transformer "R").

A one turn (0.09% winding) solid fault at x = 1.9%, at x = 17.6% and at x = 98% from the line end produced identical waveforms. The electromagnetic component increased to +4 amp. with a severely damped 72 kC oscillation still superimposed. This good fault detection sensitivity seems characteristic of disc windings and indicates good mutual coupling.

A solid fault from the line terminal to the tapping switch produced an increase in the electromagnetic component to a value of +28 amp. Similarly a fault from the tapping switch to earth produced an electromagnetic component equal to - 28 amp. In both cases the electrostatic component was reduced to negligible proportions.

These large currents under major fault conditions highlight the difficulty of providing sufficient oscillograph sensitivity for minor faults whilst ensuring that an adequate record of major faults is obtained (See Transformer "N" - full scale tests). They also indicate the need to provide good insulation in the recording circuits and across the recording shunt.

<u>Line Current</u> (I_L)

Stenkvist's emphasis on the line current record (Ref.6) led the author to record this quantity during these experiments. The results were disappointing and the reasons for this are evident from a study of Sections 1.3 and 2.3. The line current comprises the sum of the neutral and tank currents. Under "no-fault" conditions the initial charging current peak predominates, then the oscillatory electrostatic component occurs and finally the slowly rising electromagnetic component appears.

The electromagnetic indications of faults across part of the winding were similar in shape, magnitude and polarity to that obtained in the neutral current record. However, faults to earth do not produce a reversal of polarity. The electromagnetic component increases to +28 amp. for a solid fault from the tapping switch to tank.

As in the case of the neutral current, the oscillatory electrostatic component is damped to negligible proportions by major faults.

Transformer R - 500 kVA, 10/0.415 kV, delta-star, disc-layer

Fault detection experiments were conducted on this transformer using the recurrent surge generator. Transformer "R" is similar to transformer "Q" but was made by a different manufacturer. An experiment to illustrate the effect of shorting windings other than the winding under test was carried out on this transformer. This experiment and the oscillographic results were described previously in Section 2.4 - "Test Connexions" (Fig. 21(a)). Transformer "R" was also used in an experiment to check the effect of oil immersion on the neutral current waveform (See Fig.21(b)). Having shown that only second order effects occurred when the core and windings were standing in air instead of in oil, the fault detection experiments described below were made with the core and windings in air. The core and windings stood on wooden blocks to insulate the assembly from earth so that tank current records could be taken.

The most relevant oscillograms resulting from the recurrent surge fault detection experiments on transformer "R" are given in Fig.25. The method of presentation of these oscillograms is of interest to test engineers who find it necessary to reproduce similar oscillographic records conveniently and economically.

A mask was made which would cater for five different conditions on each sheet and would display three separate oscillograms of each condition.
In Fig.25 several of the oscillogram spaces have been blanked out. The titles are printed on tracing paper and stuck into the appropriate aperture. The oscillograms are similarly mounted. Contact prints are then taken from the composite negative. The resultant prints are suitable for filing in a fault detection guide for different transformers and conditions of test.

The neutral current and the tank current waveforms follow the conventional pattern. The "fundamental" or "transit" time is approximately 6.6 microseconds measured from a high speed record of the tank current. This gives a propagation

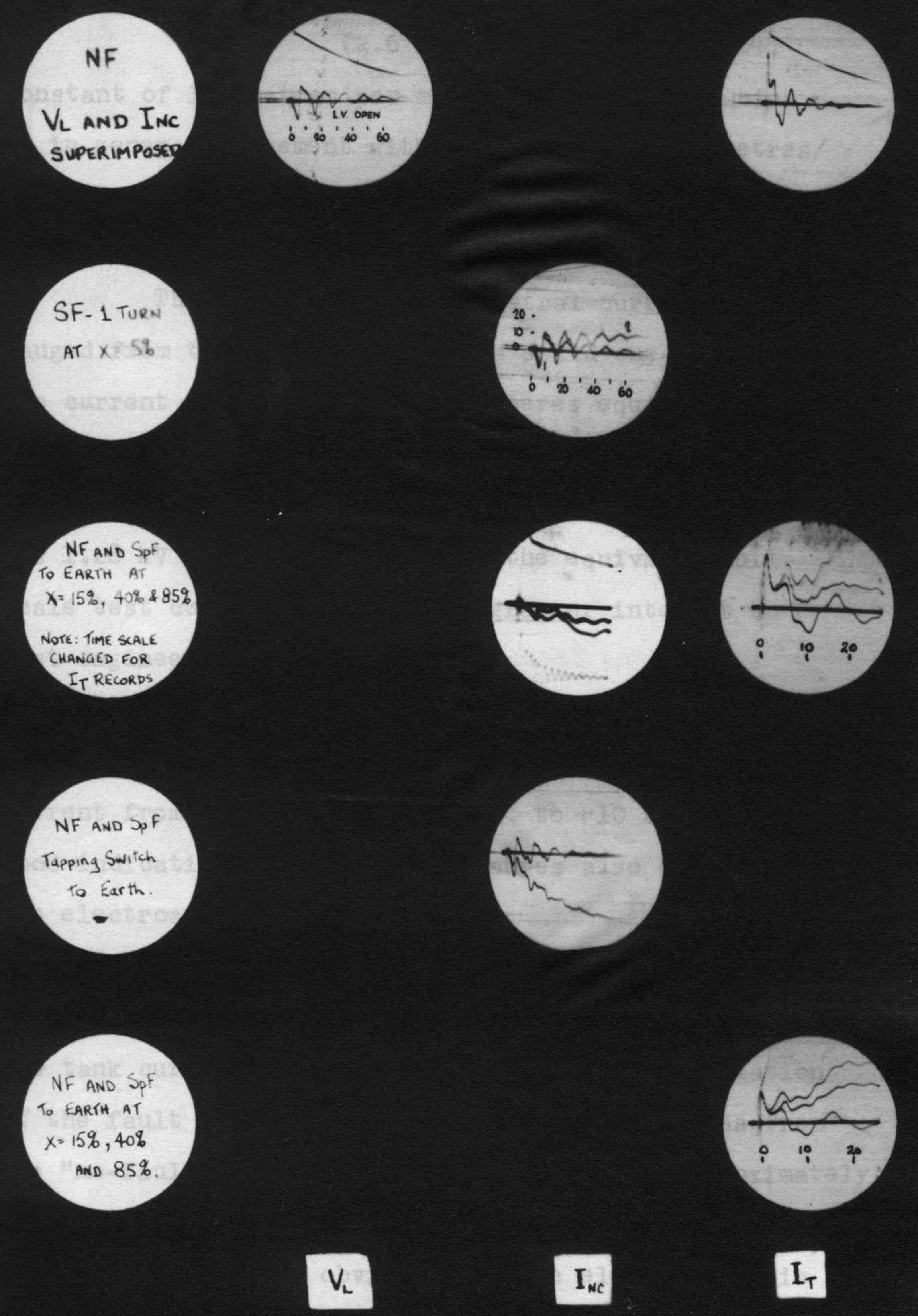
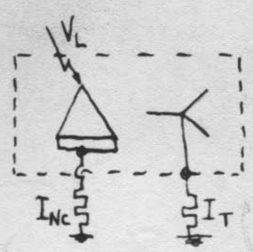


FIG: 25 FAULT DETECTION EXPERIMENTS ON A 500 KVA 10000/415 VOLT TRANSFORMER WITH DISC TYPE DELTA CONNECTED HV WINDING (TRANSFORMER R)



Time Scale the same for all records except the two I_T records marked differently.

constant of 170 metres per microsecond in air, which is in general agreement with the figure of 150 metres/microsecond quoted by overseas authorities for windings under oil.

The magnitude of the neutral current can be gauged from the oscillogram for a solid one-turn fault. The current scale is marked in amperes equivalent to the application of a 100 kV surge. The actual peak value of the recurrent surge applied during the experiments was 1.28 kV but it was felt that the equivalent full scale test currents would be of greater interest to test engineers.

The application of a one-turn solid fault increases the electromagnetic component of the neutral current from approximately +2 amp. to +10 amp., a very good indication. Fairly good changes also occur in the electrostatic component.

Sparking faults to earth were applied next, using a neon gap at x = 15%, at x = 40% and at x = 85%. The tank current (I_T) record gives positive indication of the fault and of its location. The deviations from the "no-fault" tank current record occur at approximately 1,3 and 6 microseconds respectively and the presence of an earth fault is obvious from the electromagnetic component which appears.

The time elapsed before the sparking fault occurred provided an indication of the fault location. The breakdown of the neon gap during these recurrent surge experiments simulated the rupture or flashover of some portion of the major transformer insulation under full scale test conditions. A further indication of the position of an earth fault can be obtained from the magnitude of the electromagnetic component of the tank current, this component being greater the nearer the fault occurs to the line end of the winding.

The neutral current records for sparking faults to earth revealed a weakness of this form of indication which should be noted. As usual the electromagnetic component was negative. However, it was found that the impedance of the neon gap was limiting the magnitude of the electromagnetic component and the same waveform was obtained for the x = 15% and the x = 40% earth faults. (It is not possible to directly compare the neutral and tank current records due to differences in the time scale and the vertical deflection sensitivity.)

This experimental limitation may not occur under full scale test conditions but it should be guarded against during recurrent surge experiments. Some experimenters use a controlled thyratron to apply earth faults after a given interval, but it is felt that this technique does not simulate actual insulation breakdown as well as the uncontrolled neon gap.

To further emphasise the limiting effect noticed during the sparking earth fault experiments described above, a solid earth fault was applied at the tapping switch. The neutral current record shown in Fig.25 shows the normal negative increase in the electromagnetic component and damping of the electrostatic component.

Solid earth faults were applied at x = 15%, x = 40% and x = 85% and the tank current recorded for each fault in turn, for comparison with the tank current records when sparking faults were applied at those points. The vertical deflection sensitivity was reduced by 50% because the electromagnetic components were found to have increased under the solid fault conditions. Once again a time difference existed between the instants of deviation from the no-fault tank current waveform. However, the instant of deviation was not so definite as under sparking fault conditions which are considered to more truly represent full scale test conditions.

The recurrent surge oscillograms in Fig.25 except the I_{NC} record of the sparking faults to earth, were recorded on Ilford 5B52-35mm non-halation type film. It will be seen that finer traces result from the use of this film although the contrast is less.

This type of film is suitable for repid processing at high temperature. The majority of the records were made using Kodak Triex 35 mm film since the non-halation type was not readily available.

Transformer S, 500 kVA, 10/0.415 kV, delta-star, bobbin/layer.

Experiments were originally made on this transformer to check the fault detection sensitivity employed by an overseas impulse testing laboratory when carrying out, in 1952, H.V. acceptance impulse tests in accordance with a Sydney County Council contract. The laboratory had employed test connexion No.2 (See Fig.6) but the L.V. winding had been completely short-circuited and earthed. Records of applied voltage (V_L:V_{HV}) and neutral current (I_{NC}) were taken.

The neutral current oscillogram, which was recorded using a 120 microsecond sweep time, comprised a large electromagnetic component on which was superimposed a heavily damped electrostatic component of small magnitude. It was suspected that substantial interturn faults could have been undetected during the full wave tests at 100 kV.

Recurrent surge experiments similar to those described in Section 2.4 - Test Connexions, and illustrated in Fig.21, were carried out to determine the fault detection sensitivity of the full scale test conducted at the overseas laboratory. It was found that, with the test connexions employed, the application of a solid fault across 15 turns of the H.V. winding did not give a positive change in the neutral current. It appeared that the fault detection sensitivity was about 2% under the test conditions employed, which is unsatisfactory.

Further recurrent surge experiments were then conducted to determine the optimum conditions for future full scale tests on this design of transformer. The oscillographic results of these experiments are given in Fig.26. The transferred voltage under no-fault conditions (Fig.26(a)) has a peak value of only 2.4 kV so that there is no need to short-circuit or shunt the L.V. windings. Test connexion No.2 (Fig.6) was employed with the L.V. neutral earthed to the tank.

The oscillograms of Fig.26 provide a comprehensive picture of the oscillographic evidence to be expected under full scale test conditions.

No Fault.

The transferred voltage (V_{LV}) is of similar waveshape to the applied voltage and has a peak value of 2.4% of the voltage applied.

The neutral current shows a small peak at the start corresponding to the charging of the series capacitances. The electrostatic component follows the conventional pattern for a disc type winding

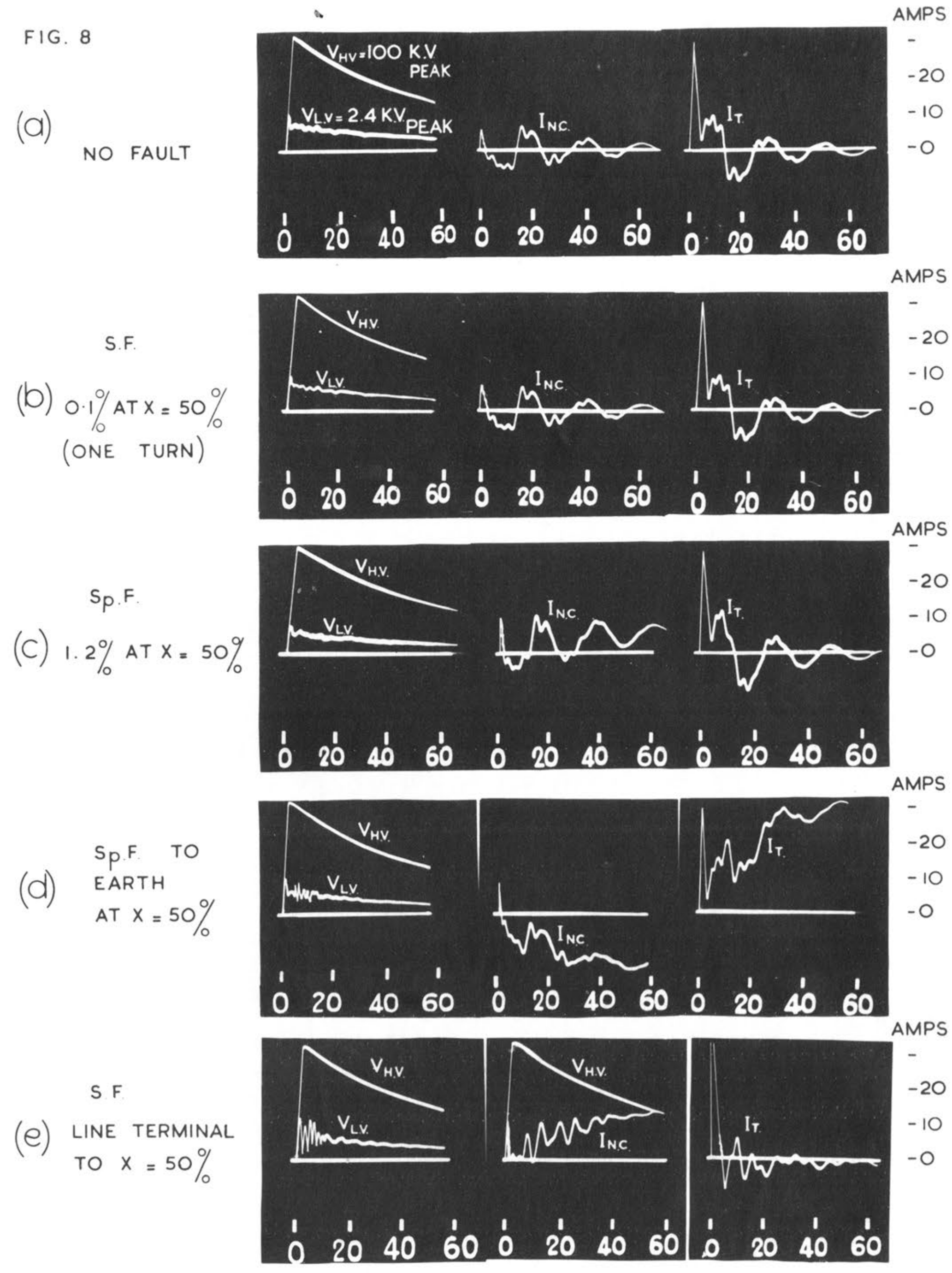


FIG. 8.26 RESULTS OF RECURRENT–SURGE FAULT DETECTION EXPERIMENTS ON A 500 K.V.A. 10,000/415 VOLT THREE PHASE DISTRIBUTION TRANSFORMER (CORE AND WINDINGS IN TANK UNDER OIL.) SURGE APPLIED TO BOBBIN TYPE H.V. WINDING. TIME SCALE IN MICROSECONDS.

NOTE: (b) AND (c) — NO DIFFERENCE WAS NOTED IN THE I_{NC} RECORDS WHEN THE SHORT-CIRCUIT WAS APPLIED AT OTHER POSITIONS IN THE WINDING. TEST CONNECTION (2) IN FIG. 4. S.F. = SOLID FAULT. Sp.F. = SPARKING FAULT.

under these test conditions. It is superimposed on a very small unidirectional electromagnetic component. The electrostatic component is very similar to the tank current but 180° out of phase. This confirms the theoretical hypothesis expounded in Section 2.3.1 and illustrated in Fig.15.

The tank current contains an initial peak which is the charging current of the shunt capacitances. The oscillations then follow the voltage conditions in the winding. The complete waveform is similar to that derived theoretically in Section 1.3 and illustrated in Fig.7.

The oscillograms of Fig.26(b) show no significant indication of the application of a one turn short-circuit at x = 50%. However, a 12 turn short-circuit (sparking fault) produced a substantial increase in the electromagnetic component of the neutral current and significant changes in the tank current. The tank current indication of this sparking fault at x = 50% occurred at approximately 5 microseconds. This confirms the usefulness of the tank current for fault location purposes since the transit time for the whole winding was 10 microseconds.

A sparking fault to earth at x = 50% produced the anticipated electromagnetic component indications in the neutral and tank currents. The time at which the latter component appears in the tank current is once again a measure of the fault location.

The short-circuit from the line terminal to tapping switch simulated a flashover down the winding stack. The transferred voltage indication does not discriminate between this type of fault and the previous fault to earth. This disadvantage is considered in more details in Section 2.7. The oscillations in the electrostatic components of the neutral and the tank currents occur at a higher frequency due to the reduction in the number of sections in the equivalent ladder network (See Fig.1).

The reduction of the total inductance of the winding stack increases the electromagnetic component of the neutral current. However, the voltages in the winding are severely attenuated by the losses in the short-circuited portion and the electrostatic components of the tank current and the neutral current are correspondingly reduced.

Summary.

These experiments on distribution transformers indicate that the anticipated electromagnetic indications of failure hold for all types of distribution transformer windings. The neutral current record appears quite adequate for layer type windings but the supplementary use of the tank current record for bobbin type windings appears essential if the fault detection sensitivity is to be improved. The disc type winding appears to present no problems.

The fault detection sensitivities given below are for interturn faults in the H.V. winding under test and the L.V. winding open. Earth fault sensitivities can never be less. The values given are conservative and an impulse testing laboratory with experience of its equipment's capabilities should be able to achieve higher sensitivities.

The voltage transferred to the 415 volt winding of the normal distribution transformer is usually less than 10 kV if the H.V. winding is rated at 11 kV or less. The accepted American impulse level for 115 volt equipment is 25 kV. Also full scale tests on locally manufactured 660 volt V.I.R. cable have proved its impulse strength to exceed 30 kV. In view of these facts it is recommended that the 415 volt windings of distribution transformers be left [illegible] ~~unearthed~~ unless

it can be shown that the transferred voltage will exceed 20 kV peak.

Bobbin Type Windings.

The neutral current and tank current waveforms under "no-fault" conditions are consistently similar and conform to the waveforms previously predicted in Sections 1.3 and 2.3. The waveforms are also similar to those obtained under full scale test conditions by other experimenters.

The fault detection sensitivity is at least 0.5 percent for 200 k VA and 0.3 percent for 500 kVA and above.

Layer Type Windings.

The direct shunt capacitances of the winding are reduced since only the end turns of each layer are directly coupled, capacitively, to the tank and core. However, the series capacitances are increased. The neutral current, therefore, gives a good electrostatic and electromagnetic indication of failure.

Fault detection sensitivity = 0.2 percent winding for 250 kVA and above.

Disc Type Winding

The electromagnetic indications were excellent, indicating good mutual inductive coupling.

The electrostatic component usually contained a higher "fundamental" frequency than similar units with bobbin type windings.

Fault detection sansitivity = 0.1 percent for 500 kVA and above.

The experimental fault detection results obtained from the transferred voltage and line current records were disappointing because:-

Transferred voltage: This quantity was relatively insensitive and indications were difficult to relate to the transient behaviour of the winding under test.

Line Current: Records of this current show the characteristics of both neutral current and tank current. Its electromagnetic indications do not discriminate between earth and interturn faults. It may be useful if only one oscillograph trace is available and an attempt is to be made to detect electrostatic and electromagnetic fault indications using a non-linear oscillograph sweep.

The erroneous test connexions used, and the resultant poor fault detection sensitivity during the full scale test on transformer S, at an eminent overseas testing laboratory as recently as 1952, indicate the need for clarification and standardisation of impulse testing practice.

The transit times for the four 500 kVA transformers used in these experiments were:-

Transformer "P": 10 bobbins - 28 microseconds

Transformer "Q": 50 discs - 14 microseconds

Transformer "R": 40 discs - 6.6 microseconds

Transformer "S": 10 bobbins - 10 microseconds.

The wide variation shows the need for careful analysis of the "no-fault" tank current record so that the correct fault location can be obtained if failure occurs. There was insufficient design data available to draw any conclusion as to the effect of the disc or bobbin type winding constructions on the generally accepted propagation constant of 150 metres per microsecond. It does not appear satisfactory to apply this method of fault location to layer type windings due to the large interlayer capacitances. The layer type winding construction offers considerable scope for further research.

2.7 POWER TRANSFORMERS

Due to the difficulty of obtaining ready access to the core and windings of large power transformers at a suitable time, the number of experiments have been limited. This fact is not so serious as it may first appear, since:-

(a) overseas experimental results published in the literature deal mainly with large units.

(b) The design of power transformers necessitates higher volts per turn than in distribution transformers. This usually means that the single turn fault is more easily detected.

The experiments conducted by the author can be summarised as:-

TABLE 6 - EXPERIMENTS MADE ON POWER TRANSFORMERS

Transformer	Rating in kVA	Voltage Ratio in kV	Type of Winding	Nature of Experiment
W	13,500	33/5.35	disc/ layer	Fault detection
X	40,000	67/22	disc/ layer	Fault detection

Results of full scale tests on a 10,000 kVA 66/11 kV transformer are also contained in the author's Impulse Testing Oscillogram File. These test results, from the laboratory of a major overseas manufacturer, are critically examined at the end of this section.

Transformer "W" - 13,500 kVA, 33/5.3 kV, delta/star, disc/layer

The oscillographic results of the experiments conducted on transformer "W" using the recurrent surge generator are given in Fig.27. It should be understood that the slow oscilloscope sweep times employed were used only for the sake of obtaining the most information to satisfy the objectives of this thesis. In actual tests the sweep speeds may be doubled, in fact, in the case of the tank current, even trebled. The equivalent full scale test voltages and currents have been indicated on the oscillograms in Fig. 27.

The results refer to a simulated test of the 33 kV delta-connected winding using test connexion No.2 (See Fig.6). Artificial faults were applied to the high voltage winding. The test was conducted with the core and coils in the tank under oil. The single turn fault was simulated by wrapping an insulated wire closely around the high voltage winding stack at x = 25% and bringing the ends up above the oil level. Other interturn and earth faults were simulated by connexions to the tapping leads.

The quantities recorded were:-

Voltage applied to the 33 kV winding (V_{HV})

Voltage transferred to 5.35 kV winding (V_{LV})

Neutral current (I_{NC})

Tank current (I_T)

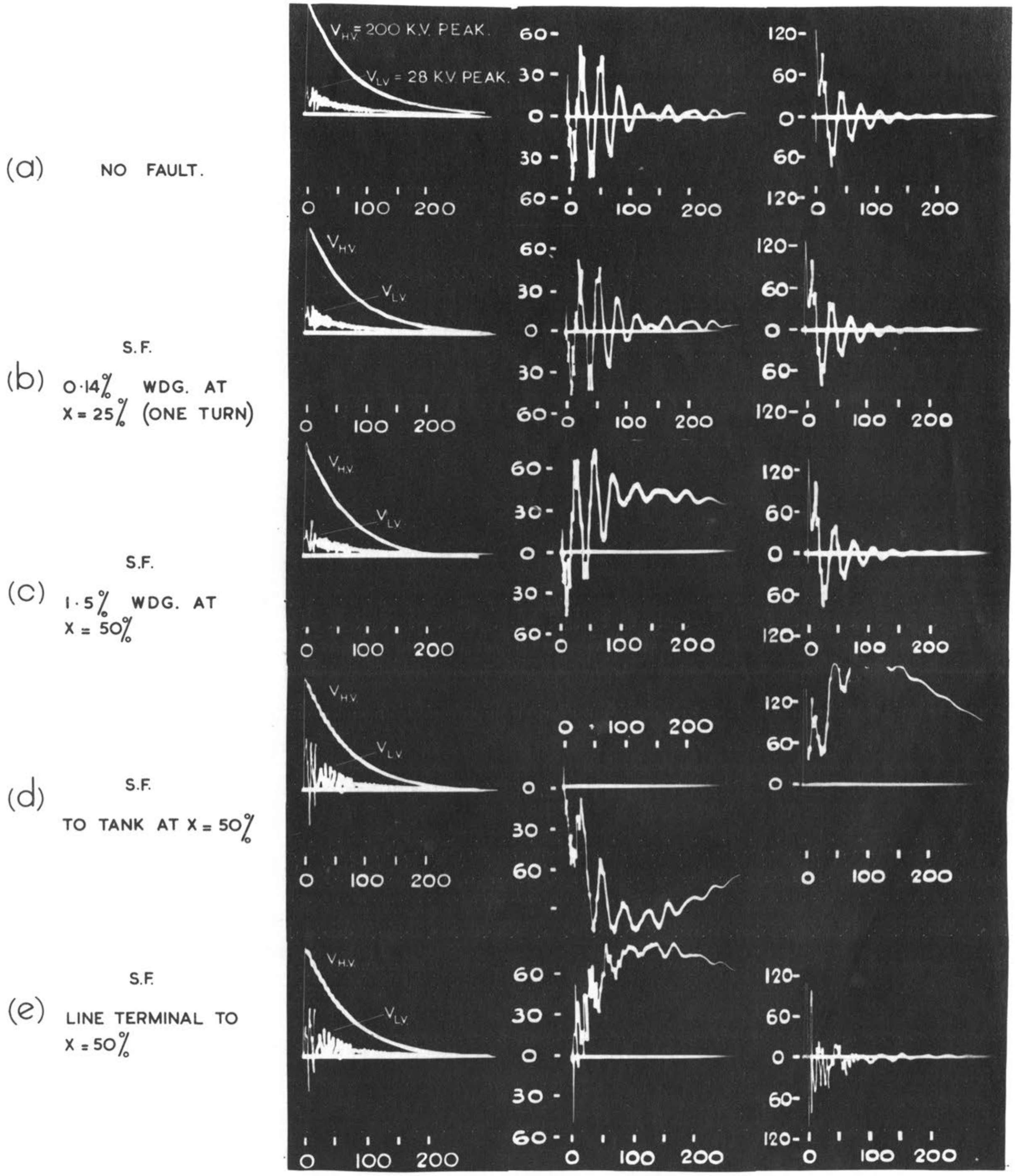


FIG. 27 RESULTS OF RECURRENT-SURGE FAULT DETECTION EXPERIMENTS ON A 13,500 K.V.A. 33,000/5350 VOLT THREE PHASE POWER TRANSFORMER (CORE AND WINDINGS IN TANK UNDER OIL.) SURGE APPLIED TO DISC TYPE H.V. WINDING TEST CONNECTION (2) IN FIG 4.
TIME SCALE IN MICROSECONDS.
S.F. = SOLID FAULT. X = % DISTANCE FROM LINE TERMINAL.

The applied voltage waveform showed little change as the various faults were applied except for marked oscillations when the two major faults, one to earth and the other across 50% of the winding, were applied.

It is interesting to note that the V_{HV} indication for both of these major faults is identical. This is to be expected since both faults represent a short-circuit across half of the equivalent ladder network. Hence, the number of network sections remaining will be the same and the frequency and magnitude of the oscillations appearing in the V_{HV} oscillograms in each case will be the same.

The transferred voltage (V_{LV}) oscillograms were superimposed on the V_{HV} records for convenience. The voltage divider used to record V_{LV} had a ratio of 7:1 whereas the V_{HV} voltage divider was 12:1. It can be seen that the voltage transferred to the 5.35 kV winding under "no fault" conditions had a peak value of 28 kV, i.e. 14% of the applied surge. The turns ratio was $\frac{33 \times 1.732}{5.35} = 10.7:1$.
The electromagnetic component of the voltage transferred is seen to conform to this ratio.

Later in the experiment when the major faults (d) and (e) were applied, the electrostatic component of the transferred voltage increased the peak value of the latter to 53 kV (i.e. 26.5% of the applied surge).

Although the time scale is too slow to properly examine the V_{LV} records given in Fig.27, it can be seen that a positive indication is given for fault (c), i.e. 1.5% winding interturn fault at x = 50%. The indication is predominantly electrostatic. Similarly, for major faults (d) and (e), the electrostatic component is greatly increased. Once again, it is noted that the waveforms for the interturn fault (e) and the fault to earth (d) are identical. Even without comparing the relative sensitivities of the V_{HV}, V_{LV}, I_{NC} and I_T records, it appears that this similarity detracts from the usefulness of the V_{HV} and V_{LV} records for fault detection purposes.

The neutral current (I_{NC}) records are of great interest. Under "no fault" conditions, Fig.27(a), the waveform follows the conventional pattern. The electromagnetic component is negligible and the electrostatic component follows closely the waveform of the tank current but with the reversed polarity. (Note: current scales for I_{NC} and I_T records are different).
The fundamental time of the oscillatory electrostatic component is 15 microseconds. Since the conductor length of the 33 kV disc type winding stack is 5830 feet (1780 metres) this gives a propagation constant of 388 feet (118 metres) per microsecond. This does not agree very well with the figure of 150 metres per microsecond given

by Ganger (Ref.27). However the order of accuracy was not very great due to the slow speed of the oscillograph time base.

The application of a one turn (0.14% winding) fault at x = 25%, produced a definite change in the electromagnetic component of the neutral current. With the oscilloscope sweep speed in use, no evidence of a substantial change in the electrostatic component was evident.

The 1.5% winding interturn fault (Fig.27(c) produced a 40 ampere positive increase in the electromagnetic component. The electrostatic component was slightly changed by the change in voltage conditions.

The major fault to earth (Fig.27(d) produced a 100 ampere negative increase in the electromagnetic component of I_{NC} and as would be expected, the electrostatic component of the neutral current was drastically changed.

The major interturn fault (Fig.27(e), which involved 50% of the winding, produced an 80 ampere increase in the electromagnetic component of the neutral current. The electrostatic component changes drastically and increases in frequency due to the reduction in the number of sections of the equivalent ladder network.

The tank current records are displayed on the same time scale as the other quantities for comparison purposes. However, normally a total sweep time of 50 microseconds would be used for fault detection purposes on this type of transformer.

The characteristic oscillatory waveform related to the voltage distributions in the winding is obtained under "no fault" conditions (Fig.27(a)). The fundamental time, or "basic transit time" as Ganger calls it (Ref.45), is the same as for the electrostatic component of the neutral current, i.e. 15 microseconds.

The one turn fault (Fig.27(b)) does not appear to produce any significant change in the tank current because the change in voltage distribution is not sufficiently great. The 1.5% winding interturn fault does produce an appreciable change and with a faster time scale the oscillogram would produce definite evidence of failure. Also, if the fault were of a "sparking" nature it would provide an indication of the location of the fault.

The major fault to earth (Fig.27(d)) is immediately detected by the electromagnetic component which now appears in the tank current record.

The effect of the major interwinding fault (Fig.27(e)) is entirely different. The short-circuiting of the top half of the winding stock apparently damps the voltage oscillations in the remaining half of the winding.

The oscillations now occur at a higher frequency due to the reduction in the equivalent network sections and the resulting tank current oscillations attenuate rapidly. The positive indication of the nature of the fault given by the tank current contrasts sharply with the ambiguity of the applied voltage (V_{HV}) and the transferred voltage (V_{LV}) indications.

Transformer X. 40,000 kVA 67/22 kV delta/star, Disc/layer.

The experiments on this transformer were carried out in the transformer testing laboratory of the British Thomson-Houston Company Limited, Rugby, England, in 1950, when the author was assisting Mr. D.Wadland of the Transformer Engineering Department. The core and windings were standing in air and test connexion No.1 (See Fig.6) was employed. Oscillographic measurements were made using a 1000 volt recurrent surge oscilloscope and a 200:1 amplifier in the recording circuits.

The 67 kV delta-connected winding was of continuous disc construction being wound in two parallel halves each occupying half the axial length of the H.V. stack. These halves were assembled so that one line lead entered at the axial centre of the H.V.stack.and the other line lead was made by connexion of the top and bottom ends of the composite winding stack. An arrangement such as that described above is clearly illustrated in Fig.P and Fig.Q in Appendix 4.2.

The 22 kV star-connected winding was of helical layer construction. During all the experiments the relevant phase of the L.V. winding was shunted by a 1000/10 ohm. potentiometer used for the recording of the transferred voltage.

"No Fault" Conditions.

Under "no fault" conditions the transferred voltage (V_{LV}) appearing across the 1000 ohm. potentiometer referred to above, was of similar shape to the 1/50 microsecond wave, with a peak value of approximately 18% of the latter.

The neutral current was of conventional shape except that the electromagnetic component was larger relative to the oscillatory electromagnetic component than that recorded for transformer "W".

This was, no doubt, due to the connexion of the 1000 ohm. potentiometer across the L.V. winding. The oscillatory electrostatic component of the neutral current contained a prominent "fundamental" with a frequency of approximately 30 kilocycles per second.

Interturn faults.

The following interturn faults were applied:-

Interturn fault	Percent Increase in Electromagnetic Component of Neutral Current.
2% winding - SF at x = 1%	450
Single turn - SF at x = 35%	320
Single turn - SF at x = 75%	280
5% winding - SF at x = 38%	940
5% winding - SF at x = 67%	820
5% winding - SF at x = 95%	400

As can be seen from the above table the electromagnetic indication of a one-turn fault in the disc type H.V. winding is excellent. The fact that the magnitude of the electromagnetic component also provides an approximate indication of the fault location is an interesting confirmation of the mutual inductance effects considered in Section 1.1 - The Equivalent Ladder Network. Due to the arrangement of the H.V. winding stack in two symmetrical halves with a common line lead at the axial centre of the stack, interturn faults in the lower half had a greater effect on the upper half of the stack when they occurred near the centre of the stack, i.e. as $X \longrightarrow 0$ at the line lead.

The electrostatic indications of the faults were also very significant even for the single turn faults.

Sparking faults were applied by a Carpenter synchronous relay and the resultant oscillograms were similar to those under solid fault conditions once the fault was applied.

Faults to Earth.

Sparking faults to earth from x = 33% were applied using the Carpenter synchronous relay.

The applied and transferred voltage oscillograms showed the presence of this major fault by a sharp drop in the tail of the voltage wave when the fault was applied. The electromagnetic component of the neutral current changed polarity and mangitude in the normal way.

A novel method of checking fault sensitivities was being used by Mr. Wadland at the time. This method depended on the principle of superposition. With no voltage applied to the line terminal of the winding and the generator represented by a passive network, a small voltage was applied across that portion of the winding which was hypothetically the faulty section. The indications appearing in the various recording circuits then represented the indications which would appear under normal test conditions. The method was called "Injected Faults for the Direct Comparison of Sensitivities". One difficulty seems to be to correctly simulate the voltage which should be impressed across the "faulty" portion of the winding.

Full Scale Tests on a 10,000 kVA 66/11 kW Delta/star Transforme

This transformer was high voltage impulse tested in 1953, at an overseas laboratory, before shipment to Sydney. Test connexion No. 2 (Fig.6) was used for the test on the 66 kV winding but the 11 kV winding was short-circuited and earthed. Oscillographic records of applied voltage and neutral current were taken. The latter was recorded using a 170 microsecond total sweep time and a very prominent electromagnetic component appeared. The electrostatic component was not very legible due to the slow sweep speed used. The fault detection sensitivities were apparently not checked, but from previous experiments described herein it appears certain that the procedure employed was inadequate.

The same fault detection conditions prevailed when the 11 kV windings were tested employing test connexion No.4 (Fig.6) with the 66 kV winding short-circuited and earthed. The excessive voltages which would be transferred to the 66 kV winding unless it was loaded by shunt impedances across its terminals, provide a reasonable excuse for the test connexions employed although the possibility of using high voltage resistors should have been explored. Once again a slow sweep speed was used, allowing only electromagnetic indication of failure.

The overall impression gained from a study of the report on these full scale tests by an eminent overseas laboratory is disappointing and indicates a need for improvement in fault detection techniques.

Summary.

These experiments show that provided the windings not under test can be left open-circuited or connected to a voltage limiting resistor, fault detection during impulse tests on power transformers is relatively simple provided the winding construction is fairly uniform. Special care must be exercised when involved constructions, such as a main disc winding with a layer type tapping winding, are encountered. A thorough examination of the fault detection sensitivities should be made using the recurrent surge generator.

When the problem of excessive transferred voltage occurs and windings have to be resistance loaded to reduce these voltages, then electrostatic indication of failure must be ensured by the use of high oscillograph sweep speeds. Under these conditions it is preferable to measure both neutral and tank currents.

2.8 PHYSICAL PHENOMENA AND THEIR DETECTION

The importance of a physical indication of failure is fully realised by test engineers engaged in high voltage testing and is recognised by standard specifications which usually accept smoke, flame, abnormal noise and the evolution of gas as positive indications of failure.

The author has had considerable experience in the location of faults in underground paper-insulated cables using a high-voltage impulse technique and expects that similar laws govern the physical indication of failure in the insulation of oil-filled transformers as govern such indications in oil-impregnated cables and oil-filled cable joint boxes.

The fundamental limitation to the generation of a physical indication at the point of failure is the fault energy available at that point. This may be thought of as the potential energy stored between the two points at which failure subsequently occurs. If a substantial quantity of energy is released by the dielectric failure across the points involved then a substantial physical indication can be expected. Energy is stored during an impulse test in the magnetic circuit and the capacitance networks of the transformer. This energy and that available in the impulse generator can contribute in varying degrees to the available fault energy.

The next limitation on the physical disturbance at the point of faulure is the way in which the energy is released. A sudden rupture of previously sound dielectric, say across an oil duct of a disc type winding, normally produces an explosive arc. If, however, a watersoaked or carbonised portion of the dielectric structure is involved, the fault energy will probably be dissipated more slowly and without an explosive arc. The heat produced may evolve gas or smoke from the dielectric materials. Ganger's experience with the oil-pressure detector suggests that the explosive type of fault is normally encountered in new transformers (Ref.47). Supply Authorities testing older units may encounter the failure of deteriorated insulation due to water or oxidisation products which produce less explosive energy.

Visual Indication

The high-voltage impulse test is usually completed within 300 microseconds (0.0003 seconds) even allowing for the dissipation of energy stored in the magnetic circuit. Consequently, light emission from an explosive type of fault is extremely rapid and it is only through the persistence of vision that it becomes noticeable to the human eye.

If it is possible, without disturbing the electrostatic field distribution of the winding under test, to remove the transformer lid during test, then it is advisable to do so. As well as enabling direct observation of the upper portions of the winding stack, the line leads and tapping switch or leads, any gas generated is detected more readily than by waiting for its appearance in the Buchholz relay.

Considerable care must be exercised by the observers so that:-

(a) the location of any flash is accurately noted

(b) misleading observations, due to reflections of light from the gaps of the impulse generator or the chopping device, are avoided.

(c) Disturbances under the oil must be detected but not confused with the electrostatic disturbance usually set up where the line leads enter the oil.

Shock Wave Indication

As early as 1936, attempts were made to detect shock waves set up in the oil by a fault. One type was constructed of wood with a mica diaphragm and stethoscope ear-pieces. It was claimed that with this microphone in the oil adjacent to the winding it was possible to differentiate between the various noises, and to say whether the impulse test was without sparkover or puncture, or with sparkover, with puncture, or with sparkover and puncture. Considerable experience is needed for this qualitative assessment however. The presence of noise from the gaps of the generator itself and, in chopped wave tests - from the chopping gaps, makes audible indication unreliable and it is not now used.

This does not mean, however, that shock-wave vibrations cannot be effectively used for fault detection. In fact, the opposite is the case. Ganger (Ref.47) gives a comprehensive description of the design and use of an "oil pressure detector", which comprises an electromagnetic microphone and a balanced amplifier feeding a string galvanometer. This galvanometer records, at relatively slow speed, the shock-wave vibrations with frequencies greater than 100 cycles per second, occurring in the oil of a transformer undergoing an impulse test. The indication can also be observed on a ground glass screen during the test. The advantages claimed for such an instrument are simplicity, robustness, speed of indication and positive detection.

For full wave tests the sensitivity of the detector is adjusted so that a light tap on the transformer tank is definitely indicated by the oscillograph. When chopped wave tests are to be made the sensitivity has to be reduced due to the extraneous vibrations resulting from the noise generated at the chopping gap. However, Ganger claims that the noise from a fault inside the transformer still gives a definite indication of failure and supports his claim by some actual test results.

The experience gained so far with this oil pressure detector has apparently been very satisfactory since it is being used alone for design tests on distribution transformers (Ref.47). Whilst the author cannot agree with such a radical step as dispensing with the voltage and current records, the experiences described, and the claims made, are so much in agreement with his own experience in the impulse proving of underground cable faults, that he agrees that this detector should be extensively employed during high voltage impulse tests on transformers. The instrument described by Ganger should provide a valuable indication of failure complementary to the indications from the voltage and current records.

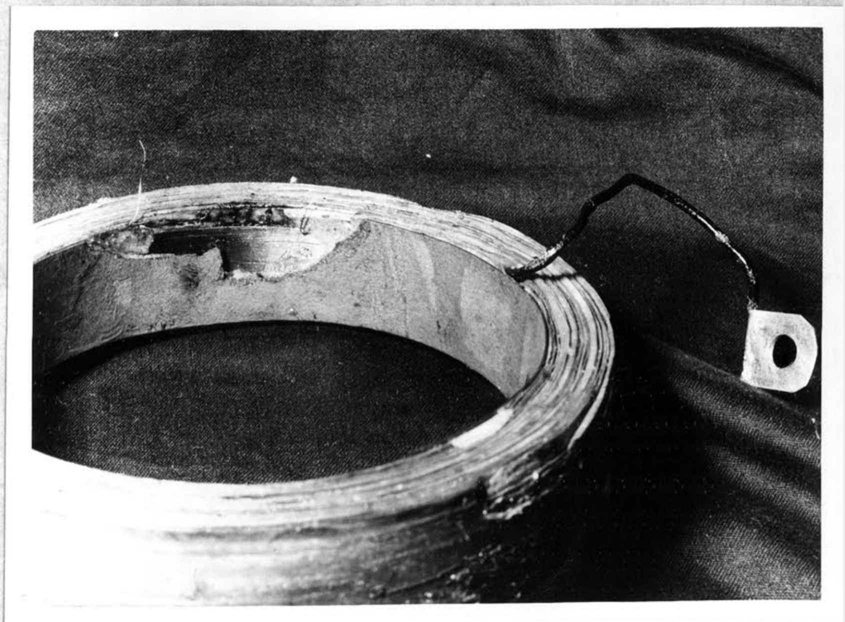
So important is the confirmation provided by a physical indication of failure that it is conceivable that laboratories will eventually take steps to separate the impulse generator and the test object acoustically as well as electrostatically.

Stripping of Winding

The final phase of fault detection is the stripping of the winding. Great care must be taken to proceed logically and to take advantage of each stage of the work. Sometimes it may be desirable to apply recurrent surge techniques, whilst the unit is standing in air and still assembled, to reproduce the current waveforms which indicated failure, by the insertion of various artificial faults.

The possible nature, magnitude and location of the fault, as indicated by the test results, should guide the stripping operation. Fig.28 shows the damage to the major insulation of transformer "B" when B phase HV winding stack was partly stripped. The carbonised hole in the main insulating cylinder was made by both impulse and power frequency testing (See section 2.5). However, the insulation resistance readings after impulse testing and the behaviour of the winding at the start of the power frequency tests, indicate that a definite radial core of carbon had been formed through the cylinder by the impulse tests.

(a)



(b)

Fig.28: Photographs of major insulation failure which occurred during 113% test level Chopped Ware Impulse Test on 11,000/110 volt voltage transformer (Transformer B)
(a) B phase stack with line end coil removed
(b) Line end coil from B phase showing line lead entry.

2.9 GENERAL CONCLUSIONS

The original objectives of the investigation described in this thesis were:-

(a) to provide an assessment of the relative merits of different methods of fault detection from an understanding of each.

(b) to develop improved methods or combinations of methods.

(c) to provide a comprehensive source of technical information on the subject for chartered engineers engaged in the introduction of the impulse testing of transformers to Australia, thereby facilitating some measure of standardisation in testing techniques.

The investigation has achieved these objectives by its own findings and by the study of concurrent overseas investigations. The investigation has successfully explored the theoretical bases of the various fault detection methods and confirmed them by recurrent surge experiments and full scale tests.

The theoretical treatment revealed the difficulty of deriving the inductive parameters of the equivalent ladder network representing a transformer winding. An empirical method of solving this problem was indicated. The equivalent capacitance network for the 132 kV winding of a 60 MVA transformer is derived.

The theories described owe much to overseas experimenters. However, the derivation of the tank current waveform from the voltage conditions appears to be an original contribution to the literature. The modified transmission line theory due to Ganger and the theory developed by the author from experiments on a model winding are complementary and adequate for a clear understanding of fault detection methods.

It is recommended that the following theoretical studies be carried out using computer aids:-

(a) Mathematical analysis of the twelve (12) bobbin experimental stack used in this investigation and subsequent confirmation by recurrent surge measurements.

(b) Investigation of the layer type winding construction and derivation of a general expression for its transient behaviour. The ladder type network conception appears inadequate for layer type windings which are being widely used up to 750 kVA, and for the extra high voltage windings of power transformers.

Research along the lines recommended above would be of value to transformer designers as well as test engineers engaged in impulse testing.

The recurrent surge experiments conducted on the experimental winding stack were of great value in clarifying the basic relationships governing the transient behaviour of the winding currents. This fact was clearly demonstrated when the equipment was used to illustrate, with the aid of closed circuit television, a joint paper presented before the Sydney Division of the Institution of Engineers, Australia (Ref.42).

The above-mentioned paper was in the nature of a preliminary report of this investigation and stimulated considerable discussion. A valuable contribution was received from G.H.Hickling, an authority of international standing.

Test Connexions.

The importance of the test connexions to be employed became obvious early in the investigation and this aspect was thoroughly investigated. It is concluded that for the highest possible sensitivity and to reproduce service conditions the non-impulsed windings should be left open-circuited. If this is impossible they must be resistance loaded in such a manner that the voltaged in them never exceed 70-80% of the prescribed test level. When windings are resistance-loaded greater precautions must be taken to ensure that the correct currents are measured and that the optimum time sweeps are used.

The conclusions arrived at by the author are at variance with those propounded by manufacturer's test engineers (Ref.32) but are supported by an independent testing authority of international standing (Ref.46).

The resistance loading of non-impulsed windings of large units may not appreciably affect the severity of the voltage conditions. In the case of smaller units, resistance loading of such windings will reduce the severity of the voltage stresses in the windings under test.

The international controversy over test conditions has emphasised an important relationship between the normal impulse test procedures and service conditions. The main question relates to the excessive voltages transferred to the higher voltage winding when the lower voltage winding is subjected to an impulse test at its rated level. It appears that a similar effect would occur in service and that surge arrestors across the higher voltage winding would be essential to limit the transferred voltage.

Fault Detection Methods.

The objective of any fault detection method should be kept clearly in view at all times. In the impulse testing of transformers the usual objective is the detection of faults which will affect the service life of the unit under test. Wherever detection methods can be simplified whilst still attaining this objective, this should be done.

The applied voltage waveform has to be measured to ensure that the testing requirements are met. It will indicate faults of a more or less severe nature, depending on the impedance of the impulse generator. Although any indications of failure in the applied voltage waveform must be recognised, fault detection must be guaranteed by measurement of the neutral current and tank current.

The neutral current can often be used alone, and, in the case of layer type windings, would be quite sufficient. The complementary measurement of the tank current waveform not only increases the fault detection sensitivity under practical test conditions but also provides an indication of the fault location.

The use of two current measurements allows greater flexibility in the choice of time-sweep speeds and shunt values so that every type of fault is encompassed.

Resistance measuring shunts should be used and the insulation of measuring leads and oscillograph deflection circuits made adequate to withstand the voltages liable to occur under no fault and fault conditions. If a capacitance has to be used in parallel with a resistance shunt due to a high inrush current, its value should be kept as low as possible so that high frequency indications will not be lost.

The experimental results described herein illustrate the recording times necessary for the various sizes of transformers and in some cases provide actual current magnitudes to be expected.

It is recommended that research be carried out into the use of non-linear oscillograph sweep speeds and non-linear recording shunts.

The general indications of failure can be summarised as:-

SUMMARY OF OSCILLOGRAPHIC INDICATIONS OF FAILURE DURING FULL WAVE TESTING

Type of Fault.	I_{NC}	I_T	V_L
Line terminal to tank.	Electromagnetic component decreases to zero.	Large increase	Severe drop
Tapping switch to tank or core.	Decreases or reverses polarity.	Increase after time lag.	Decrease depending on impedance of generator X
Major interturn fault.	Substantial increase.	Higher frequencies evident but overall decrease X	Decrease depending on impedance of generator X
Minor interturn fault	Increase depending on winding involved and construction	Change depending on winding involved and construction X	Little effect X

X A high frequency electrostatic indication may appear.

The following fault detection sensitivities for full wave tests should be possible at any testing laboratory using neutral current measurement for fault detection. The sensitivities could be improved with experience of the capabilities of any particular laboratory's equipment.

Disc Type windings - 0.1 per cent winding for 500 kVA and above.

Bobbin type windings - 0.5 per cent for 200 kVA
0.3 per cent for 500 kVA and above.

Layer type windings - 0.2 per cent for 250 kVA and above.

These sensitivities are for inter-turn faults. Earth fault sensitivities can never be less.

The differential techniques described by Rabus (Ref.48) and Wadland (Ref.49) offer promise of greater sensitivity. It appears, however, that the extra expense and complexity of the testing equipment would only be occasionally justified. They should prove very suitable for tests of voltage transformers. However, it is recommended that direct recording techniques be employed by high voltage laboratories commencing impulse testing, until considerable experience has been obtained.

The value of the tank current in indicating the fault location must be remembered and fully exploited when setting up recording facilities.

The experience overseas with an oil-pressure detector for detecting shock waves generated by a fault is in accordance with similar experience the author has had in the detection of underground cable faults. It is recommended that this simple and robust device be fully utilised for the full scale impulse testing of transformers. Scope exists for the development of a transistor amplifier and recorder for this type of detector.

The detection of failure under chopped wave test conditions depends on three methods:-

(a) Use of the oil pressure detector

(b) Changes in the neutral current waveform - the time-to-chop being controlled.

(c) Simultaneous application of a power frequency voltage or subsequent application, with the fault de-ionisation time, of a full wave impulse voltage to another winding.

Methods (a) and (b) are the most promising and the least complicated. Further development of these methods is felt to be desirable but not essential to continued use of the chopped wave test.

In service no power frequency current will flow due to the voltage conditions existing and rapid operation of the protective systems. Consequently, only permanent damage due to a chopped wave test is of significance. The British and American practice of following chopped wave tests by full wave tests should detect such damage.

Recording Facilities.

It is recommended that high voltage impulse testing laboratories should be provided with the following facilities for fault detection during the impulse testing of transformers.

(a) A comprehensive earthing system and electrostatic and electromagnetic shielding of the recording equipment.

(b) Three oscillograph recording channels with time sweeps independently variable from one (1) microsecond to three hundred (300) microseconds, and associated voltage dividers, shunts, etc.

(c) A recurrent surge oscilloscope.

(d) High voltage resistors to load windings not under test.

(e) An oil pressure detector for detecting shock waves in the oil.

(f) A controlled chopping gap.

(g) An acoustic and electrostatic shield to facilitate use of item (e) and the recording of tank current.

(h) A projector for comparing oscillograms, preferably incorporating a provision for differential enlargement of two records taken at different test levels. This provision could be readily provided if 75% test level oscillograms were recorded at 75% of the normal sweep speed.

The electronic techniques examined during the development of the recurrent surge oscilloscope indicate that there is considerable scope for the production of electronic monitoring instruments to simplify impulse testing procedure and fault detection methods. Instruments which directly indicate quantities such as the crest voltage of the applied wave, wave front and wave tail times and time-to-chop will make the normal setting up and testing times comparable with those necessary for power frequency tests.

Specifications

The draft specification of "High Voltage Testing Techniques" promulgated in February,1958 by the I.E.C. Technical Committee No. 42 and the draft publication I.E.C. No. 44 proposed by the I.E.C. Technical Committee No. 38 (Instrument Transformers), contain good examples of the specification of test procedure and fault detection requirements.

The draft revision of B.S.S. 171-1936, Power and Lighting Transformers, which is based on BEAMA Publication No. 156: "Recommendations for the Insulation Level of Transformers", and the clause described in Section 2.5 of this thesis, are good examples of the requirements. However, both of these should be amended to permit use of the tank current, in addition to the neutral and line currents, for fault detection.

Most specifications encountered do not sufficiently emphasise the need to leave windings not under test on open circuit as far as possible.

The installation of four (4) impulse generators, ranging in size from 120 kV to 2250 kV, in and around

Sydney during the last few years, has provided excellent facilities for further development of this form of high voltage testing of transformers. It is hoped that the investigation described herein will help to guide such development along sound lines.

2.10 ACKNOWLEDGEMENTS

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Assistance received from British transformer manufacturers during 1949-1952 when the author was working in the United Kingdom was very valuable. The co-operation and guidance of Messrs. H.L.Thomas, D.McDonald and D.Wadland of the British Thomson-Houston Co. Ltd., and Mr. E.C. Rippon of C.A. Parsons Co. Ltd., was most helpful. Mr. W.Tyree of the Tyree Electrical Co., Australia, and Mr. J.Buchan, of the British General Electric Co., have also provided encouragement and assistance from the early stages of the experiments in 1954 and this is gratefully acknowledged.

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APPENDIX 4.1

"INVESTIGATION OF FAULT DETECTION METHODS FOR THE IMPULSE TESTING OF TRANSFORMERS"

by
G.C.Dewsnap M.E.E., A.M.I.E. Aust.
and E.G. Williams A.M.I.E.E., A.M.I.E. Aust.

and

DISCUSSION

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Investigation of Fault Detection Methods for the Impulse Testing of Transformers

BY

G. C. DEWSNAP, M.E.E. (*Associate Member*) and E. G. WILLIAMS (*Associate Member*)*

Summary.—This investigation has been carried out primarily for the guidance of testing engineers and others associated with impulse testing procedures and specifications.

The experiments which form the basis of the investigation were made using a locally designed and built recurrent surge generator. Some details of this recurrent surge generator are described after brief mention of the experimental generator used for preliminary experiments.

The interdependence of impulse test connections and successful fault detection methods is stressed before a fault detection and location theory is considered. The theory of fault detection which is presented is qualitative and supported by oscillographic evidence.

Fault detection experiments on distribution transformers show that winding construction affects the maximum sensitivity obtainable. Typical sensitivities are given based on " solid ", or metal to metal, faults which are the hardest to detect.

Results of experiments on a 500-kVA and a 13,500-kVA transformer are presented, and a positive method of determining the position of earth faults is described.

The paper concludes with specific recommendations concerning fault detection during the impulse testing of transformers.

1.—INTRODUCTION

The impulse testing of high voltage power system equipment has become increasingly important as greater knowledge has been gained. Whereas a transformer winding may experience increased dielectric stresses due to increases in the power frequency supply voltage at intervals of months or years, it is subjected to transient overvoltages several times per week. These transient overvoltages are caused by atmospheric disturbances, or system disturbances such as the opening of a circuit breaker.

The ability of a transformer to withstand increases in the power frequency voltage is adequately demonstrated by works and site tests which impress twice or three times the normal power frequency dielectric stresses in the insulation.

Most purchasers of transformers now require impulse voltage tests to prove the ability of a transformer to withstand the transient voltage stresses which it will experience probably several times each week of its service life. These tests can only be made if the testing authority employs adequate fault detection methods to ascertain whether any dielectric failure occurs during the test, which will affect the service life of the transformer under test.

The equipment and methods of impulse testing have been well described in the literature (Refs. 1, 2), and this paper deals only with fault detection methods associated with commercial impulse testing. It has always been appreciated by supply authorities and manufacturers that the introduction of impulse testing must be accompanied by positive fault detection techniques.

The experimental work described herein was performed in connection with the candidature of one of the authors for a Master of Engineering Degree at the N.S.W. University of Technology. At present only full wave impulse testing has been considered.

Since recurrent surge techniques are very useful in fault detection experiments, the authors developed suitable equipment for use during the experimental work. This equipment is now described.

2.—DEVELOPMENT AND CONSTRUCTION OF RECURRENT SURGE GENERATORS.

An experimental recurrent surge generator was found necessary so that fault detection experiments could proceed during the development and construction of the final recurrent surge generator.

2.1—*Experimental R.S.G.*;

The experimental generator utilised the 2-kV D.C. power pack of a ex-R.A.A.F. Power Supply Unit Type A20. The generator was of orthodox design, the surge being developed by the discharge of a 1-microfarad condenser through a Mullard Type 4C35 Hydrogen Thyratron into a wave shaping unit. Synchronisation with the Cossor Oscilloscope Type 1035 used as a display unit was achieved by triggering the oscilloscope and the thyratron trigger circuit of the generator from the same peaking transformer.

2.2—*Final Design*:

The generator was required to be transportable with its output viewable on a standard commercially available oscilloscope with a sufficiently fast triggered time base. To avoid troubles likely to arise from oscilloscope amplifiers, it was decided to apply the voltages to be viewed directly to the oscillograph plates. This necessitated a " high level " generator giving as a matter of convenience a maximum output about 2 kV. This has proved perfectly satisfactory, particularly as the currents flowing in the windings or to the tank can be displayed as voltages appearing across appropriate shunts wired into the circuits under test.

The main design details of the generator have been described elsewhere (Ref. 34), but it will be convenient to recapitulate some of the points. The equation for a 1/50 surge can be given by the expression

$$v(t) = 1.016\ V(\epsilon^{-0.0142t} - \epsilon^{-6.073t})$$

Where V = peak voltage of the surge
and t = time in microseconds.

This response may be obtained from the basic circuit shown in Fig. 1, where C_1 is charged to a suitable voltage and discharged into the shaping network of R_1, R_2 and C_2. The desired surge appears across C_2. In the unit described the recurrence frequency is 50 cycles per second, which is a reasonable compromise between suitable cathode ray tube brightness and power supply requirements. The value of the output capacitor C_2 is governed by two

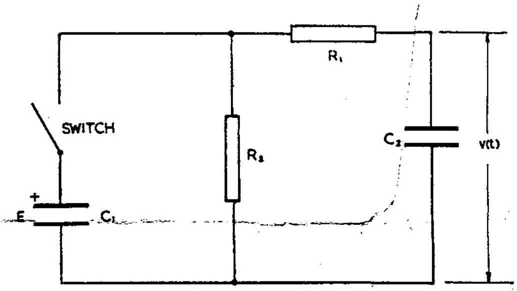

Fig. 1.—*Equivalent Surge Formig Circuit.*

*This paper, No. 1284, originated in the Sydney Division of The Institution, and is to be presented before a meeting of the Electrical and Communication Engineering Branch of the Division on 26th March, 1958.

An experimental winding stack will be used to demonstrate certain fundamental phenomena at the presentation of this paper. Voltage and current waveforms will be displayed on a projection type cathode ray oscilloscope or on several commercial oscilloscopes.

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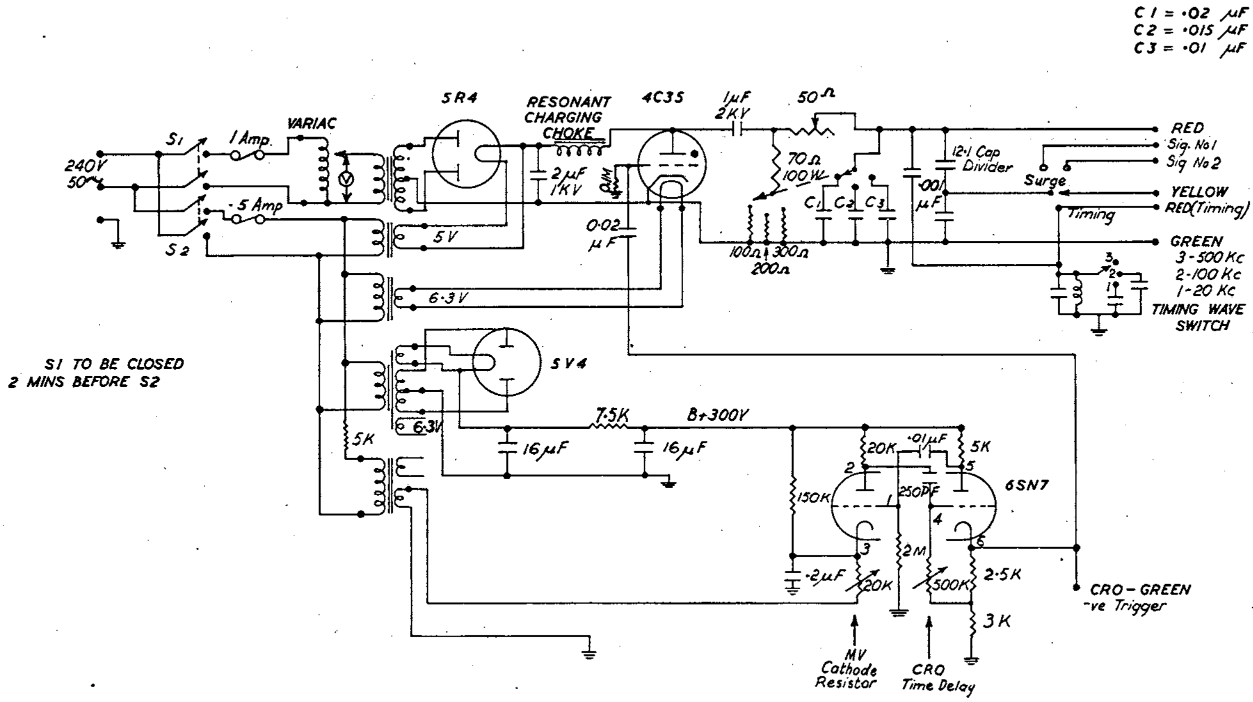


Fig. 2.

factors. One is the maximum allowable peak current in the switch, and the second is the equivalent capacitance of the load connected across the output. With the switch tube used here, the hydrogen thyratron type 4C35, the peak current allowable is 90 amps. This limits the capacitor C_2, for 2-kV output, to a value of 0.005 μF if C_1 is 1.0 μF.

The range of values of effective terminal capacitances of transformers, under travelling wave conditions is given in Table 1 below (Ref. 8).

TABLE I.

Transformers	Capacitance — μF		
	Max.	Min.	Ave.
Distribution	0.002	0.0004	0.001
Power	0.001	0.0002	0.0005
Non-resonating	0.003	0.0010	0.002

These values may cause a significant load on C_2 so that a range of values of C_2 should be provided along with independent control of R_1 to maintain the wave shape. If the voltage to which C_1 is charged may be reduced, then C_2 may be increased beyond the nominal maximum value of 0.005 μF without overloading the complete circuit which is shown in Fig. 2. It is convenient to provide adjustment also in the value of R_2.

For best operation the thyratron should be triggered after the oscilloscope time base so that the whole of the waveform applied to the device under test may be studied. In the generator is a multivibrator circuit triggered 50 times per second from the mains by a peaking transformer. Two steep fronted output signals are available, one of which is used to trigger the oscilloscope sweep and the other to fire the thyratron, in that order. The interval between these firing pulses is constant for a given setting, but is adjustable over a range of 40 microseconds, so that different parts of the output response may be studied.

The signal which fires the thyratron is also used for brightening the C.R.O. trace. In this case a slight modification is made to the circuits of the Cossor Type 1035 oscilloscope used.

A calibrating timing wave may also be switched into the output circuit for calibrating the oscilloscope time base.

To be able to extend investigations to fault detection during chopped wave impulse tests, it would be desirable to incorporate means for chopping the output wave, usually a few microseconds after the peak of the wave has been reached. For greater flexibility, the time of chop should be variable and should occur within a fraction of a microsecond. The circuits of the unit would have to be modified to accommodate a further thyratron, similar to the main switch, with an additional control circuit designed to fire the second thyratron at a fixed time after the first tube.

When testing multiwinding transformers, very greatly increased sensitivity for small differences in windings may be obtained by providing an amplifier to the oscilloscope with a differential input. The amplifier obtains and amplifies the difference between currents flowing in or voltages appearing across selected parts of two windings tested together. As the two windings are nominally identical, only a slight difference in configuration is necessary to produce a viewable trace on the oscilloscope which will be typical for the transformer tested. Any further change in one or other of the two windings is then very easily detected, and it is claimed that changes of only one turn in one winding are detectable.

In the equipment described above, the voltages being observed are applied directly to the oscillograph plates. However, auxiliary equipment (voltage dividers, amplifiers) must have a frequency response good enough to reproduce, within the general limits of accuracy, the waveform being measured.

By specifying that the equipment pass all frequencies in the band spectrum of the surge up to where the amplitude falls to one per cent of its initial value, it can be shown that the standard 1/50 surge requires a pass band of from 0 to 220 kilocycles per second. The required pass band for a chopped wave varies with the conditions of chopping, but may extend up to about 6 megacycles per second. Accepting the specification of required pass bands these ranges, of course, will also apply to any equipment required for full-scale surge testing.

The generator surge output was adjusted for duration by comparing it with the wave from a calibrated signal generator, while the voltage amplitude was checked by both resistance and capacitance dividers. The currents flowing in various parts of the equipment under test were measured from the voltages appearing across known non-inductive resistors. In all the oscillograph records reproduced in the paper the quantities (voltages and currents) were adjusted to equivalent full scale values.

Fig. 3 shows the Recurrent Surge Generator being used for tests on a 500-kVA transformer.

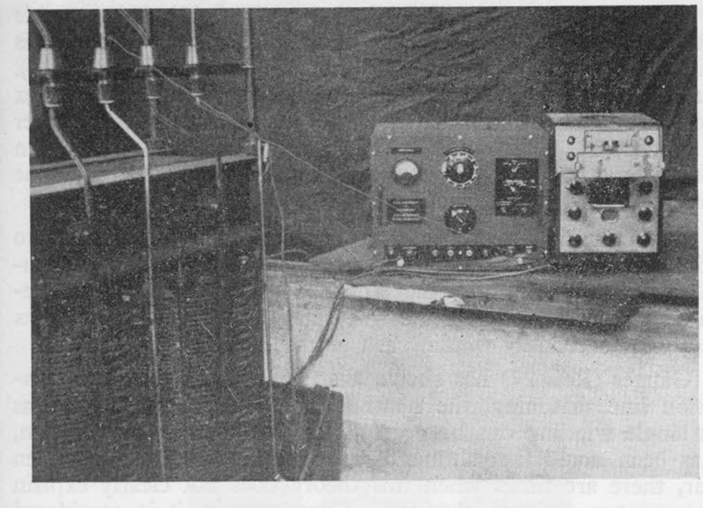


Fig. 3.—2-kV Recurrent Surge Generator being used for Experiments on a 500-kVA Transformer.

3.—Test Connections.

The success or otherwise of many fault detection methods is so dependent upon the test connections employed that it is necessary to consider this aspect first.

Since an impulse test is related to the actual overvoltages which occur in service, it is necessary to apply the test under service conditions as far as possible. Consequently, as far as the winding under test is concerned, the terminal not connected to the impulse generator should be earthed through a resistance not greater than 500 ohms. This ensures the most severe voltage distribution in the winding.

Windings not actually under test, except by transferred voltages in the transformer, should be earthed at one point only if possible. It is important not to short-circuit these windings since this reduces the inductance of the winding under test to such an extent that the additional reduction caused by an internal winding fault may be insignificant. Fig. 4*a* shows the effect of shorting the low voltage winding of a 10,000/415-volt 500-kVA transformer on the neutral current record. It can be seen that the fault indication is severely " masked " and the oscillogram heavily " damped ". A compromise is necessary if it is shown, prior to test, that excessive voltages will occur in the windings not under test. In such a case, a high voltage resistor must be connected across each winding so that the overvoltage is reduced to the basic impulse level for that winding.

Fig. 5*a* illustrates the various recording points which are used for fault detection during impulse tests. Symbols are in accordance with the list of Symbols and Abbreviations at the end of the paper. Fig. 5*b* shows typical test connections employed for testing three-phase transformers.

It has been found that recurrent surge tests can be made with the transformer core and coils out of oil and still obtain faithful records of the electromagnetic components. This convenient fact is illustrated by Fig. 4*b* where the neutral current records of a 500-kVA 10,000/415-volt transformer are shown with the core and windings in oil and in air.

However, the increase in shunt capacitance (C_g in Fig. 6) affects the velocity of propagation of the surge through the winding, and the frequency of oscillation of the electrostatic component is lower when oil-immersed. The increase in C_g also increases the magnitude of this component in the neutral current. The reason for this is considered later.

Oscillograms obtained from recurrent surge experiments on transformers, also subjected to full scale tests, have shown good correlation with records of the latter tests.

4.—Fault Detection.

The fundamental techniques of fault detection during or after an impulse test on a transformer can be summarised as—

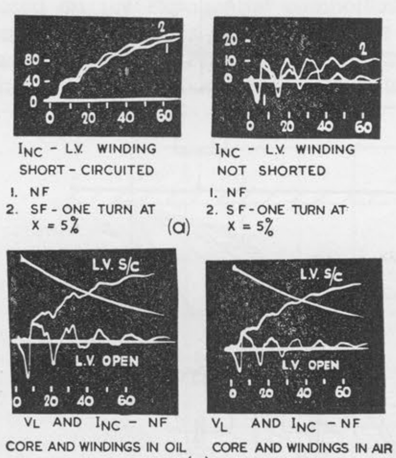


Fig. 4.—Recurrent Surge Oscillograms of a 500-kVA 10,000/415-Volt Transformer with Disc-type Delta-connected H.V. Winding Test Connection (2) in Fig. 5.

Current scale (amps) is for a 100-kV, 1 × 50μ sec. applied wave. Time scale in microseconds.

(*a*) Effect on the neutral current method of a short circuited low voltage winding.

(*b*) Effect of oil immersion.

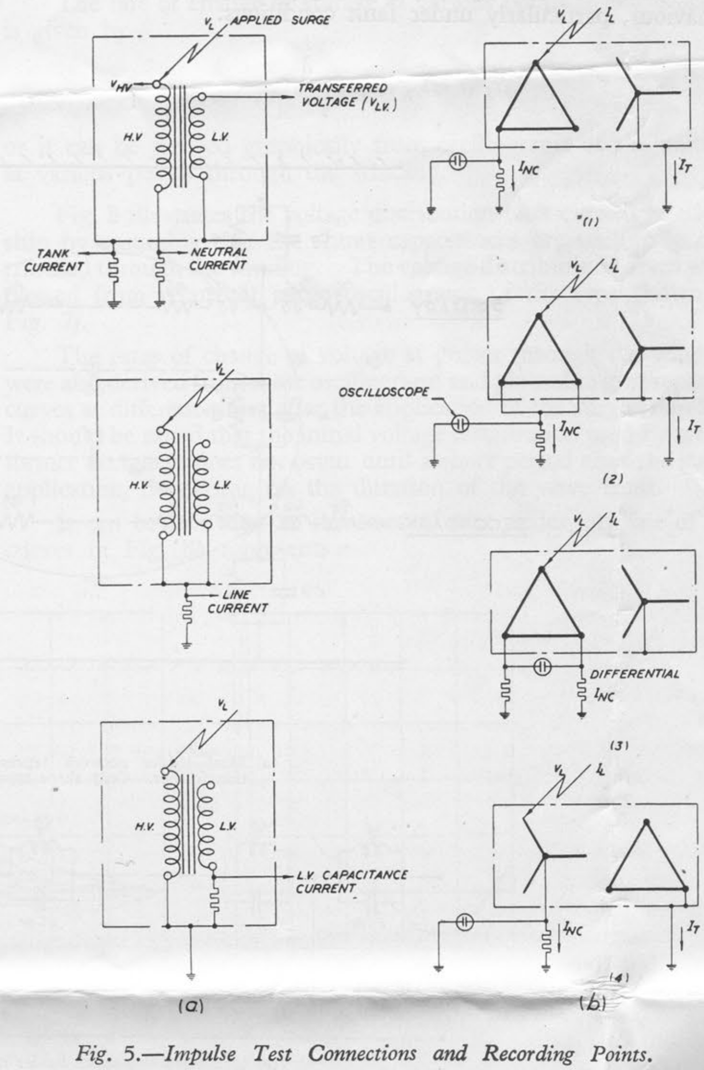


Fig. 5.—Impulse Test Connections and Recording Points.

(*a*) Illustration of various recording points which can be used for fault detection during impulse testing.

(*b*) Typical connections for test on a three-phase delta-star transformer.

(*a*) Measurement of the change in the electrostatic or the electromagnetic components of the currents produced in the transformer,

(*b*) Measurement of the change in output voltage of the impulse generator, due to the increased impedance drop caused by the fault current,

(*c*) Measurement of the change in the electrostatic or the electromagnetic components of the voltage transferred to another winding or the core or the voltage at a tapping in the winding under test,

(*d*) Detection of abnormal physical disturbances such as smoke, gas bubbles, flame or noise,

(*e*) Subsequent power frequency tests,

(*f*) Stripping the winding.

These methods have been examined thoroughly (Refs. 20, 22, 14), and it is generally accepted that methods (*a*), (*b*) and (*c*) are the most convenient and reliable.

A distinction is made between " electrostatic " and " electromagnetic " indication. The former is associated with a change in the higher frequency components of the oscillographic record, that is, components with frequencies greater than, say, 20kc. The indication usually occurs during the first passage of the voltage wave into the winding, say, in the first 30 microseconds.

An " electromagnetic " indication is a much lower frequency change in the oscillogram and is best displayed on a slow-speed record with a total sweep-time of 100 to 200 microseconds.

4.1—*Theory of Fault Detection*:

Fig. 6*a* shows the ideal network representation of a transformer, three typical sections being shown. The mutual coupling parameters, *M'*, *M''*, *M'''*, play a very important part in the network's behaviour, particularly under fault conditions.

By laborious and detailed calculations (Ref. 13), it is possible to reduce the ideal network to that shown in Fig. 6*b*. In turn this equivalent network can be analysed mathematically (Ref. 9). Even then, however, the resulting expressions are too complex to act as a guide towards the behaviour of any particular design under test conditions. Consequently, the theory outlined below has been built up by study of experimental results and correlation with the limits of the network shown in Fig. 6*a*.

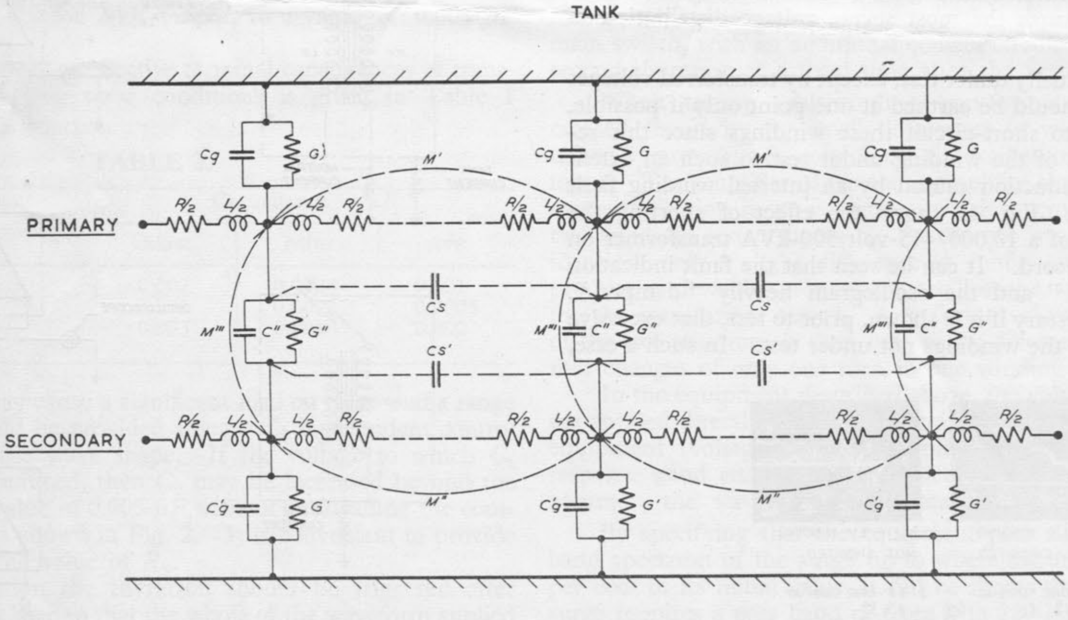
It is best, first, to consider the primary winding, assumed to be the higher voltage winding throughout this theoretical consideration of the problem, standing alone. Having examined the behaviour of the currents in the free standing winding, the effects of core and secondary winding can be assessed.

Ganger (Ref. 27) has shown that, by using a form of transmission line reasoning, the neutral and tank current waveforms of a single winding can be predicted. During this investigation, it has been noted that although these predicted waveforms often occur, there are times when this theory does not clearly explain the current waveforms obtained. Consequently, it is considered that these two major currents should be regarded as comprising :—

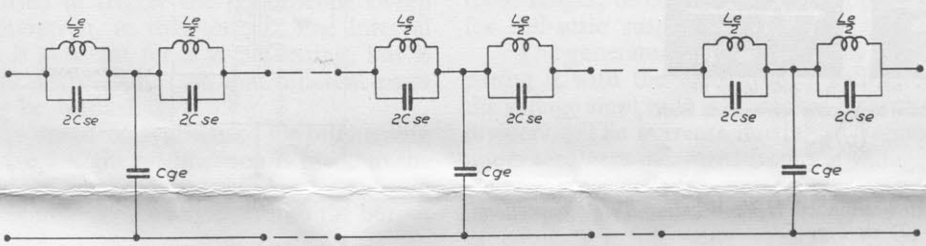
Neutral Current.—an inrush peak and an exponential component on which is superimposed a higher frequency component related to the tank current.

Tank current.—an inrush peak and an oscillatory component dependent on the transient voltage behaviour of the winding.

Oscillograms obtained during experiments with a free standing high voltage winding are shown in Fig. 7. The winding was one phase of a 200-kVA, 10,000/415-volt transformer. Twelve bobbins were used for this experimental stack, with a total conductor length



(*a*) Ideal ladder network representing a two-winding single phase transformer. Only three typical sections shown.



(*b*) Simplified equivalent ladder network for determination of transient behaviour of a particular winding.

Fig. 6.—Representation of a Transformer Winding by Ladder Type Networks.

of 3,270 metres and a total D.C. resistance of 19.3 ohms. Oscillograms 7*a*, 7*d* and 7*g* illustrate the effect on the neutral current (I_{NC}) of adding the earth plane and then the core.

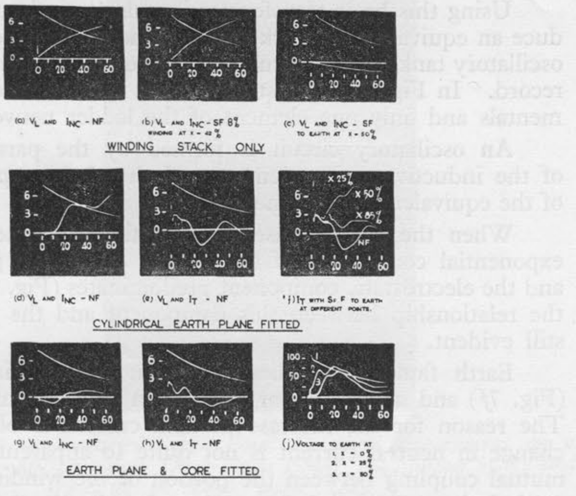


Fig. 7.—Oscillograms from Tests on a Free Standing Experimental Winding Consisting of Twelve Bobbin-type Coils.

The cylindrical earth plane and the iron core were placed through the centre of the stack. Current scales are for a 100-kV, 1 × 50 applied surge. Time in microseconds

The experimental stack standing alone without earth shield or core is practically a plain inductance, the values of shunt capacitance (C_{ge} in Fig. 6) being small and non-uniform. The initial current peak of the neutral current record (Fig. 7*a*) is due to the charging current transmitted through the series capacitances (C_{se} in Fig. 6*b*). This initial charging coincides with the front of the applied wave and generates the well-known initial voltage distribution throughout the winding. This initial peak is always present in the neutral current, but may be small compared with other components and not discernible in the test oscillograms.

The exponential component, related to the exponential decay of the applied voltage by the relationship $i = \frac{1}{NL_e}\int v.dt$, now appears. This component is the basis of the electromagnetic indication of faults. A decrease in total inductance of the winding causes an increase in the neutral current (Fig. 7*b*). As has been shown previously (Fig. 4), the increase depends on the percentage change in inductance.

Superimposed on the exponential component is a high frequency component which seems to be dependent on the value of the shunt capacitances (C_g in Fig. 6). A comparison of Fig. 7*a* and 7*d* illustrates this point since for the latter test, the value of C_g of the experimental stack sections was increased by provision of a cylindrical earth plane inside the coil stack. Fig. 4*b* also illustrates the relationship since, in that case, C_g was increased by oil immersion. This aspect will be further considered after the theoretical derivation of tank current.

The shape of the tank current oscillogram can be confidently predicted if the voltage distribution curves for a given transformer are known, since this current is only dependent on the voltage variations throughout the winding and the shunt capacitances.

Lewis has shown that the voltage at any point in a transformer with earthed neutral is given by the relationship—

$$v_{xt} = 1 - \frac{x}{100} - \sum_{K=1}^{N} A_K \cos w_K t$$

where K is an integer, A_K is a constant dependent on X, N, C_g and C_s, and W_K is a constant dependent on N, L_e, C_s and C_g. Both A_K and W_K are different for each value of k.

Fig. 7*j* illustrates the steady state and oscillatory components given by this expression.

Fig. 8*a* shows voltage distribution curves for the high voltage winding of a locally built three-phase distribution transformer, rated 30 kVA, 7.6/0.445 kV. The tank current of this transformer can be derived from the relationships—

$$i_T = \int_0^x C_g \cdot \frac{dv}{dt}$$

at any given time.

The rate of change of voltage at various points in the winding is given by—

$$\frac{dv}{dt} = \sum_{K=1}^{N} A_K W_K \sin W_K t,$$

or it can be derived graphically from oscillograms of the voltage at various points through the winding.

Fig. 8 illustrates the voltage distribution-tank current relationship by assuming that the shunt capacitances are uniformly distributed through the winding. The voltage distribution curves were plotted from recurrent surge oscillograms of the type shown in Fig. 7*j*.

The rates of change of voltage at points through the winding were also derived from these oscillograms and plotted to give separate curves at different times after the application of the surge (Fig. 8*b*). It should be noted that the initial voltage distribution used by transformer designers does not occur until a short period after the surge application, depending on the duration of the wave front.

It can be seen that an incremental area under any one of the curves in Fig. 8*b* represents

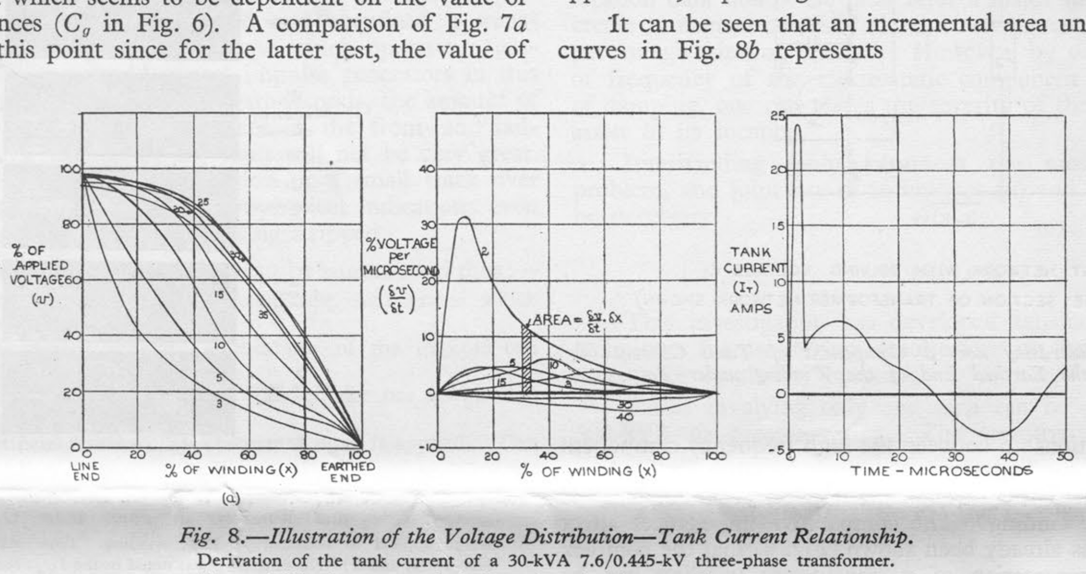


Fig. 8.—Illustration of the Voltage Distribution—Tank Current Relationship.

Derivation of the tank current of a 30-kVA 7.6/0.445-kV three-phase transformer.

Note: 1. Numbers on graphs indicate times in microseconds.
2. Current scale (amps) for 100-kV, 1 × 50 applied surge with a winding capacity to earth per phase = 1,100$\mu\mu$F.

$$\frac{dv}{dt} \cdot dX$$

Multiplying this expression by the total shunt capacitance, NC_g, it becomes an element of tank current. Integration then gives

$$I_T = NC_g \int_0^x \frac{dv}{dt} \cdot dx,$$

so that the area under each curve in Fig. 8*b* is proportional to the value of tank current at that time.

Using this approach, the tank current wave shape for the 30 kVA 7.6/0.445 kV was derived, assuming a shunt capacitance per phase for the high voltage winding of 1,100 $\mu\mu F$. The resultant wave is shown in Fig. 8*c*. It will be seen that it has the same basic shape as actual oscillographic records obtained during experiments with the recurrent surge generator.

The tank current is important, not only because of its value in detecting and locating earth faults, but also because it greatly affects the neutral current waveform. This fact is illustrated clearly in Fig. 7. If the tank current (i_T) with only an earth plane present (Fig. 7*e*) is subtracted from the neutral current (i_{NC}) which occurs when no core is present, the dotted curve shown in Fig. 7*d* is obtained. This derived curve is very similar to the recorded value of neutral current for the specified condition.

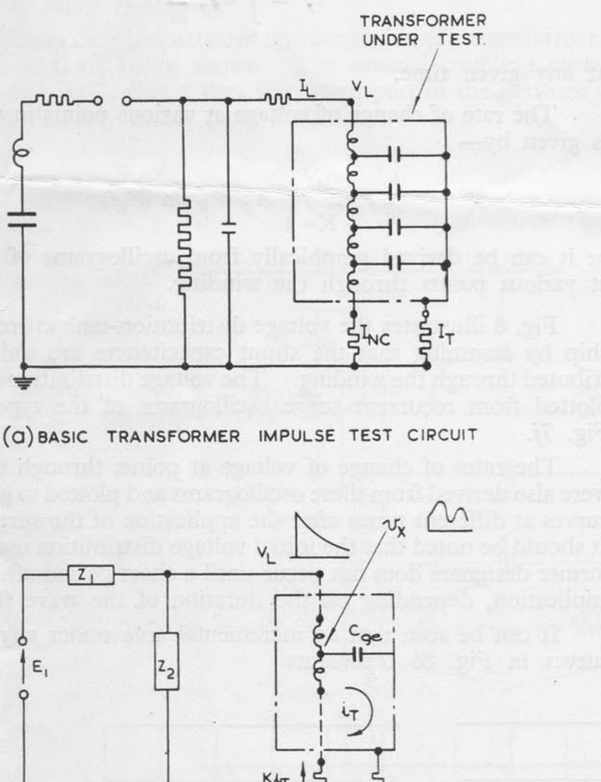


Fig. 9.—Diagram Illustrating how a Component of Tank Current (I_T) Circulates in the Earthed End of the Winding under Test.

This close relationship between the high frequency component of the neutral current and the tank current is due to the latter returning via parallel paths through the impulse generator and the neutral end of the winding. The comparative impedances affect the division. It has already been shown (Fig. 6) that the complex ideal network representation of a transformer winding can be simplified for mathematical treatment. If, now, this simplified network (Fig. 6*b*) is considered coupled to the basic representation of an impulse generator, the circuit shown in Fig. 9*a* results. The series capacitance elements have been omitted since they do not affect the following explanation.

Using this basic transformer impulse test circuit one can produce an equivalent network which demonstrates the reason for the oscillatory tank current component appearing in the neutral current record. In Fig. 9*b* the test circuit has been reduced to its fundamentals and only one element of the ladder network shown.

An oscillatory circuit is formed by the parallel connection of the inductive series element and the shunt capacitive element of the equivalent transformer network.

When the core is inserted into the experimental stack, the exponential component of the neutral current is greatly reduced and the electrostatic component predominates (Fig. 7*g*). However, the relationship between this component and the tank current is still evident.

Earth faults are indicated by an increase in tank current (Fig. 7*f*) and a decrease or reversal in neutral current (Fig. 7*c*). The reason for the increase in tank current is obvious, but the change in neutral current is not quite so apparent. It is due to mutual coupling between the portion of the winding carrying the earth fault current, and the portion virtually short-circuited by the earth fault. A current circulates in the latter portion in opposition to the normal neutral current. Depending on the relative fault and neutral current shunt impedances, this current will either reduce the neutral current or reverse it.

Interwinding faults, as mentioned previously, increase the neutral current due to a decrease in the inductance of the winding. They may also be detected by a change in the tank current waveform due to their effect on the voltage distribution throughout the winding.

High frequency disturbances, usually at 1 megacycle or above, caused by sparking faults may appear in the voltage and current records if the faults are of sufficient magnitude. The tank current provides the best means of detecting such disturbances due to the direct coupling provided by the shunt capacitance network.

4.2—*Fault Detection Experiments*:

Since 1954, experiments have been made on distribution and power transformers at manufacturers' works or at the overhaul depots of supply authorities. The records made during these experiments have been supplemented by experimental results obtained by one of the authors during a training period with a British trans-

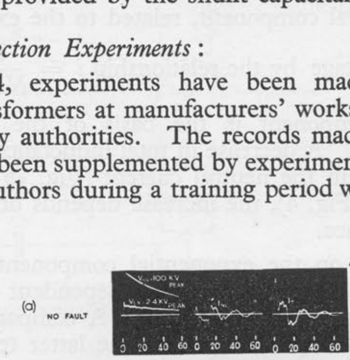


Fig. 10.—Results of Recurrent-Surge Fault Detection Experiments on a 500-kVA 10,000/415-Volt Three-Phase Distribution Transformer (Core and Windings in Tank under Oil).

Surge applied to bobbin-type H.V. winding. Time scale in microseconds.
Note: (*b*) and (*c*)—No difference was noted in the I_{NC}, records when the short-circuit was applied at other positions in the winding. Test connection (2) in Fig. 5. S.F. = Solid fault. Sp.F = Sparking fault.

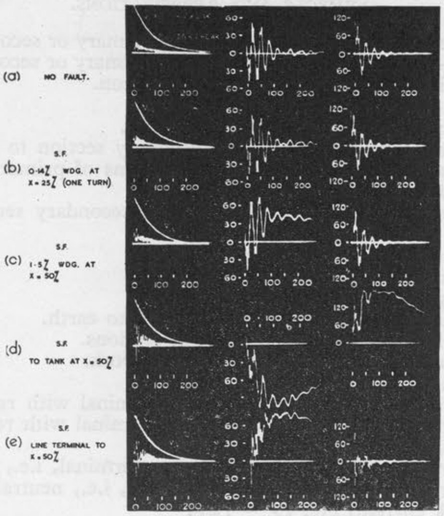


Fig. 11.—Results of Recurrent-Surge Fault Detection Experiments on a 13,500-kVA 33,000/5,350-Volt Three-Phase Power Transformer (Core and Windings in Tank under Oil).

Surge applied to Disc type H.V. winding test connection (2) in Fig. 5. Time scale in microseconds. S.F. = Solid Fault. X = % distance from line terminal.

former manufacturer some years previously. The experiments described here have been limited to full wave testing. The latest developments in chopped wave fault detection require special equipment for experimental investigations which has not yet been built.

Space will not permit the presentation of a comprehensive series of test results, but Figs. 10 and 11 show typical records obtained when using resistive shunts only. The distribution transformer (Fig. 10) was a 500-kVA 10,000/415-volt three-phase unit with a bobbin type H.V. winding and a layer type L.V. winding.

Fig. 11 shows oscillograms obtained during experiments on a 13,500-kVA 33/5.35-kV power transformer.

At this stage it is possible to state that the following fault detection sensitivities are possible:

Disc type windings.—0.1 per cent winding for 500 kVA and above.
Bobbin type windings.—0.5 per cent for 200 kVA, 0.3 per cent for 500 kVA and above.
Layer type windings.—0.2 per cent for 250 kVA.

These sensitivities are for interwinding faults. Earth fault sensitivities can never be less.

5.—Fault Location.

The importance of obtaining as much information as possible regarding the location of any fault detected will be obvious, particularly to engineers who have tested and examined a transformer for an incipient fault of the type which operates a gas-alarm relay. Since one would expect impulse generators in this country to store no more than 20 kilowatt-seconds, the amount of energy available, after subtracting losses in the front- and tail-resistors, for causing damage at any fault will not be very great. A puncture through conductor insulation or a small track over an insulating surface may be the only physical indications even after the unit is untanked and the winding stripped.

The basic fault location techniques can be summarised thus:—

(*a*) Location from interpretation of actual test oscillograms which detected the failure.
(*b*) Observations during repeated applications of the impulse test voltage which caused failure.
(*c*) Subsequent power frequency tests. Experience has shown that this technique is of little value.
(*d*) Applying artificial faults whilst a recurrent surge is applied. This is continued until one obtains oscillograms similar to those recorded during the actual test causing failure.
(*e*) Examination of the winding.

5.1—*Earth Faults*:

Fig. 7*j* shows how the voltage to earth develops through the winding, some time elapsing before the lower portions are subjected to any appreciable stress to earth. This time delay is the basis for most fault location techniques (Ref. 14). These techniques assume that failure will normally occur near the instant of maximum stress, that is, it will not be caused by the initial distribution. This is a reasonable assumption since failure would otherwise have occurred on the 75-per cent calibration test normally made. The main weakness is the inherent time-lag associated with insulation failure under impulse conditions. This lag may delay breakdown for 1-5 microseconds, and the actual location will be further up the winding than is indicated by the oscillograms.

The neutral current gives a reliable electromagnetic indication (Fig. 7*c*). However, since this is associated with a flux change in the core, the instant of failure may not be sharply defined unless the fault is of a major nature, i.e., towards the line end.

The tank current does not suffer from this disadvantage. It instantaneously records any increase in the current flowing to the tank. Fig. 7*f* illustrates this and also shows the important fact that the electromagnetic component is related to the position of the earth fault. This phenomenon, which is related to the effective inductance for the various fault positions, provides a very useful check on the location obtained by considering the instant of breakdown.

Elsnar (Ref. 14) describes the location techniques based on a constant speed of propagation of the voltage surge through the winding. The application of the technique is fairly obvious when one considers the earth faults placed onto the experimental stack using a neon gap (Fig. 7*f*). The total conductor length of the winding is 3,270 metres. The fault at $X = 85$ per cent occurred 17 microseconds after application of the impulse.

Hence speed of propagation $= \dfrac{0.85 \times 3270}{17} = 164$ metres per microsecond.

Although this test was made with the winding in air, the propagation constant compares favourably with the values used by Elsnar (Ref. 14) (146 m./microsecond) and Ganger (Ref. 27) (150 m./microsecond) for oil immersed units.

5.2—*Interwinding Faults*:

It can be shown (Ref. 17) that the maximum interwinding stresses occur sequentially through the winding. Consideration of Fig. 7*j* or Fig. 8*a* demonstrates this fact. Consequently the breakdown time technique can be employed, using the tank current to indicate the instant of breakdown. It does this most effectively when a high frequency disturbance occurs at the point of failure.

The increase in the electromagnetic component of the neutral current due to an interwinding fault does not provide any useful location data unless the fault is of a major nature. Also, the increase in neutral current follows a non-linear relationship with the percentage winding shorted. However, by observing the change of frequency of the electrostatic component and/or the amount of damping, one can assess the severity of the fault and this may assist in its location.

Interwinding faults represent the most difficult location problem, and joint use of techniques (*a*) and (*d*) above will often be necessary.

6.—Conclusion.

This investigation has developed satisfactory fault detection techniques for use during impulse tests on transformers, either for acceptance or design purposes.

Faults involving only one turn can be detected in units of 500-kVA or greater rating. The sensitivity for smaller units, particularly those with bobbin-type windings, is somewhat less. However, any fault which will affect the service life of a transformer can be detected provided the following quantities are recorded.—

(*a*) Applied voltage (60)
(*b*) Neutral current (150)
(*c*) Tank current (60)

The recommended sweep time in microseconds is given in brackets. Resistive shunts should be used to ensure that no high frequency oscillations are lost. Care must be taken to insulate the shunt adequately to prevent flashover during a major fault.

Earth faults can be adequately detected and located by the tank current record. The check provided by the magnitude of the electromagnetic component appears to be an original contribution to the art. Table II summarises the indications to be expected.

TABLE II.

SUMMARY OF OSCILLOGRAPHIC INDICATIONS OF FAILURE DURING FULL WAVE TESTING.

Type of Fault	I_{NC}	I_T	V_L
Line terminal to tank.	Electromagnetic component decreases to zero.	Large increase.	Severe drop.
Tapping switch to tank or core.	Decreases or reverses polarity.	Increase after time lag.	Decrease depending on impedance of generator.*
Major inter-winding failure.	Substantial increase.	Higher frequencies evident but overall decrease.*	Decrease depending on impedance of generator.*
Minor inter-winding failure.	Increase depending on winding involved, and construction.	Little effect.*	Little effect.

*A high frequency electrostatic indication may appear.

There is considerable scope for further work, particularly with respect to non-linear shunts and sweep-times, and in the development of more sensitive methods for small distribution transformers and potential transformers. The most promising approach to fault detection during chopped wave testing seems to be the use of a subsequent lower voltage full wave about 5 microseconds after the "chop" (Ref. 15). This technique requires more development.

Despite this, the established test procedure of

(*a*) one full wave followed by
(*b*) two chopped waves, followed by
(*c*) two full waves,

is capable of detecting any fault which will affect service life, provided sound fault detection techniques are used.

The electronic techniques examined during the development of the recurrent surge oscilloscope indicate that there is considerable scope for the production of electronic monitoring instruments to simplify impulse testing procedure and fault detection methods. It is estimated that electronic monitoring instruments could reduce the setting up and testing time for a distribution transformer from approximately 8 hours to 2 hours, assuming no failure. Fault location time would not be greatly affected since it depends mainly on the nature of the fault and its position in the winding. Even with full facilities it may take up to 30 hours testing time to locate a difficult fault.

7.—ACKNOWLEDGMENTS.

The authors gratefully acknowledge the permission and assistance received from Professor R. E. Vowels, M.E., A.M.I.E.Aust., Electrical Engineering School, N.S.W. University of Technology, and the General Manager, The Sydney County Council. They also wish to thank their colleagues who assisted in the experimental work and in the preparation of the illustrations. The co-operation of local supply authorities and manufacturers is acknowledged with thanks. The Tyree Electrical Company has been particularly helpful.

(Written contributions to the discussion of this paper will be appreciated, as research is continuing into this subject.—Editor.)

SYMBOLS AND ABBREVIATIONS.

R, R'	Wire resistance of each section of primary or secondary winding.
L, L'	Self-inductance of each section of primary or secondary winding.
Le	Equivalent self-inductance per section.
M', M'', M'''	Mutual inductance between sections.
C_g, C_g'	Capacitance of primary or secondary section to earth.
C_s, C_s'	Capacitance between adjacent sections of primary or secondary winding.
C''	Capacitance between primary and secondary sections.
G, G', G''	Conductances between sections.
n	Number of turns.
l	Length of winding (metres).
C_{ge}	Equivalent capacitance of a section to earth.
C_{se}	Equivalent capacitance between sections.
N	Total number of sections in the network.
t	Time (microseconds).
V_{LV}	Voltage at low voltage winding terminal with respect to earth.
V_{HV}	Voltage at high voltage winding terminal with respect to earth.
V_L	Applied surge (line voltage).
I_L	Current entering transformer line terminal, i.e., line current.
I_{NC}	Current leaving winding under test, i.e., neutral current.
I_T	Tank current, i.e., $I_L - I_{NC}$.
X	Relative distance from beginning of winding under test.
N.F.	No fault.
S.F.	Solid fault, i.e., a low resistance path exists before application of test voltage.
Sp.F.	"Sparking" fault, i.e., the arc path is through insulation ruptured by the test voltage subsequent to the wave front.

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N.S.W. University of Technology.

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Lectures will commence on Monday, 17th February, 1958. Applications for enrolment should be made as early as possible.

Applications and enquiries regarding further details should be addressed to the Professor of Civil Engineering, Broadway, Sydney, N.S.W.

Personal

Mr. R. G. KNIGHT, M.C., M.C.E., M.I.E.Aust., Chief Designing Engineer of the State Rivers and Water Supply Commission, Victoria, is retiring in January and will be succeeded by Mr. R. A. HORSFALL, M.B.E., M.C.E., B.Mech.E., A.M.I.E.Aust.

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For many years it has been a matter of great concern to the Council of The Institution and to a large number of individual members that Australian engineering qualifications and membership of The Institution have not been accorded the recognition they have merited in countries overseas. It is therefore gratifying to be able to announce that The Institution of Civil Engineers and The Institution of Mechanical Engineers have now accepted the examinations of this Institution as exempting from their examinations, and that The Institution of Electrical Engineers has accepted them as exempting from all but one subject. This is a timely contribution to what was quickly becoming a very serious problem.

The Development of a National Institution:

The isolation of Australia from the rest of the world has made it necessary for us to develop our systems of engineering education at Universities and Technical Colleges to meet our own needs. Our isolation also contributed to the establishment of this Institution as an independent national body to promote the science and practice of all branches of engineering in Australia and to ensure high standards of technical education. Before its foundation, Australian engineers were obliged to join English Institutions if they desired to have ready access to professional literature, and, in many cases, to acquire the hall-mark of a recognized qualification. As the years have gone by, our professional engineers have joined The Institution in increasing numbers and relatively few seek membership of the English Institutions on which we modelled ourselves and from which we drew our inspiration. In Australia, membership of The Institution of Engineers, Australia, is now the generally accepted criterion of professional standing.

The Conference of Engineering Institution of the British Commonwealth held in 1946 accepted the national character of The Institution and resolved not to encroach within Australia upon the essential functions of The Institution. Both the establishment of examination standards for Australia and the publication of the advances made in engineering in Australia are recognised as the proper province in Australia of The Institution of Engineers, Australia.

The Problem of Reciprocity:

Whilst we cannot too highly value the strength and distinction which this national development of The Institution has brought to the profession, it is natural that the engineers of older countries may have tended to become somewhat isolated from and even unaware of the large volume of engineering being undertaken in Australia, a distant land which few of them have visited. This in turn may have contributed to a reluctance to accept the qualification of membership of The Institution as being valid for professional engagements outside Australia in the way that membership of English Institutions continues to receive general recognition in other countries.

Often it has come as a shock to Australian engineers of high standing in the profession, to find when they travel abroad that their qualifications are not immediately recognized. Reciprocity is, however, by no means a simple problem. On the one hand the Council of every Institution has the responsibility of deciding the suitability of every applicant for admission to the grades of corporate membership, and this is a responsibility which it would not readily delegate to another body, no matter what its prestige and standing might be. That an applicant holds an examination qualification is a matter of fact, but training, experience, responsibility and professional standing are matters for the judgment of an applicant's peers, a responsibility conferred on the Council of our Institution, and on the Councils of a number of other British Commonwealth Institutions, by the Crown through a Royal Charter

On the other hand, some common standards of requirements for training and experience should be possible, and if uniformity can even in part be achieved, a corporate member of one Institution would have to that extent met the requirements of another. At the 1946 British Commonwealth Conference of Engineering Institutions our representatives soon saw the difficulties in the way of full reciprocity, but they did believe that uniformity of examination standards was a possible immediate objective, although there were obvious difficulties as between branches of the profession, and between Institutions which included all branches, and those which included members of one branch only.

Revision of The Institution's Examination Standards:

At that time the Council of The Institution was well aware that its own examinations were not completely adequate. We had the anomalous situation that The Institution would consider for exemption from its examinations only those qualifications which were awarded after a broadly-based, balanced and integrated course, while its own examinations appeared to provide a choice of subjects from which a limited range might be selected. Although the standard required in the individual subjects, and the difficulties of private study, prevented all but a very few from qualifying in this way, the standard of an Institution is judged on its apparent minimum qualification, and this weakness had long been due for review.

The Institution therefore set about the revision of its examination syllabuses, a long and tedious task, which was not completed until 1952. Although the Constituent Institutions had agreed in 1946 that the syllabuses of the English Institutions should be the models to be followed, there were differences between them that made this difficult, and it was necessary to adhere to principles, rather than attempt to work on a subject-for-subject basis. The result was a tribute to the patient work of the Board of Examiners and all those who were co-opted to help over the six-year period.

Training Asian Students:

The 1954 meeting of the Commonwealth Conference was not, however, prepared to acknowledge that we had achieved equivalence in our amended examination standards. This was not a matter for mere disappointment, as during those eight years circumstances had arisen which made recognition of Australian qualifications a matter of international importance. During that period Australia had become a recognized training centre for students from Asia. There have been, and still are, at any one time hundreds of such students undertaking engineering courses at Universities and Technical Colleges in all States. In addition to the large number of Colombo Plan students, there are many under some other sponsorship and those who have come under their own arrangements.

Because of the lack of recognition of this Institution and Australian qualifications in other countries, many of these students have found that the opportunity to follow the profession for which they have been trained is being denied to them. The fundamental reason for this might have been found in the Regulations of the Colonial Service, which prescribed examination qualifications recognized by the appropriate English Institution as a requisite for initial appointment, and corporate membership as a requisite for advancement. Other employers in the colonial territories had understandably adopted these criteria for appointments, and governments and employers in the countries which have recently become independent have continued to do so. Although we must commend the wisdom of employers who adopt a recognized yardstick for professional appointments, and although we would wish to see regulations approved by the British government used for this purpose, the situation as it stood was a most serious one for a large percentage of those who had been our welcome guests. The regulations virtually divided them into two groups, one with practically no chance of finding initial appointments and the other with the prospect of a barrier against advancement.

The English Institutions have published as exempting qualifications the degrees of Australian Universities, the N.S.W. University of Technology having recently been added. Only one diploma of an Australian Technical College has been so published. The Commonwealth Office of Education has ensured that Colombo Plan students entered courses that would lead to one of these published qualifications. Many others, because of availability of accommodation, or for a variety of other reasons, have entered courses that do not lead to qualifications recognized by the English Institutions, although of high standard and fully recognized in Australia. Many would find difficulty in entering the English Institutions because of requirements for practical training under a corporate member, or post-graduate apprenticeship in an approved industry, or some other condition readily available in England, but not always so elsewhere. Australian engineers who have joined English Institutions can provide opportunities for only a limited number of young engineers to receive approved training.

Recognition of The Institution's Examinations:

The Council of The Institution has felt that the only real solution to this problem would be to include in the Colonial Service Regulations qualifications recognized by this Institution and corporate membership of it, as additional qualifications to those already listed. It has persistently discussed this with the English Institutions and has endeavoured to have its views made known through government channels. It has been in constant touch with the Right Honourable R. G. Casey, Minister for External Affairs, himself an engineering graduate of Cambridge, who has been directly concerned on behalf of the Colombo Plan Students, and who has been tireless in his efforts to have the problem understood and solved.

Although our representations of 1954 appeared to be fruitless, our colleagues of the English Institutions assured us they would give the subject their urgent consideration. The Institution as a whole must greatly appreciate the efforts they have made to understand and solve the problem. The recent announcements by the three Institutions are a most important contribution from which a complete solution must finally emerge.

Recently, The Institution of Civil Engineers advised that the examinations of The Institution of Engineers, Australia, had been accepted for the purpose of exemption from its examinations. The Institution of Mechanical Engineers advised that candidates who had passed the examinations under the 1952 Syllabus would be exempted from its examinations, provided that they passed Theory of Machines and the Mechanical Engineering Group of subjects in Section B. The Institution of Electrical Engineers advised that candidates who had passed the examinations would be exempted from all but the subject of Advanced Electrical Engineering, provided they had selected papers in the electrical groups.

Effect of Recognition:

At first sight it might appear that these decisions will not affect engineers who have trained and qualified in Australia. The Institution does not encourage candidates to sit for its examinations. Indeed, in order that they may be encouraged to follow ordered courses leading to exempting qualifications, it will not accept candidates who have opportunity to do so. Only one candidate has so far qualified by passing the whole of the 1952 Syllabus, and very few may be expected to do so in the future. Nevertheless, the effect of these decisions will be profound. Recognition by Institutions which are themselves known internationally will certainly tend to accord recognition, not only to our own examinations, but to Australian qualifications, generally. We have already received advice from South East Asia that this is so.

On behalf of our Asian students and all those who may be affected, we thank sincerely those members and officers of the English Institutions who have listened patiently and sympathetically to our representations and have once again demonstrated the unity within the British Commonwealth when a real problem has to be faced.

DISCUSSIONS AND COMMUNICATIONS - INVESTIGATION OF FAULT DETECTION METHODS FOR THE IMPULSE TESTING OF TRANSFORMERS*

BY G.C. Dewsnap, M.E.E., A.M.I.E. Aust. and E.G. Williams, A.M.I.E. Aust.

(Journal I.E. Aust. Oct - Nov 1958 p.318)

Mr. R.K. Edgley (Associate Member Sydney Division): -

Impulse testing of transformers has been used on an increasing scale for the past 25 years or so; initially only for experimental and developmental work, more recently for type testing of production prototypes, and today, in America, even for routine testing (of distribution transformers at least) for insulation quality control.

Engineers in general have always been reluctant to accept impulse testing, for two main reasons. Firstly, it was thought that the testing process - intended to be a proving operation - might itself initiate deterioration of the insulation. It is, however, generally accepted today that if any such deterioration would result from the test it would be apparent in the test results.

Secondly, there is the problem of interpretation of test results; this problem is still with us. The value of an impulse test lies in the oscillographic record obtained and in its interpretation by the test engineer; and correct interpretation requires considerable experience in this field. Herein lies the true value of the present paper. It provides an ingenious and economical method of obtaining large numbers of test records by means of the recurrent surge generator under known and controlled conditions so that engineers may readily acquire experience that might otherwise take many years of actual impulse

* For text of paper, see THE JOURNAL, Vol. 29, No. 12, December 1957, p.311

testing. Of particular value is the use of a long afterglow C.R.O., which enables both healthy and faulty trace to be seen on the screen together for comparison.

The method must be applied carefully, however. In a recent paper,* and in his written contribution to this discussion, Hickling points out that with disc-type windings self-sealing faults of very brief duration are possible. Such faults would be difficult to simulate artificially. Furthermore, it requires actual impulse tests to discover that they may occur; the recurrent surge generator could not do this. There will be other similarly obscure conditions.

The authors conclude that their investigation has revealed satisfactory fault detection techniques. Satisfactory to whom? It still remains that fault detection may often depend on the observation of comparatively small differences between two oscillograph records. These records may be to different basic scales (it usually being necessary to carry out a reduced voltage test to obtain a "healthy" record for comparison); they are obtained through voltage dividers and/or electronic amplifiers which may not be perfectly stable; they are recorded by a wet photographic process with subsequent individual enlargement, all possible sources of distortion; and often the quantity of interest is masked by super-imposed oscillations. The difficulty is for the untrained engineer (e.g., the manufacturer or purchaser) to recognise the significant differences.

* High Voltage Impulse Testing of Transformers: G.H. Hickling, B.Sc., A.M.I.E.E.; Electrical Review, 31/8/56 and 12/10/56, pp. 389 and 667.

The technique is certainly satisfactory to the test engineer who knows his equipment and its characteristics; the question is, will manufacturers and users accept him as arbiter?.

The authors' method, as so vividly demonstrated to us tonight, will greatly assist a more general understanding of fault detection techniques, but they will, I am sure, be the first to agree that for commercial impulse testing to be fully acceptable in Australia there is scope for the development of new or improved techniques which will make the differences between faulty and non-faulty conditions more obvious to the untrained engineer.

Mr. G.H. Hickling (of C.A. Parsons & Co. Ltd., England).

I have recognised since about 1950 that reliance on changes of the "electromagnetic component" of neutral current only (the method dealt with in the paper by E.C. Rippon and myself published in 1949) is to be restricted for reliable use to small bobbin-type transformers. In larger windings, having disc coils separated by oil, impulse punctures may not persist long enough to produce any perceptible change in this type of oscillogram. Due to the effective self-sealing of such faults, furthermore, it is not sufficient to rely on the test shot sequence indicated in Section 6.0 of the paper to reveal chopped-wave faults subsequently by full-wave recording methods. For these reasons I feel that low voltage impulse techniques have a somewhat limited use in studying impulse fault detection methods.

Impulse testing practice in Great Britain, for a number of years now, has been to earth solidly all untested terminals except on small wire-wound units, and except also where, on very large transformers, resistance earthing of secondary windings becomes necessary to obtain specified wave durations. Neutral, line or tank current, or a combination of these, is recorded with relatively short sweep durations (10 - 50 S) to give fault indication by the electrostatic method, and these oscillograms are now being taken (with suitable reduced voltage comparison records) on chopped-wave as well as on full-wave impulse shots. With these methods no difficulty has been experienced in detecting any normal type of winding failure; interest centres mainly on the detection of more obscure faults such as corona or tracking discharges on insulation surfaces which do not produce failure, or of single-turn punctures. On bobbin-type transformers, also, chopped-wave failures may present a difficulty. Operational experience on units which have passed an impulse test has been entirely satisfactory.

Dealing with the main topic raised - that of neutral current versus tank or other current records for impulse fault detection. A great deal has been written in various countries on the various possible recording circuits, but comparatively few of the papers published, in my estimation, have been backed by any extensive practical testing experience. The main claim made for the line current (or tank current) connection is that of permitting the location of inter-coil faults, on the basis of time of occurrence. Faults of this nature are, however, comparatively straightforward and usually not difficult to locate.

Our company has tried most if not all of the various recommended circuits for fault detection in actual H.V. impulse tests and we have occasionally used some of the alternatives to the neutral current connection during the further investigation of an indicated fault. Neutral current is nevertheless our standard method, variations made to suit different transformers being limited generally to shunt value, single or differential current recording, and time sweep duration. The practical drawback to tank current, line current, L.V. winding capacitance current (Elsner's method) and similar arrangements is that they are extremely sensitive to extraneous disturbances external to the transformer on test as well as to minor corona discharge effects on the bushings or within the transformer, and thus tend to obscure the main issue of detecting actual insulation breakdown.

It will, of course, be appreciated that tank current is simply the difference between the "line" current and neutral current. On the most simple designs of transformer these waveforms are <u>all</u> quite simply related to the travelling wave pattern in the windings, although this relationship does not in itself appear to be of much use in fault detection or location. But with a great many practical winding designs the impulse behaviour is complicated by the existence of separate tapping windings, tapping switches, parallel winding sections and so forth, as well as by interaction between H.V. and L.V. and possibly tertiary winding oscillations. In such instances the whole mechanism of surge transfer in the windings may be quite complex and the interpretation of current oscillograms, whether on sound windings or showing indication of a fault, is obviously much more difficult. Faults which are really difficult to locate are such things as surface discharge effects, induced faults in other windings, or flashover of isolated metal parts not connected to the windings.

On the question of short-circuiting windings not under test, we also demonstrated the apparent high sensitivity of fault detection by the magnetic transient method with secondaries left open-circuited in 1947-49 as shown in our paper published in the latter year. As mentioned in my previous notes we still retain this method for multi-turn bobbin wound distribution transformers in which inter-turn or inter-layer faults are likely to remain permanently effective and for which also the "electrostatic" methods tend to be ineffective. On larger windings (on which most of our impulse testing is done), however, it has been realised for a number of years now that premature arc extinction may make the magnetic transient method unreliable, and it also fails on chopped wave tests. Faults must consequently be detected by the voltage disturbance occurring at the instance of their occurrence - hence the relatively short time sweeps used. Faults at times later than 50 S can scarcely occur, unless by major insulation breakdown when they will certainly be detected. Short-circuiting of windings not under test actually gives maximum inter-coil voltage stresses. It also simulates reasonably well the operating conditions, and by avoiding the necessity for investigation induced voltages in other windings effects a material time saving during production tests.

Considering now the remaining points raised, we have done some experimental work with the acoustic fault detector which seems to support Messrs. Brown Boveri's claims for it, but we have not so far found it convenient to introduce it for commercial tests. We cannot therefore usefully comment further on this. The electronic impulse monitoring instruments are described in the Electrical Review article which ~~...~~ Mr. Edgley refers to (Part I - 31st August, 1956). They are not directly related to failure detection but are a useful contribution to the general speed and efficiency of commercial impulse testing.

With reference to Mr. Shear's comment on radio-frequency detection of ionisation effects during power-frequency tests, I wish to draw attention to a paper by Dr. G.M. Mole - "Improved Methods of test for the insulation of electrical equipment", Proc. I.E.E. 1953, Vol.100, Pt. IIa, p.276. Equipment as developed by Dr. Mole at the E.R.A. is manufactured in this country. I might mention in passing that the detection of ionisation or corona during impulse tests is a more difficult problem, related to the subject already discussed which is now receiving considerable attention. A paper by Lech et.al. "Impulse Ionisation in Transformer Windings" - C.I.G.R.E. paper No. 116, 1956, is an appropriate reference.

Mr. H. Harrison (Associate Member, Sydney Division):-

In view of the availability of computers, would it not be possible to simulate the problem mathematically and correlate the results with the experimental oscillographic results.

Mr. P. Shears (Associate Member, Sydney Division):-

Would not double power frequency testing be useful to detect faults after impulse testing? A radio influence voltage detector is available for use during such tests.

Mr. W.A. Shaw (Associate Member, Sydney Division):-

Is the method of test described applicable to other plant such as motor and generator windings? Also, could not a higher voltage surge be used? Could a reflected pulse type fault locator, as used for transmission line faults, be used to ascertain the distance of the fault from the line end of the winding?

Mr. A.W. Tyree (Associate Member, Sydney Division):-

From design and test experience I can substantiate the distinctions drawn by Mr. Williams. I should also like to bring to your notice my experience with insulation breakdown under both impulse and power frequency conditions. A 33-kV winding which failed under impulse test conditions subsequently passed the power frequency test, and up to date has operated satisfactorily in service for three years. Do you feel that, should a fault be produced in a small distribution Transformer winding under impulse, it is worthwhile going to this trouble of locating it by your method, or would it be more economical to rewind the coil since these transformers can be stripped and rewound so quickly?

There is also the fact that a recurrent surge test against power frequency test is ever so much more costly. I doubt whether the fault in the 33-kV winding mentioned above would have been picked up by the recurrent surge test.

Mr. R. Clark (communicated):-

I agree generally with the statement that windings not actually under test except by transferred voltages in the transformer, should be earthed at one point only if possible. However it should be borne in mind that under service conditions, other windings are "shorted" through normal loads.

Would the failure to close, say, a secondary circuit alter the parameters of the ladder network to such an extent that the test would not represent service conditions? The high voltage resistor, referred to in Section 3, offsets this condition only slightly.

<u>Mr. C. Lamerton (communicated)</u>:-

Would the shorting of other windings affect the voltage distributions in the winding under test?

AUTHOR'S REPLY TO THE ABOVE DISCUSSION.

G.C. Dewsnap and E.G. Williams.

The contributions to the discussion on this paper have been most objective and will help to achieve the original aim of the investigation, which was clarification of the impulse testing techniques and procedures to be used in this country. The overseas contribution from Mr. G.H. Hickling is of great value in view of his experience and international reputation in this field.

Several of the contributions indicate that it was not clearly understood that the recurrent surge measurements are not intended to be insulation tests. They only predict the form in which the oscillographic results of a full-scale (i.e. normally 25 kV or greater) impulse test will appear.

Messrs. R.K. Edgeley and G.H. Hickling raise the possibility of short-duration (or "transient") faults which will extinguish before any change in the "electromagnetic component" of neutral current occurs. This further emphasises the need to measure the three quantities referred to in Section 6 of the paper since a fault of this nature during a full wave test would be detected by the tank current.

The practical difficulty, mentioned by Mr. Hickling, of extraneous disturbances affecting the tank current record, has been encountered by the authors during full scale impulse tests. However some European testing laboratories have overcome this problem and we consider the improvement in fault detection and location is worthwhile. The LV capacitance current may have to be used when space in the test area is limited and the transformer's tank cannot be shielded.

A transient fault occurring during a chopped wave test only becomes significant if it causes damage which affects the service life of the transformer since under service conditions no power frequency current can flow. Such damage would normally be detected by the subsequent full wave test.

Messrs. G.H. Hickling, R. Clark and C. Lamerton question the effect of short-circuiting windings, other than the winding under test, on the voltage conditions in that winding. From a theoretical viewpoint it seems that any reduction in the inductance parameters of the equivalent ladder network by short-circuit of another winding (Fig. 6 in the paper) would damp the voltage oscillations and reduce the severity of the voltage conditions after the first fundamental time.

Fig. A* shows the voltage to earth at various points through the HV windings of an 11000/110 volt voltage transformer and a 10000/415 volt distribution transformer, with and without short-circuiting of the LV windings. The intercoil voltages have been derived and analysed and the results are shown in Table I.

Table 1 - Comparison of Intercoil Voltages with and without Short-circuiting of the LV Windings.

11000/110 volt Voltage Transformer (4 bobbin coils per phase, Star/star connection).	Intercoil Voltages as a percentage of the peak applied voltage. LV Open	LV S/C
1st Bobbin coil	62	61
2nd " "	37	26
3rd " "	42	13
4th " "	31	22

* See Fig. 20

200 KVA 10000/415 volt Transformer (Delta/Star connection)

Line B to X = 25%	25	23
X = 25% to X = 50%	46	47
X = 50% to X = 75%	42	33
X = 75% to Line A	37	33

It can be seen that in both cases the intercoil voltages are more severe when the LV winding is open-circuited. These experimental results question the validity of Mr. Hickling's statement that short-circuiting of windings not under test actually gives maximum intercoil voltage stresses.

Tank current experiments by Ganger (Ref. 27 in paper) seem to indicate that in some designs the change in voltage conditions could be insignificant. The experiments by the authors show that short-circuiting of other windings can reduce the value of the impulse test. A large number of voltage distribution experiments on a variety of designs would be necessary to draw a general conclusion as to the comparitive severity of the voltage conditions. Supply authorities will normally require the most severe condition during the test.

It is felt that the service conditions must be considered as well as the impulse testing economies which are available to manufacturers who adopt the overall policy of short-circuiting other windings for all tests. For example, a voltage transformer can never be considered as having its LV winding short-circuited. Also power transformers may often be left energised but isolated at the lower voltage terminals. Switching surges are usually impressed on transformers after the other windings have been disconnected from any shunt load impedance. The authors can see no purpose in short-circuiting or shunting other windings unless the voltages to be transferred to those windings will be excessive. Provoost, * a European testing authority, supported this viewpoint at the 1954 Symposium on Precision Electrical Measurements at the National Physical Laboratory, England.

The use of computors as suggested by Mr. H. Harrison for an investigation of the type described in the paper would not have provided such comprehensive results within a reasonable time. The equivalent ladder network is very complex and, due to the gradually increasing influence of the core during the full-wave test the inductive parameters are changing. However possibilities do exist for further work along the lines suggested initially, perhaps, with an experimental winding of the type used for the demonstration. This approach has been used for design purposes by overseas transformer manufacturers but it is felt that the results are only applicable to the first 20-50 microseconds, due to the change in the inductance parameters. A mathematical investigation using a computer could lead to a better understanding of fundamental phenomena.

The use of power frequency tests after an impulse test as suggested by Mr. P. Shears is of limited value for fault detection. The experience described by Mr. A.W. Tyree is typical. It is considered that a radio influence voltage detector would be of no use for detecting the type of faults introduced by an impulse test.

* PROVOOST P.G.: "Testing of transformers with special reference to the assessment of the results of such tests". Precision Electrical Measurements (London, H.M.S.O. 1955). Proceedings of Symposium at National Physical Laboratory, 1954 .

The doubts expressed by Mr. R.K. Edgeley seem to be over-emphasised. Test engineers experienced in high voltage and short-circuit testing often have the responsibility of making decisions based on test procedures and results which would not be easily interpreted by less experienced persons. The literature reveals the ability of testing authorities to successfully handle the additional responsibility of making decisions associated with the impulse type of high voltage test. Even the possible development of indicating type monitoring instruments so that oscillograms will not be required, will still leave considerable technical responsibility with the test engineer.

Mr. W.A. Shaw asks if the method is applicable to other plant. Recurrent surge generators have been used for fault detection in rotating electrical machines in the past and a local motor manufacturer uses a 10 kV rotating surge generator in routine testing. A higher surge voltage could be used, but a big advantage of the R.S.G. is its compactness and the smallest equipment giving reliable patterns is the one to use. The whole basis for the use of the R.S.G. in the applications given in the paper lies in the linearity of the components under test. If the behaviour is not linear, the whole low level method of testing breaks down and no voltage except the standard test voltage would do. If the behaviour is linear, and it appears to be so, then any convenient voltage will be satisfactory. For the equipment demonstrated, the voltage is determined largely by the switch ratings. The next larger available thyratron handles 350 amps as a peak current. If this were used, for the same component values, the output voltage could go to 8 kV, still not very high but beginning to produce some insulation problems, and the equipment would require a power supply of 1.6 kW all of which is dissipated in the unit.

To our knowledge, a reflected pulse fault locator has not been used perhaps because of the very short pulses needed. The time of surge travel through the winding is of the order of 20 microseconds and the test pulse would need to be a small fraction of this in length. This involves far more complicated equipment both to produce the pulses and to match impedances. To obtain an indication the fault would have to be permanent in which case it could be burnt out with a power frequency supply.

Mr. A.W. Tyree's questions raise interesting aspects of the commercial implications. If the impulse test is for design check purposes then location of the fault would be important. On the other hand if failure occurs during an acceptance test the manufacturer may decide that it was only a quality or process defect and not go to the trouble of locating the fault. Supply authorities carrying out investigational tests will invariably endeavour to locate the weakness so that remedial measures can be taken.

APPENDIX 4.2 - DERIVATION OF AN EQUIVALENT CAPACITANCE NETWORK FOR A TRANSFORMER WINDING.

This example shows a calculation of the equivalent capacitance network for the line end portion of a 132/66kV 60 MVA Transformer. This particular calculation is made on the assumption that the core is the earthed surface and that the winding is oil-immersed but similar calculations also have to be made, in the design stage, under the following conditions:

High voltage winding in oil, low voltage winding surface as earth.

High voltage winding in air, core as earth.

High voltage winding in air, low voltage as earth.

Low voltage winding itself in oil.

The calculations for air are to enable recurrent surge generator checks of the voltage distribution to be readily made on the assembled core and windings.

The winding details are:

High Voltage (132 kV - Graded Insulation - Star Connected)

Centre Terminal Disc Type 84 Sections, 714 Turns.

The top and bottom halves (each of 42 sections) are symmetrical and are separated by a radial end shield which is connected to the line terminal.

Low Voltage (66 kV - Fully Insulated - Delta Connected)

Disc Type 30 Sections 357 Turns.

Insulation Details are given in the following calculations which are self-explanatory. The winding portion considered is shown in Figure P and the resultant network in Figure Q. The derivation is

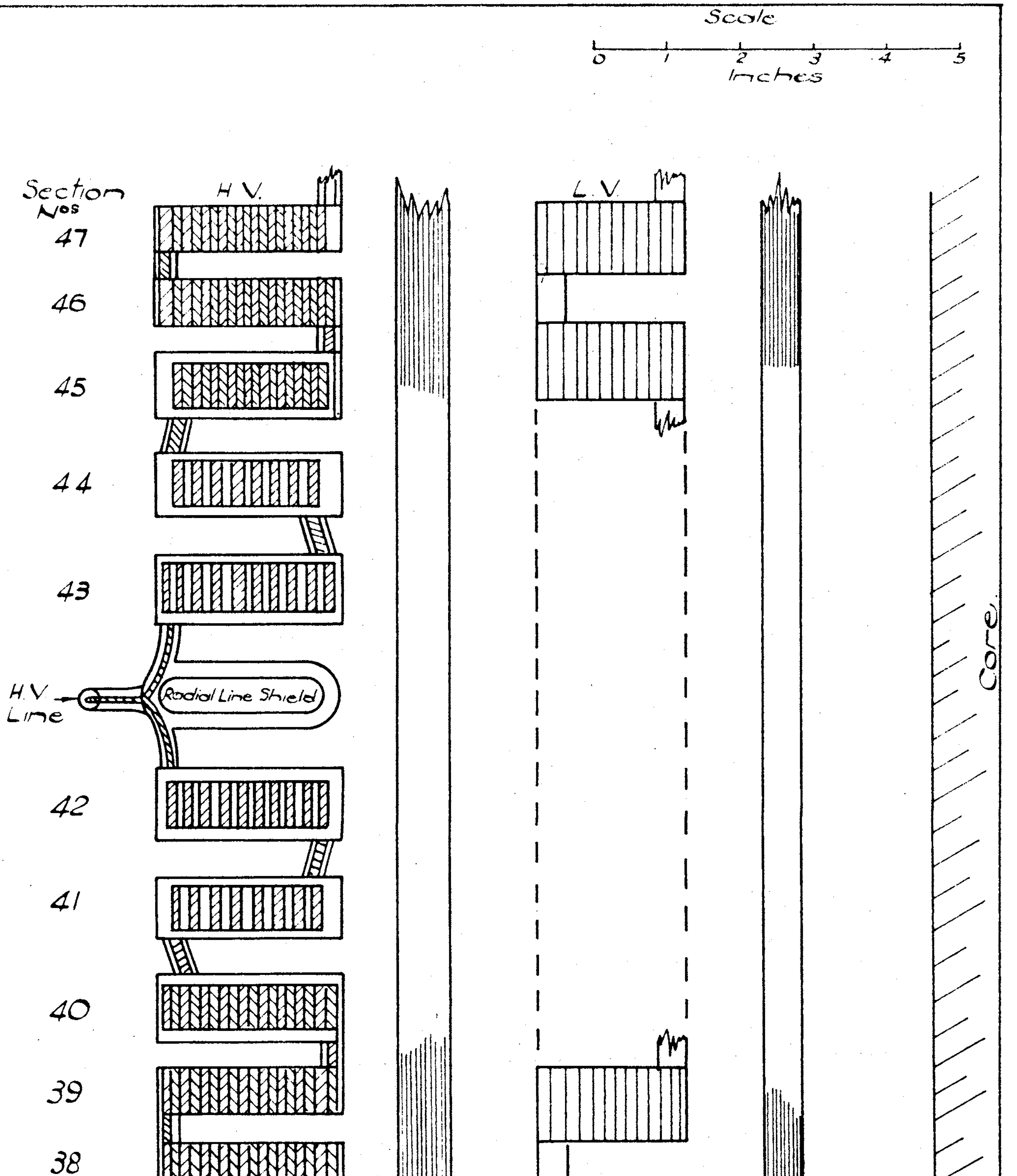


Fig P Section of Winding
Arrangement at Line End

4.2 ctd.

carried out by considering five separate regions:

Region 1	-	Core to L.V. winding	)
Region 2	-	L.V. winding	) for Cge
Region 3	-	Outside of L.V. to inside of H.V. winding.	)
Regions 4 and 5	-	Inner and outer halves of H.V. windings Radial Shield to first Line sections Coil to Coil (Axially) in H.V. winding.	

Dimensions in inches.

Region 1 - Core to L.V. Winding		
1	L.V. internal dia. (copper to copper)	37.13
2	Max. core leg	30.00
3	Core to LV = $\frac{1}{2}$ (1) - (2)	3.565
4	Cylinder thickness 1.(	0.312
5	2.(	0.250
6	Total solid	0.562
7	Total oil = (3) - (6)	3.00
8	0.85 x oil	2.55
9	For oil calc. = 0.5 x solid	0.281
10	Equiv. oil (8) + (9)	2.836
11	Mean radius $\frac{1}{2}$ ((2) + (3))	16.78
12	Elastance ratio (10) ÷ (11) *	0.169

* see note at end of calculations.

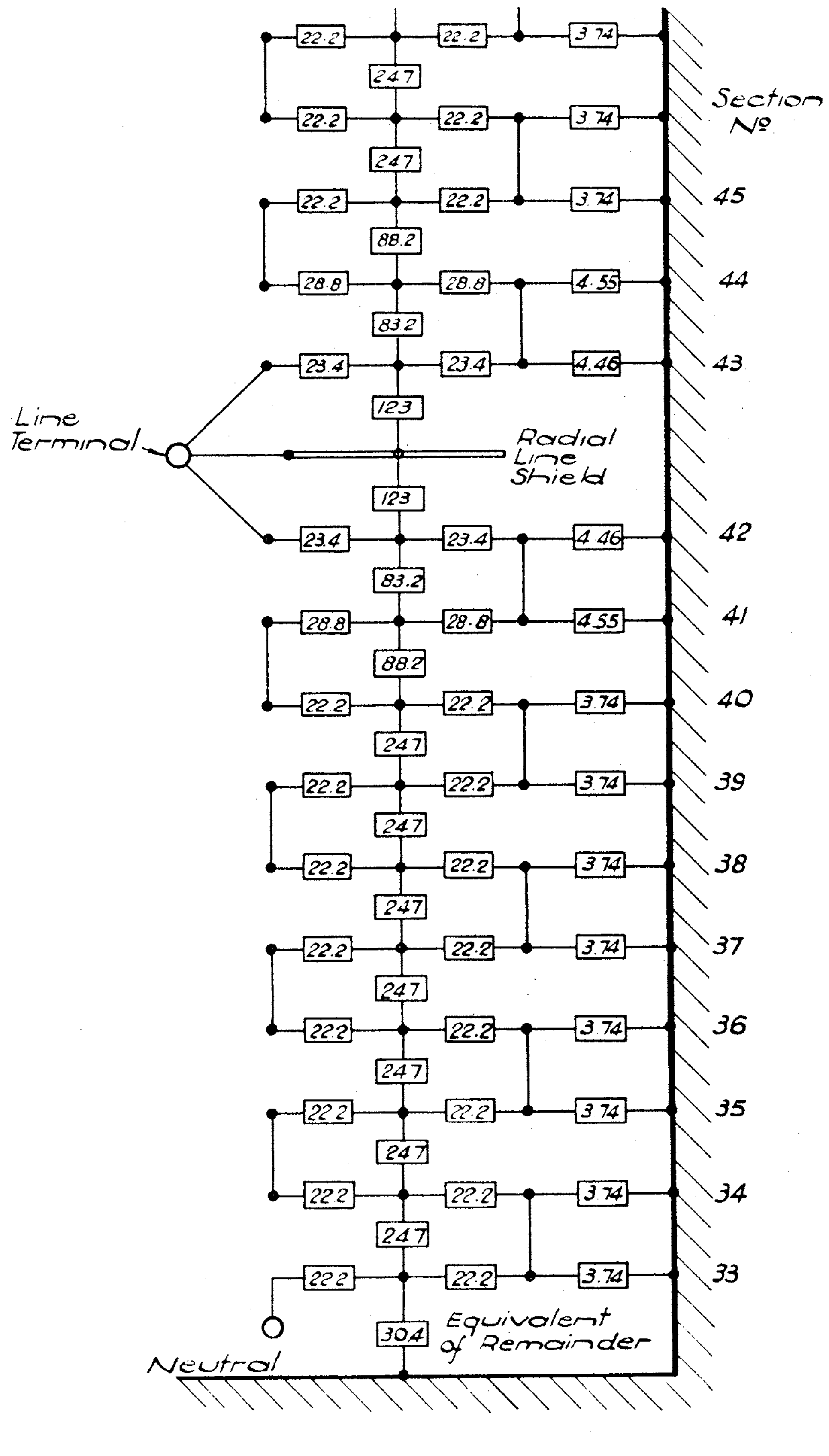


Fig Q : Equivalent Capacitance Network.

Region 2	L.V. Windings (Disc.)	
1	No. of conductors radially	12
2	Total radial insulation ((1) -1) x t	0.550
3	Equivalent oil-for oil calc.=0.7 x (2)	0.385
4	Mean radius	19.55
5	Elastance ratio (3) ÷ (4)	0.0197
6	Elastance Region 1	0.169
7	" " 2	0.0197
8	Total Elastance (6) + (7)	0.189

t = total insulation = .050 inch in this case.

l = thickness of interlayer insulation.

4.2 ctd.

Region 1-3	(3 = outside LV to inside HV winding)			
	H.V. SECTION NO.	43 & 42	44&41	Main
1	Total H.V. to L.V. distance (copper to copper)	2.58	2.58	2.12
2	Total cylinder and flange collar thickness	0.687	0.687	0.687
3	Foundation Ring or Packing	0.200	0.300	-
4	Tape and Radial thickness (one side)	0.190	0.125	-
5	Turn insulation (one side thickness)	0.085	0.085	0.060
6	Total Solid	1.162	1.197	0.747
7	Total oil (1) - (6)	1.418	1.38	1.373
8	0.85 x oil	1.202	1.17	1.168
9	For oil cal. = 0.5 x Solid	0.581	0.598	0.373
10	Equivalent oil (8) + (9)	1.783	1.768	1.541
11	Mean Radius (Region 3)	21.89	21.89	21.97
12	Elastance - Region (3):(10)+ (11)	0.0815	0.0810	0.070
13	Elastance - Regions 1 and 2	0.189	0.189	0.189
14	Total Elastance (12) + (13)	0.270	0.270	0.259
15	Capacitance 1.0 + (14)	3.7	3.7	3.86
16	Duct Pitch	1.35	1.37	0.970
17	Zone Factor to Modify Duct Pitch	0.9	0.9	1.0
18	(16) x (17)	1.21	1.23	0.970
19	Capacitance H.V. winding to core (15)x(18)*	4.46	4.55	3.74

* see notes at end of Calculations.

4.2 ctd.

REGION 4 AND 5. INNER AND OUTER HALVES OF H.V. WINDING.

	Section Numbers	43 and 42	44 and 41	Main
1	No. of conductors radially	10	8	18
2	Conductor insulation (2 sides)	0.120	0.120	0.070
3	(1)x(2) = Total Conductor Insulation	1.20	0.96	1.26
4	Equivalent oil 0.7 x Solid	0.84	0.672	0.882
5	Mean radius of coil	24.52	24.52	24.46
6	Zone Factor: Sect.Coil = width of coil Cont. Disc = width of bare conductor.	0.400	0.400	0.400
7	Capacitance of whole coil = (5)x(6) + (4)	11.7	14.4	11.1
8	Capacitance of half coil = 2 x (7)	23.4	28.8	22.2

RADIAL SHIELD TO 1ST LINE SECTION

1	Tape on ring - one side	0.19			
2	Tape on coil - " "	0.19	8	Equivalent oil = (6) + (7)	0.563
3	Paper on coil - " "	0.06			
4	Total paper and tape	0.435	9	Mean radius	24.55
5	Oil Duct	0.300	10	Zone Factor: 1.1 x mean radial depth of coil and ring	2.83
6	0.85 x oil	0.255			
7	Oil : 0.7 x tape and paper	0.308	12	Capacitance: Oil = (10) x (9) + 8	123

COIL TO COIL (AXIALLY) H.V. WINDING				
Section Numbers		42-41 43-44	41-40 44-45	Main
1	Tape between coils	0.315	0.185	-
2	Turn insulation between middle points	0.120	0.102	0.070
3	Total tape and paper	0.435	0.287	0.070
4	Oil Duct	0.600	0.600	0.400
5	0.85 x oil	0.510	0.510	0.340
6	Oil immersion: 0.7 x Tape and paper	0.304	0.201	0.049
7	Equivalent oil: (5) + (6)	0.814	0.711	0.389
8	Mean Radial depth H.V.	2.53	2.35	3.55
9	Mean radius H.V. excluding tape	24.38	24.23	24.46
10	Zone factor 1.1 x (8)	2.78	2.59	3.92
11	Capacitance for oil immersion: (9) x (10) ÷7*	83.2	88.2	247

* The capacitances given can be converted to micromicrofarads by multiplication by 3.1 (i.e. $\frac{\text{inches}}{\text{centimetres}} \times \frac{1}{9} \times \frac{1}{2} \times$ Permittivity of oil)

<u>Equivalent Capacitance of Remainder of Winding</u>.

C = capacity of a main section to earth (see Regions 1 to 3) = 3.74

K = series capacitance of main sections (see Regions 4 & 5) = 247.

Equivalent Capacity = CK = 30.4

<u>Effect of Inter Coil Connections</u>: Waldvogel and Rouxel (Ref. 37) point out that if these connections are omitted the capacitance of coil to coil as calculated above, has to be divided by a factor of 3.

APPENDIX 4.3.

SPECIFICATION FOR RECURRENT SURGE OSCILLOSCOPE.

INDEX

1. General

The recurrent surge oscilloscope described in this specification is for observing transient voltage phenomena in the windings of transformers or in transformer impulse testing equipment prior to full scale impulse testing. The transformer ratings range from 5 kVA to 30,000 kVA. The recurrent surge oscilloscope may often be used on site or in transformer overhaul depots or at testing stations. Consequently it must be robust and portable.

2. Rating.

2.1 Supply Voltage.

The supply voltage is to be 240V, 50 c.p.s.
The equipment shall be continuously rated for full load operation on this supply voltage. (See "7. Tests After Completion").

2.2 Surge Generator.

The R.S.O. must be capable of generating, at the output terminals of the wave shaping unit, a surge having a wave shape in accordance with B.S.S. 923-1940* and a maximum amplitude of approximately 2000-2500 volts. The amplitude must be adjustably in 25% steps. The surge must recur at least fifty (50) times per second. The maximum load at the output terminals of the wave shaping unit shall be taken as 0.05 μF.

* i.e. a 1 μsec. wave front time and 50μsec., decay time to 50% of the peak. The wave shaping unit should give control in both directions from this standard.

2.3 Display.

The display must be on a 6" - 8" Flat screen cathode ray tube.

A selector switch must give displays as follows:-

"VIEW" - voltage applied to "VIEW" terminals.

"TIMING" - Timing wave - See below.

"SURGE" - Surge Voltage at output terminals of WAVE SHAPING UNIT.

The frequency of the timing wave must be variable in the following steps 5, 1.0 and 0.1 megacycles.

The time base must be variable in the following steps 1, 10, 75, 150 and 300   sec., and be capable of magnification by a "Fast-Slow" switch. The following controls must also be provided: Y-Shift (calibrated); X-Shift, Brillance & Focus, separate switches for heaters and surge generation.

2.4 Wave Shaping Unit.

This unit must be robust and an integral part of the R.S.O. equipment.

2.5 Amplifier.

For measuring small voltages, particularly during the checking of full scale impulse test parameters, an amplifier is essential for display purposes.

The gain must be variable in definite steps, viz.:

100:1, 200:1, 400:1

For the examination of transients occurring in the region of the wave front the amplifier must be linear up to 2.5 megacycles.

3. Physical Arrangement including Maximum Dimension & Weights.

The equipment is to be arranged in two separate units unless the total weight does not exceed 30 lb. The weight of each unit must not exceed 30 lb. The unit(s) are to be assembled in sheet steel cases with a light grey enamel finish. Suitable handles are to be provided in a plane above the centre of gravity of each unit.

4. Circuit Wiring.

The wiring shall be arranged so that no interference occurs between the generating and recording circuits. Where necessary electro-static and electromagnetic shielding shall be provided.

All connections shall be made in a workmanlike manner and soldered joints shall be sufficiently robust to withstand vibration effects occurring during transport to test sites. Output terminals shall be of the insulated post type with captive terminal nuts.

5. Components.

The components used must be of high quality. Component ratings must be suitable for continuous operation of the unit.

6. Camera Attachment.

The Display Tube must be mounted so that a Cossor oscilloscope Camera can be securely placed in the correct position for photographing the recurrent trace.

If another type of camera is offered, its cost and the type of mounting must be shown as an alternative.

7. Tests after Completion.

If the unit complies with the general requirements of this specification, such as regards weight, finish etc., it will be subjected to the following tests.

(a) The Insulation Resistance of each circuit is to be greater than two (2) Megohm when measured with a 1000V megger.

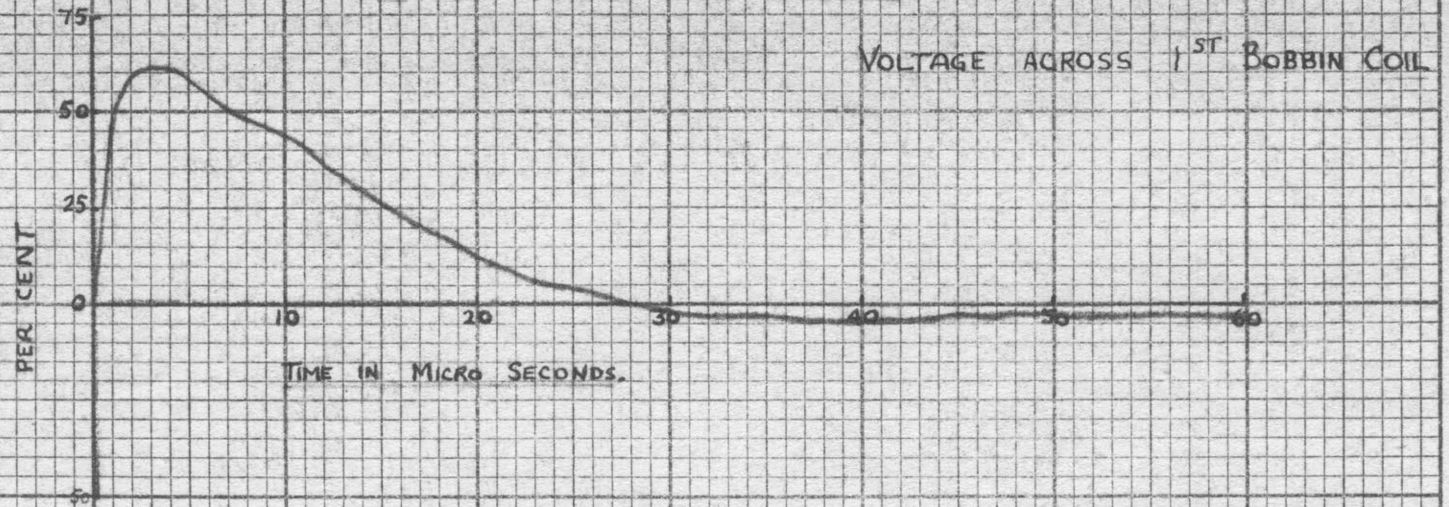
(b) The output waveform and its peak value are to be checked for compliance with this specification when operating on no-load and when supplying a 0.05 microfarad load.

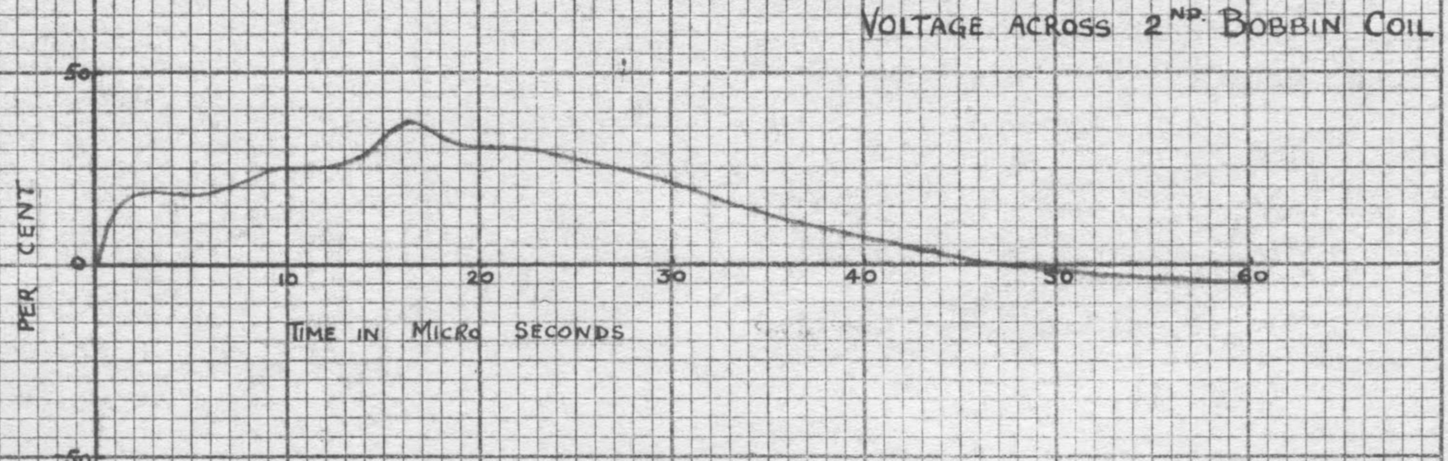
(c) The output voltage control is to be operated twenty (20) times on full load. No instability in the generator shall occur.

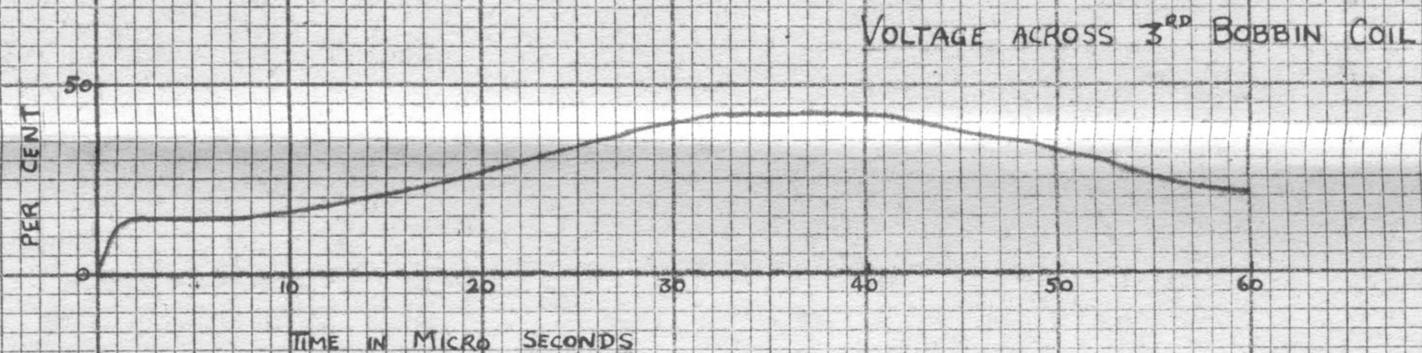
(d) A Temperature Rise test shall be conducted under full load conditions. The temperature rise of the various components must not exceed the British Standard limits for the class of insulation used.

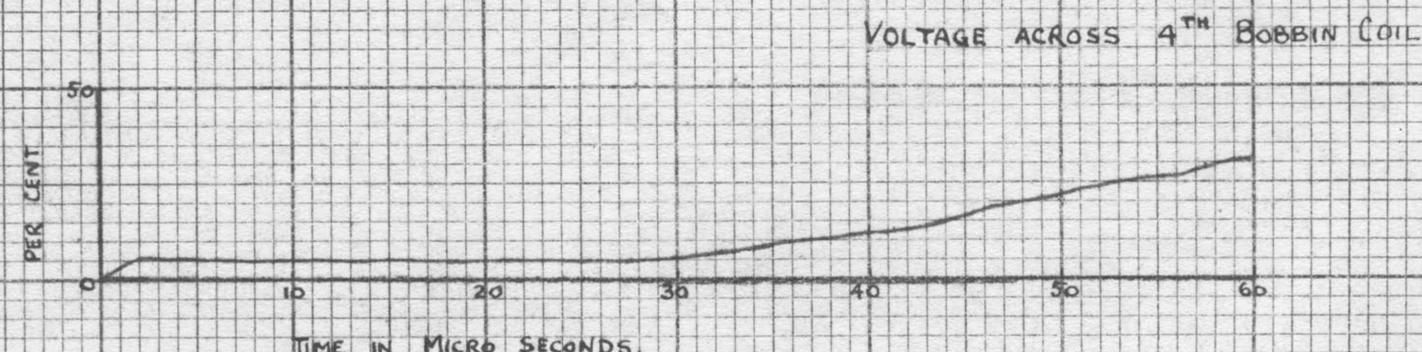
(e) Photographs of the output surge wavefront shall be taken using the one (1) microsecond sweep on the Display Unit. The resultant oscillograms must be quite legible. High speed photographic film (ASA rating 200) will be used in this test.

VOLTAGES ACROSS 'B' PHASE H.V. WINDING SECTIONS WHEN SUBJECTED TO 1/50 IMPULSE TEST VOLTAGE.







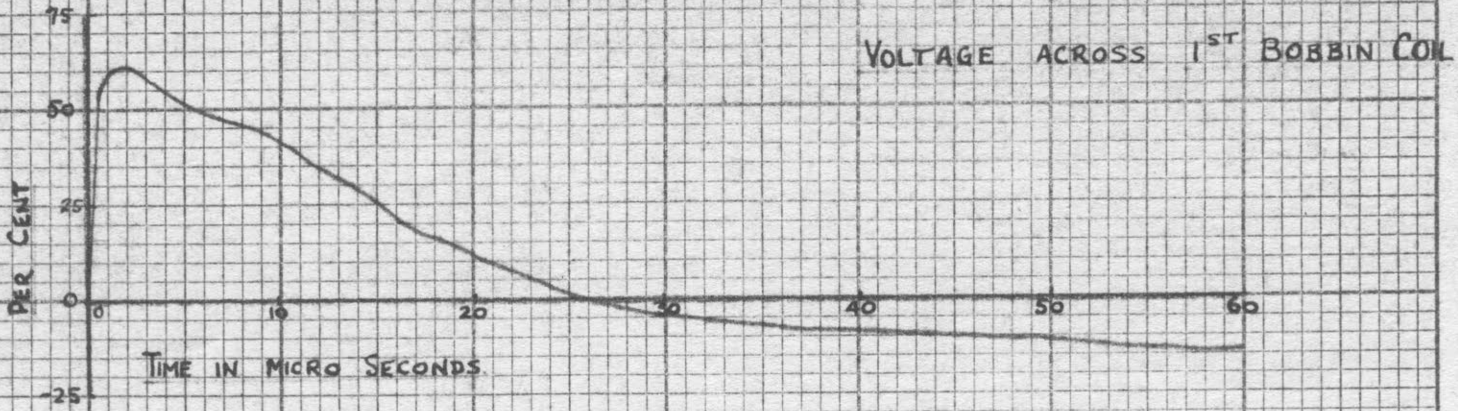


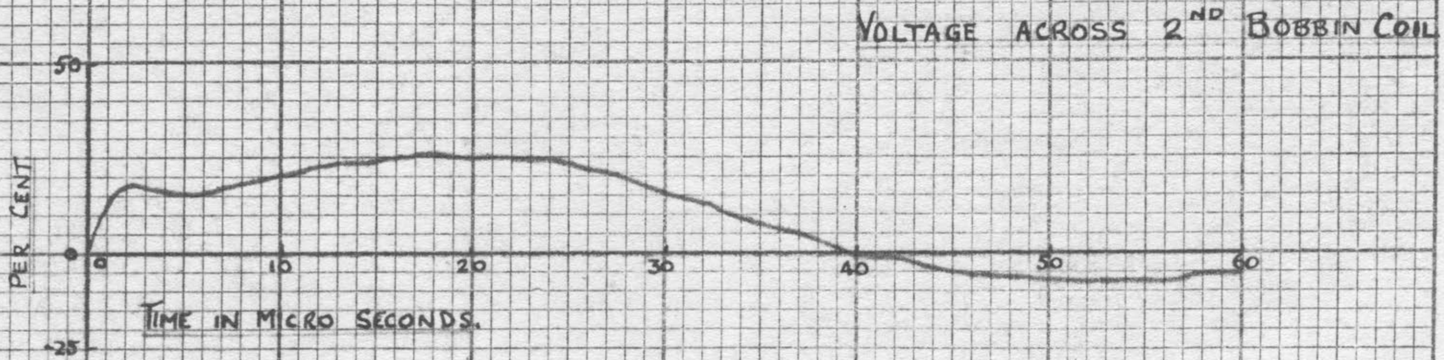
NOTES

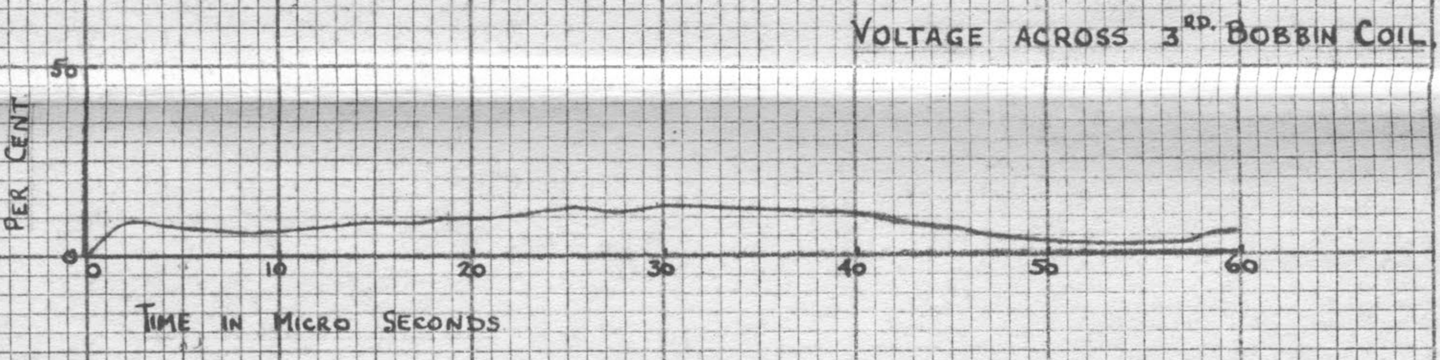
1. VOLTAGES DERIVED FROM RECURRENT SURGE MEASUREMENTS WITH WINDINGS & CORE OUT OF OIL.
2. WAVEFORMS PLOTTED FROM OSCILLOGRAM No. 2. (SECONDARY OPEN CIRCUITED)
3. READINGS ON PER CENT COMPONENT REPRESENT PER CENT OF PEAK V_L VOLTS.

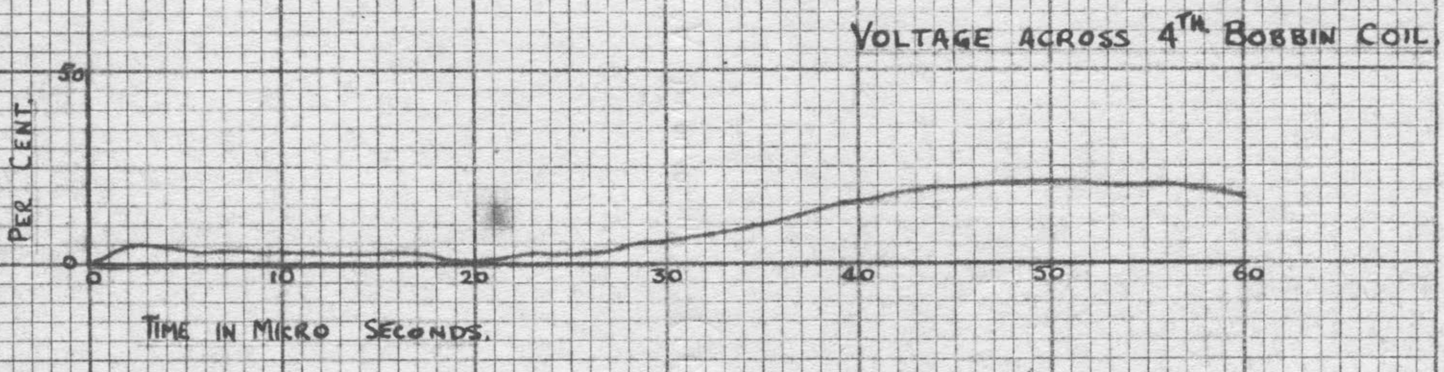
11000/110 VOLT VOLTAGE TRANSFORMER

VOLTAGE ACROSS 'B' PHASE H.V. WINDING SECTIONS WHEN SUBJECTED TO 1/50 IMPULSE TEST VOLTAGE







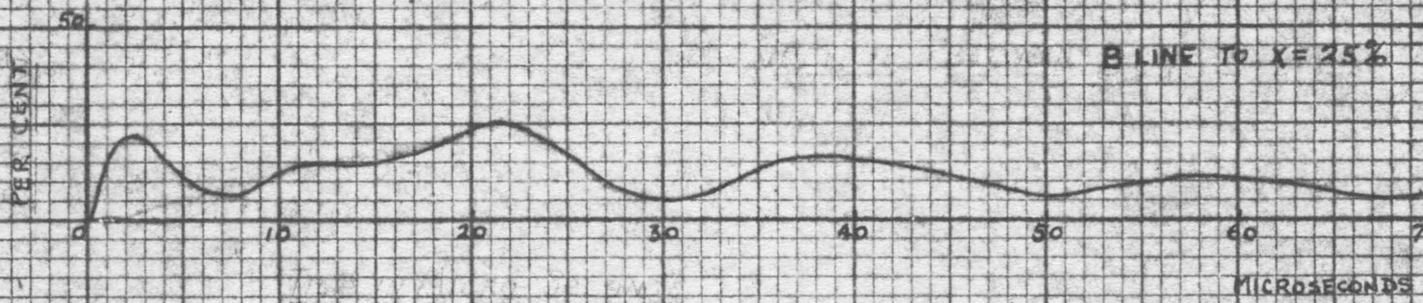


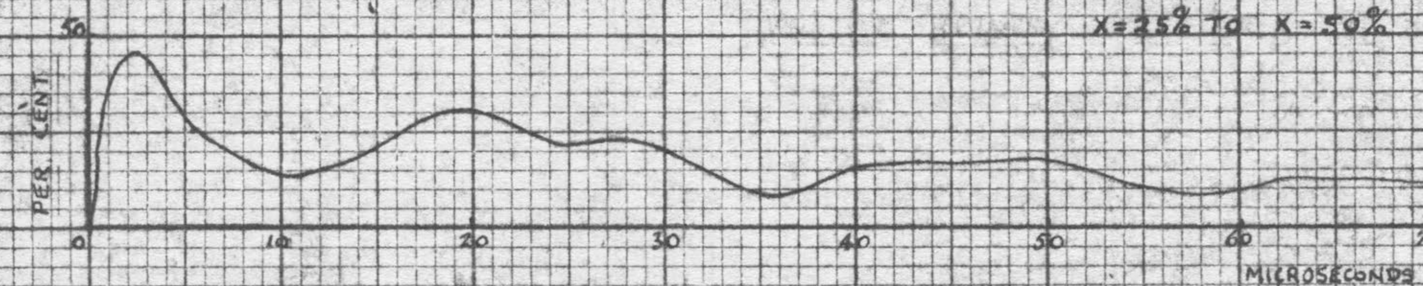
NOTES:

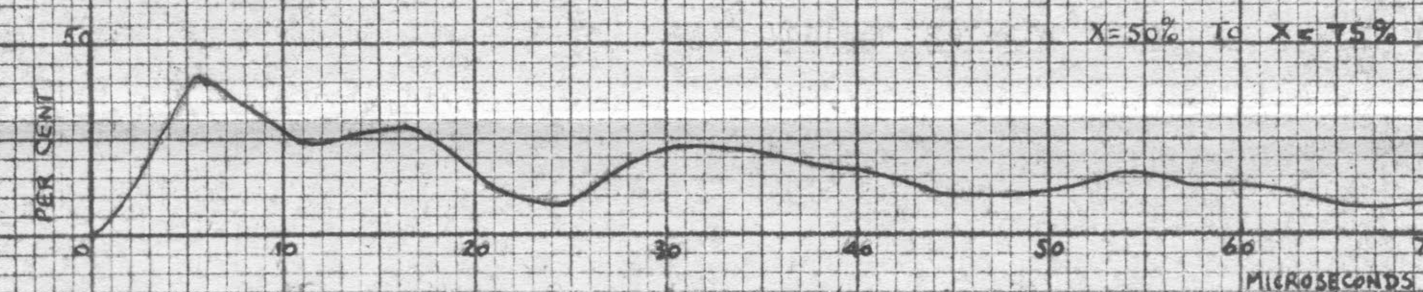
1. VOLTAGES DERIVED FROM RECURRENT SURGE MEASUREMENTS WITH WINDINGS & CORE OUT OF OIL.
2. WAVEFORMS PLOTTED FROM OSCILLOGRAM No. 1. (SECONDARY SHORT CIRCUITED)
3. READINGS ON PER CENT. COMPONENT REPRESENT PER CENT OF PEAK V_L VOLTS.

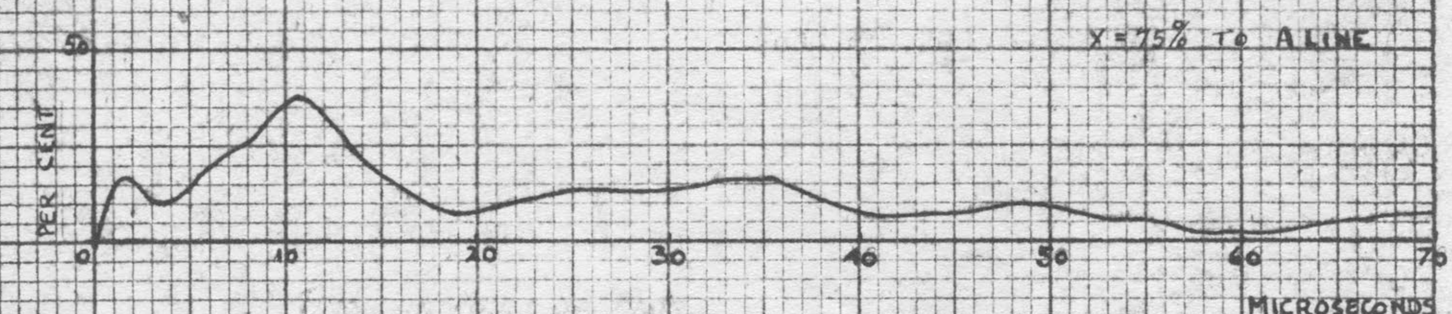
11000/110 VOLT VOLTAGE TRANSFORMER.

VOLTAGES ACROSS 'B' PHASE H.V. WINDING SECTIONS WHEN SUBJECT TO 1/50 IMPULSE TEST VOLTAGE.









NOTES

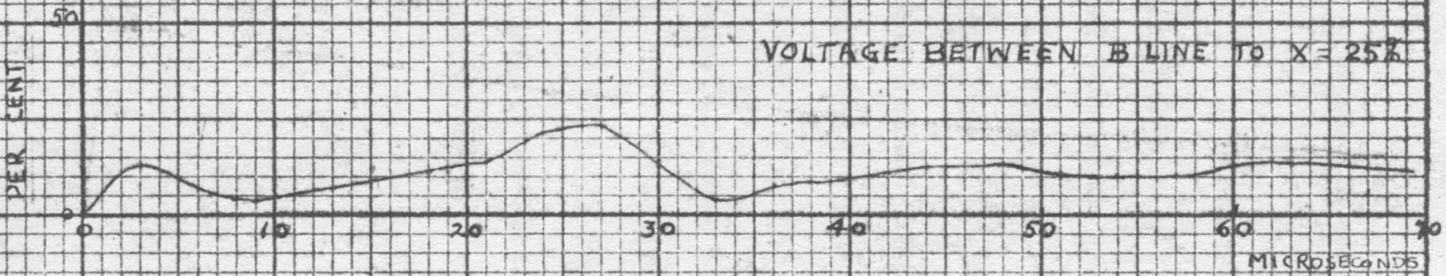
1. VOLTAGES DERIVED FROM RECURRENT SURGE MEASUREMENTS WITH WINDINGS & CORE OUT OF OIL.
2. WAVEFORMS PLOTTED FROM OSCILLOGRAM No 2A (SECONDARY OPEN CIRCUITED)
3. READINGS ON PER CENT COMPONENT REPRESENT PER CENT OF PEAK V_L VOLTS.

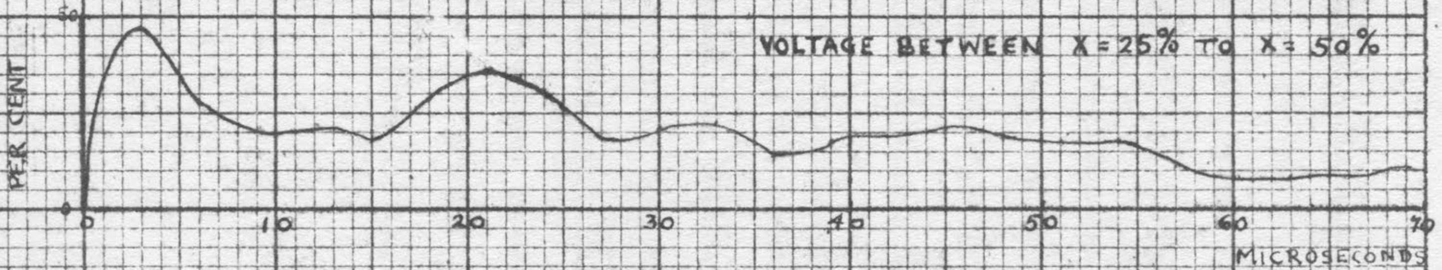
200KVA TRANSFORMER.

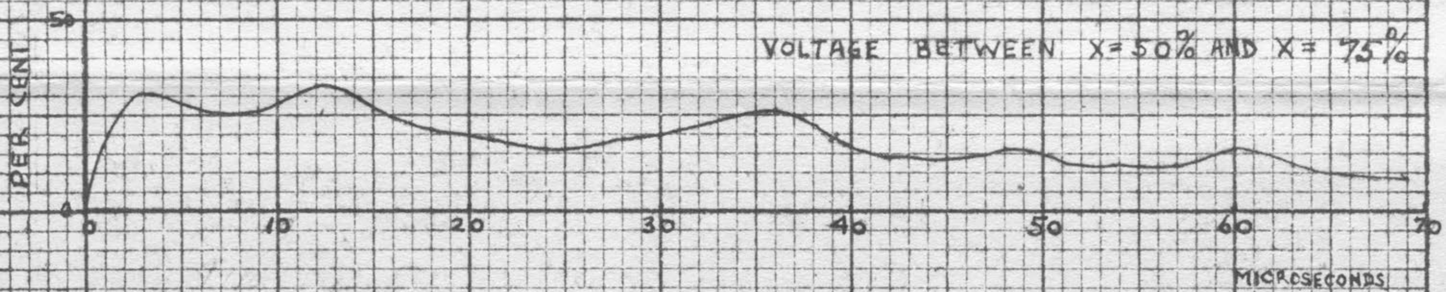
200KVA TRANSFORMER

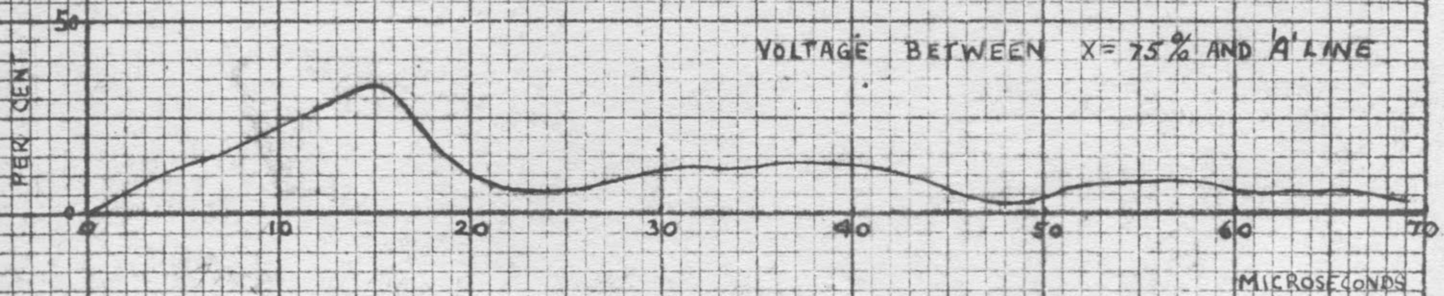
250 KVA E.P.M. TRANSFORMER

VOLTAGES ACROSS 'B' PHASE H.V. WINDING SECTIONS WHEN SUBJECT TO 1/50 IMPULSE TEST VOLTAGES.









NOTES:

1. VOLTAGES DERIVED FROM RECURRENT SURGE MEASUREMENTS WITH WINDINGS & CORE OUT OF OIL.
2. WAVEFORMS PLOTTED FROM OSCILLOGRAM No 1A (SECONDARY SHORT CIRCUITED)
3. READINGS ON PERCENT COMPONENT REPRESENT PER CENT OF PEAK V_1 VOLTS.

200KVA TRANSFORMER

APPENDIX 4.5

LOG OF FAULT DETECTION AND LOCATION EXPERIMENTS

In order to preserve the clarity of Part 2 of the thesis, which deals with the Fault Detection and Location Experiments and the analyses of the results, experimental details are kept to a minimum. These details are given in this Appendix, both for the author's own work and, as far as possible, for experiments by others, the results of which have been described in the thesis.

The log of the experiments given below has been compiled from the author's original log which contains full circuit data and oscillographic records for each experiment. The original log also has an appendix containing confidential transformer design data. The log given below follows a chronological sequence except for its grouping into four sections to facilitate cross-reference to Part 2 of the thesis.

KEY TO APPENDIX 4.5 -

LOG OF FAULT DETECTION AND LOCATION EXPERIMENTS.

4.5.1: EXPERIMENTAL EQUIPMENT

At the commencement in September, 1953, of the author's original work in connexion with the thesis, no experimental equipment was available to him. A 300 kV impulse generator was still under development at the University of Sydney, and the building of the 2,000 kV impulse generator by the University of New South Wales had not commenced.

The author's experience overseas had shown him that the most positive investigational approach required the use of a recurrent surge generator. The portability and simpler operational requirements of a recurrent surge generator, referred to hereafter as an R.S.G. were considered necessary to obtain the basic experimental results. This decision was justified later when it was found that supply undertakings and manufacturers would make transformers available for experiments for limited periods only. Also, the author often had to carry out the experiments in a transformer overhaul depot or at a manufacturer's works, setting up the experimental equipment and dismantling it within a few hours. The introduction of artificial faults often involved lowering of oil in the transformer tank or complete removal of the core and windings from the tank. The main advantage of the R.S.G. is the ability to display the transient phenomena as a steady oscilloscope picture so that adjustments can be made before oscillograms are photographically recorded. The time required for developing oscillograph films before making an adjustment, as occurs in full scale experiments, is is saved and experimental results obtained more repidly.

It was agreed in September 1953 that:-

(a) the author would confine his theoretical and experimental investigations to fault detection aspects of impulse testing and not encroach on the other extensive field of impulse strength design. Hence, the development of the experimental equipment should aim to meet the author's specific requirements as quickly as possible.

(b) the author should devote as much time as possible to study of the literature, theoretical aspects and analysis of experimental results, and that the electronic design and construction work associated with the R.S.G. required, should be carried out by the staff of the University of New South Wales.

It was found that it was not possible for the University staff to render the assistance stipulated in (b) immediately and in fact, the final 2 kV R.S.G. shown in Fig. 12 of the thesis, was not available to the author until the first term in 1956. In order to obtain experimental data during 1954 and 1955 the authori designed and constructed an experimental 1000 volt R.S.G.. This work took considerable time and effort and due to limitations of the experimental R.S.G. the records obtained were not as high a quality as was desired. Nevertheless, the experimental experience gained by the author proved invaluable during the latter years of the investigation and the results obtained during 1954 and 1955 guided the author in his analysis of the literature and in his theoretical study of the subject.

4.5.1.1: THE EXPERIMENTAL RECURRENT SURGE GENERATOR

The author's lack of experience in electronic circuit design, meant that he had to base the design of the experimental R.S.G. on an R.S.G. circuit used by the British Thomson-Houston transformer design department, with whom he worked during 1950.

The B.T.H. circuit was of early origin, having been developed in 1938 by Wilkinson (Ref.41). The actual R.S.G. was housed in a wooden case to reduce internal capacitance effects. Its output waveshape was adjustable with the limiting shape of a 0.4 x 100 microseconds wave.

The author's design for the experimental R.S.G. was intended to be simple and robust since it was anticipated that its useful life would be short. If it had been known that the final 2 kV R.S.G. would not have been available until 1956 a more sophisticated design would have been attempted, possibly along the lines described by White and Nethercot (Ref.4).

The 2 kV D.C. supply for the R.S.G. was obtained by modifying a R.A.A.F. Power Supply Unit - Type A20. This unit was placed in the basement of the Electrical Engineering Machinery Hall at Ultimo in February, 1954 and a "breadboard" construction of the R.S.G. mounted on top.

A 1 microfarad 2000 volt condenser was charged to approximately 800 volts by the D.C. supply unit via a voltage divider and discharged through a B.T.H. thyratron, type BT5. The triggering of the thyratron was controlled by a Phillips peaking transformer, supplied from an 80 volt, 50 c.p.s. winding on the thyratron ~~was employed in the primary of a grid~~ filament transformer, the secondary output of which fired the Mullard type 4C35 thyratron. This was the circuit finally employed in the experimental R.S.G. and described in Section 2.2, page 27, of the thesis.

The experimental R.S.G. was used in October, 1954 at the Tyree transformer works, Kingsgrove, N.S.W. for the first experiments on commercial transformers. Until the commissioning of the final 2 kV R.S.G. in the 1st. term, 1956, the experimental R.S.G. was employed for all R.S.G. experiments made by the author in Sydney.

4.5.1.2: THE 2 KV RECURRENT SURGE GENERATOR

The design of this R.S.G. by Mr. G.C.Dewsnap was based on the use of an earthed cathode discharge thyratron and generation of a negative polarity output pulse. During 1954 the author prepared a specification for the guidance of Mr. Dewsnap (See appendix 4.3). The design of the R.S.G. is described by Dewsnap in two papers (Ref. 34 and Ref. 42) and the final circuit is given in Fig. 11 of the thesis.

The fundamental difference between the specification given in Appendix 4.3 and the final 2 kV R.S.G. is that the latter does not include a display unit. It is arranged to operate with a Cosser 1035 Cathode ray oscilloscope as the display unit. The oscillopcope has to be slightly modified so that pulse brightening is achieved by a positive pulse from the R.S.G. trigger circuit.

The trigger circuit caused some concern during the final commissioning tests of the R.S.G., due to unstable operation of the blocking oscillator. A "jitter" of approximately 13 microseconds was occurring and made photography impossible. Mr. Dewsnap was overseas at the time and the author had to investigate the problem. The final solution was to substitute a multi-vibrator trigger circuit developed by Mr. J.K.Reavley, a test engineer with the Sydney County Council. This trigger circuit produced a negative polarity pulse, which could be used to trigger the oscilloscope time base, and several microseconds later, a positive polarity pulse which fired the R.S.G. thyratron and simultaneously brightened the Cossor oscilloscope trace.

Fig.11 shows the final multi-vibrator circuit. The terminal marked "CRO - Green, negative Trigger" was connected to the external trigger terminal and to the brightness circuit of the Cossor oscilloscope. The latter connection is made between resistors R49 and R50*, the following connexions having been open-circuited:-

(a) Anode lead of diode V7

(b) Connexion between R47 and R48*.

This simple modification was suggested by Dr. Parnell of Queensland University.

Details of the output and the operation of this R.S.G. are given in Section 2.2, p.28, of the thesis.

---

* Resistance reference numbers for a Cossor type 1035 oscilloscope.

4.5.1.2:

The normal arrangement of the 2 kV recurrent surge generator and the Cossor oscilloscope is shown in Fig.12 when the equipment was being used for a demonstration before the Sydney Division of the Institute of Engineers on 26th.March,1958.

4.5.1.3: ACCESSORIES FOR RECURRENT SURGE EXPERIMENTS

The accessories required for recurrent surge experiments were:-

(a) Current shunts

(b) Voltage dividers

(c) Loading resistors

(d) neon gap to simulate artificial "sparking" faults.

(e) oscilloscope camera and suitable film.

(f) shielded and unshielded leads with bull-dog clip and spade connectors, for recording, surge connection and application of artificial solid faults.

Due to the magnitude of the peak voltage output of the 2 kV R.S.G. it was possible to connect directly to the vertical deflection plates of the oscilloscope, thus avoiding any distortion in the oscilloscope amplifiers.

It was found that resistance shunts of the composition type were sufficiently non-inductive for fault detection experiments.

In August 1955 experiments were carried out on Transformer "N", a 200 kVA, 33/11 kV unit, to compare R.S.G, and full scale test oscillograph records (See section 2.2, p.27, and Fig.10). The author carried out the R.S.G. experiment at a transformer manufacturer's works in Sydney. Through the courtesy of Dr. Parnell, the corresponding full wave test oscillogram was recorded when transformer "N" was at the University of Queensland high voltage laboratory for subsequent design tests. The successful result of these experiments showed that the correct R.S.G. technique was being employed and that the composition type resistance shunts were satisfactory.

A resistance shunt board was constructed giving a range from 5 to 1000 ohms in convenient steps. This shunt board is in the middle of the demonstration table shown in Fig.12.

For the reasons described in Section 2.2, p.32, resistance shunts only were employed by the author.

Resistive and capacitive voltage dividers were employed for calibration and voltage distribution measurements respectively. Considerable attention was paid to calibration of the R.S.G. records so that the oscillograms could be scaled in equivalent full scale test values of voltage and current. It was felt that such scales would be of value to testing authorities when determining shunt impedances and oscilloscope recording sensitivities. The resistive voltage dividers used for this purpose were constructed from composition type resistors and usually employed resistance values of 10,000 ohm plus 1,000 ohm.

The capacitive voltage divider was intended for voltage distribution and transferred voltage measurement using direct connexion to the oscilloscope vertical deflection plates. It was convenient because the R.S.G. had an integral 12:1 capacitance divider which matched the oscilloscope sensitivity. However, the high voltage condenser of the capacitance voltage divider had a capacity of 430 micromicrofarads and it was found that this affected the voltage recordings. Consequently, this divider was only used for approximate indications and voltage distribution records were made by reducing the output voltage of the R.S.G. to enable all winding voltages to be directly connected to the oscilloscope. Transferred voltage records were sometimes obtained in a similar manner, suitable calibration records being taken.

Loading resistors, for connexion across windings not under test, were of the composition type.

"Sparking" faults, that is, faults which occur when healthy insulation is ruptured by the surge voltage, can be simulated in two ways:-

(a) by the use of a synchronous relay, either electro-mechanical (Carpenter) or electronic (synchronised thyratron.)

(b) by insertion of a small spark-gap or neon gap.

The author found that the neon-gap produced a realistic type of "sparking" fault since it only broke down when the voltage stress at that point in the winding reached a given magnitude. The neon tube used by the author was fitted into a plastic insulating sleeve and permanently connected to two short flexible leads which terminated in small bull-dog type connectors.

The oscilloscope camera used by the author was made available, on loan, by the General Manager of the Sydney County Council. It was a Cossor fixed focus type with manually operated shutter and film winding. Recordings were obtained on 35 millimetre unperforated film. High speed "Triex" film (ASA rating 200) was employed for most of the experiments but a small quantity of Ilford 5B52 Non-Halation film was tried during the 3rd.Term of 1956. The latter gave good quality, fine oscillograms but was not sufficiently superior to the "Triex" film to justify importing the quantities required.

Shielded and unshielded leads of various lengths and with spade and bull-dog connector terminations were made up during the investigation. A multicore interconnecting cable between the R.S.G. and the oscilloscope was made up so that experiment time was saved by the facility of rapid changeover to display various quantities one after the other. As mentioned previously, it was essential to carry out experiments expeditiously since transformers were often available for short periods only. Fig. 11 shows the changeover switch built into the 2 kV R.S.G..

4.5.1.4: EXPERIMENTAL WINDING STACK & ACCESSORIES

The author's study of Dr. Ganger's work with an experimental winding assembly (Ref.27) convinced him that experimental results of this type were needed to develop a basic theory of the transient behaviour of currents in a transformer during an impulse test. In 1956 the author had the following equipment constructed so that he could repeat Dr. Ganger's experiments:-

(a) one experimental winding stack comprising twelve (12) bobbin type coils.

(b) one cylindrical earth screen for insertion through the centre of (a).

(c) three packets of Stalloy for insertion through the centre of (b).

The construction and characteristics of this experimental assembly are given in Section 2.2, pages 32 to 34. Figs. 12 and 14 show the physical layout and the schematic circuit of the experiments conducted with this equipment, respectively.

4.5.1.5. FULL SCALE IMPULSE TEST EQUIPMENT

During his work the author has only had very limited access to full scale test equipment. Fortunately, experience overseas enabled him to offset this to a certain degree by the study and analysis of full scale tests and experiments made by others and described in the literature.

1000 kV Impulse Generator at B.T.H. Rugby, England.

In 1950 the author was working with Mr. D. Wadland of the British Thomson-Houston Transformer Design department. He assisted in the experiments on transformers "C" and "X", the results of which are given in Sections 2.5 page 83 and 2.7, page 121 respectively. The recurrent surge oscilloscope which was employed, has been briefly described previously. The full scale test equipment comprised:-

(a) 1000 kV impulse generator.

(b) 100 kV D.C. charging unit

(c) Sphere gap/capacitance voltage divider.

(d) Auxiliary impulse generator to trigger (a).

(e) Control unit for (d).

(f) continuously pumped cathode ray oscillograph.

Fig.R. is a schematic layout of the above equipment and their interconnexion.

The 1000 kV impulse generator comprised 12 stages each of 0.2 microfarad capacity, in a six column spiral arrangement. The trigger and stage gaps were arranged vertically in the centre of the spiral and were adjusted by a pilot motor drive. The stage condensers were high voltage tested before commissioning with 130 kV D.C. for 30 seconds. The stored energy was 12 kW secs.

The keep the inductance of the generator as low as possible, sections of the tail resistor were connected across each stage. A typical resistance value of one of these sections was 360 ohms. The inductance of the generator at one megacycle

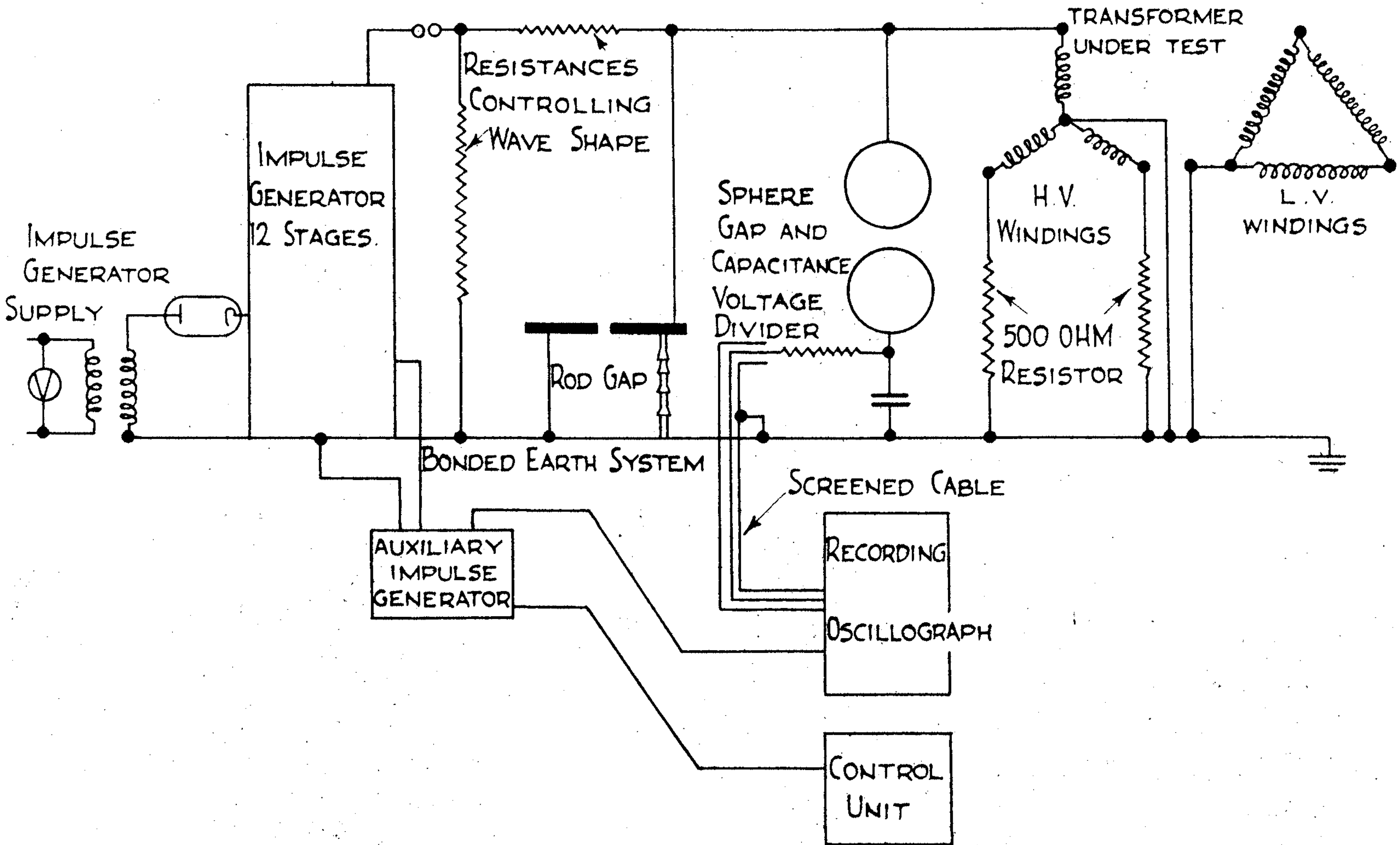


FIG. R — 1200 K.V. IMPULSE GENERATOR — B.T.H.
TRANSFORMER DEPARTMENT, RUGBY, ENGLAND.
SCHEMATIC ARRANGEMENT

2000 kV, 28 kW-sec. impulse generator of modern design to supplement the 1000 kV generator described above.

100k V Impulse Generator at Sydney County Council, Australia.

From 1953 to 1958 the author was employed as a test engineer by the Sydney County Council Electricity Undertaking. His responsibilites as second-in-charge of the Heavy Engineering section of the Testing Branch included high-voltage insulation tests. In 1952 the Sydney County Council specified impulse tests for transformers purchased and was also interested in the impulse strength of various types of cable terminations etc. used on its overhead 11kV system.

It was in connection with the latter that the author constructed a 100k V impulse generator for full scale impulse testing. The generator was commissioned in May, 1957 for tests on cable terminations, switchgear bushings etc. Since two commercial impulse generators were being built in Sydney at the time, very little money was made available for author's project and this resulted in considerable compromise in the final construction. Nevertheless several useful tests were made with the equipment and the building and operating experience was of value to the author and his testing staff.

The generator was of single stage design and utilised three high-voltage condensors, each rated at 150kV, 0.015 microfarad, in parallel. These condensors had been purchased some years ago from a hospital where they had

4.5.1.5.

formed part of the voltage doubling circuit of an early X-ray unit.

The impulse generator was initially assembled in a room at the Sydney County Council substation at Camperdown. Fig.S/1 shows the initial arrangement. The generator was arranged for charging from the S.C.C. 120kV mobile testing equipment through a charging resistance.

The condensor bank discharged through the vertical firing gap into the tail resistance. The front resistance was connected from the bottom electrode of the firing gap to the object under test. Voltage calibration was achieved with a 12.5 centimetre diameter sphere gap. Waveshape control was relatively straight forward due to the single stage construction. The basic relationship given by Craggs and Meeke (Ref.2) were employed.

The initial arrangement (shown in Fig.S/1) was employed for investigational tests on cable terminations, but was found to suffer from the following serious disadvantages:-

(a) Firing of the generator was not controlled and depended on the voltage to which the generator was charged and the firing gap setting.

(b) Excessive ionisation occurred at charging voltage over 50kV and this caused voltage variations due to the high value (20 megohms) of the series charging resistance. This, in turn, affected the firing of the generator and the gap behaviour was inconsistent.

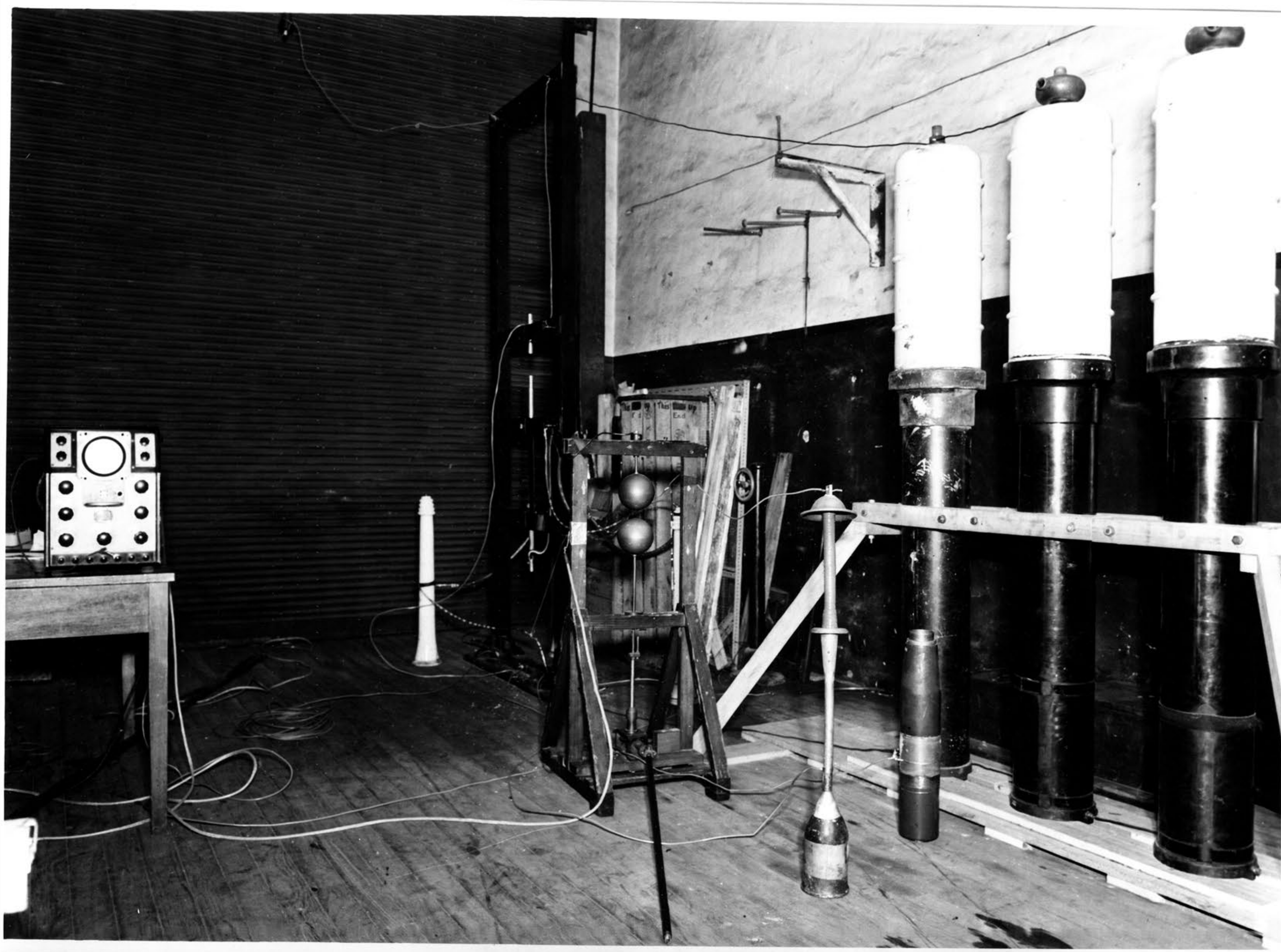


Fig.S/1 Original 100kV Impulse Generator at S.C.C.Substation,Camperdown.

(c) The low impedance output of the S.C.C. 120kV mobile testing equipment tended to produce multiple firing of the impulse generator particularly when attempts were made to improve the consistency of firing by reducing the value of the charging resistance.

(d) The construction of the charging resistance, the front resistance, the tail resistance and the resistance voltage divider was based on the uses of normal commercial composition type resistances connected in series. The resistance chain was contained in clear plastic tube. Sometimes these tubes were filled with a high voltage cable end filling Compound, Regent No. 3. Nevertheless failures of these units occurred at various times due mainly to voltage flashover along the surface of the resistance components. In the case of the front resistors it was found necessary to design for increased voltage and thermal stresses which occurred when the object under test failed or the calibrating sphere gap flashed over.

These defects provided valuable experience which led to design improvements by the author when the S.C.C. 100kV impulse generator was moved to Waverley substation for full-scale tests on Transformer "B", an 11000/110 volt voltage transformer. The re-erection of the impulse generator at Waverley substation and the commencement of full-scale tests on transformer "B" occurred during the second term of 1958.

The improved impulse generator installed at Waverley substation is shown in Fig. S/2. The test object shown is a voltage transformer but not Transformer "B".

It will be seen that although the same storage condensors and firing gap stand are employed the following improvements have been effected:

(a) High voltage connections are made with corona-free busbars comprising 4" copper tube and 6" copper spheres at joints and busbar ends. A 12" copper sphere is used at the connection point of the high voltage D.C. supply.

(b) The high voltage D.C. supply is obtained from a voltage doubler circuit consisting of a 33000/110 volt voltage transformer, a 0.05 microfarad capacitance and two selenium rectifier banks. (see diagram of connections - Fig. S/3). To reduce corona effects in the rectifier unit 2" diameter flexible connections terminating at 4" diameter spheres are used. Rectifier junctions are shrouded by 1" diameter brass spheres.

(c) Robust liquid tail resistors were employed instead of composition type resistors.

(d) The firing gap electrodes were changed from the rod type to hemispheres of 3" radius. The lower hemispherical electrode was fitted with a firing

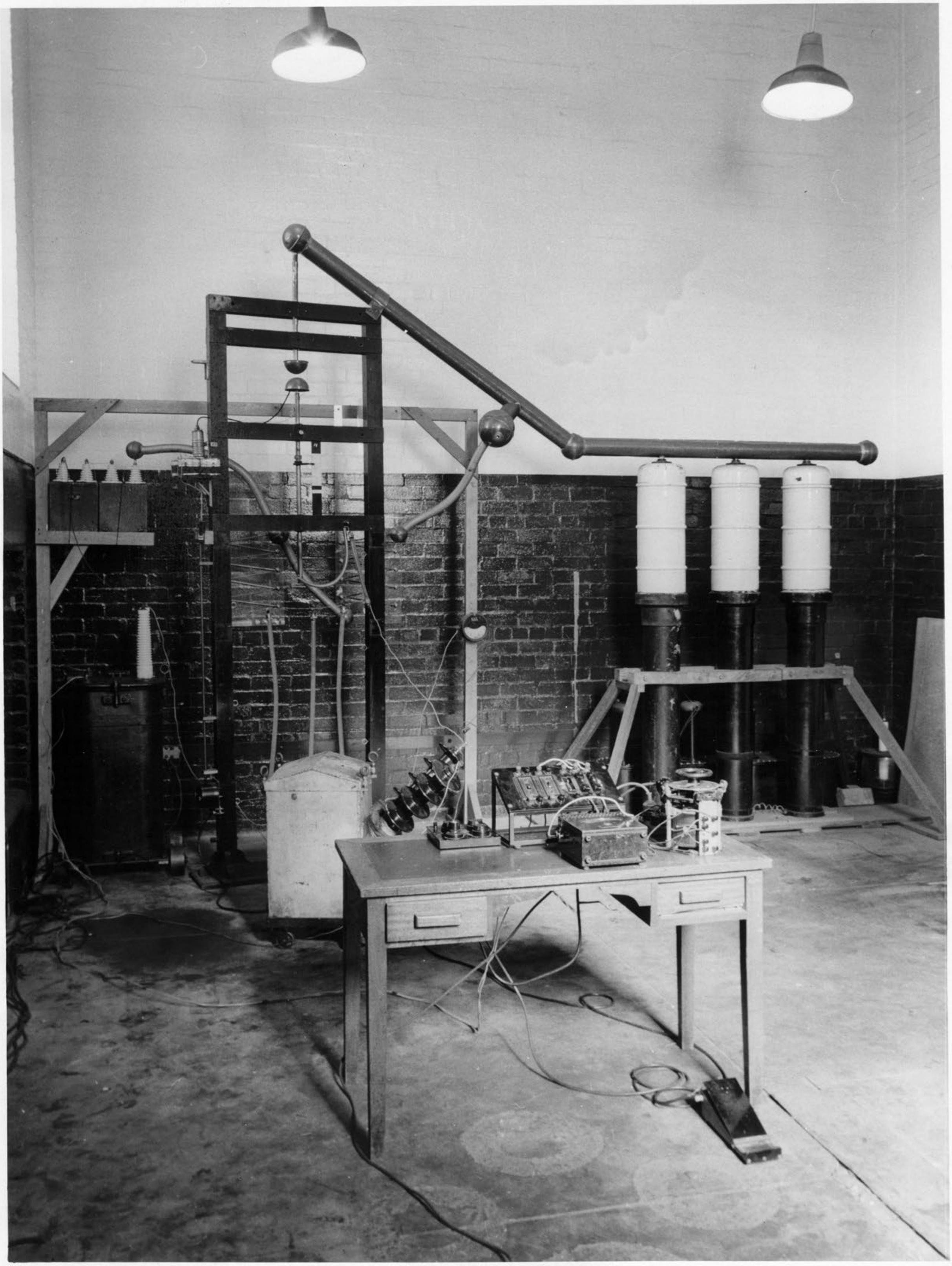


Fig. S/2. Final arrangement of 100kV Impulse Generator at S.C. Substation, Waverley.

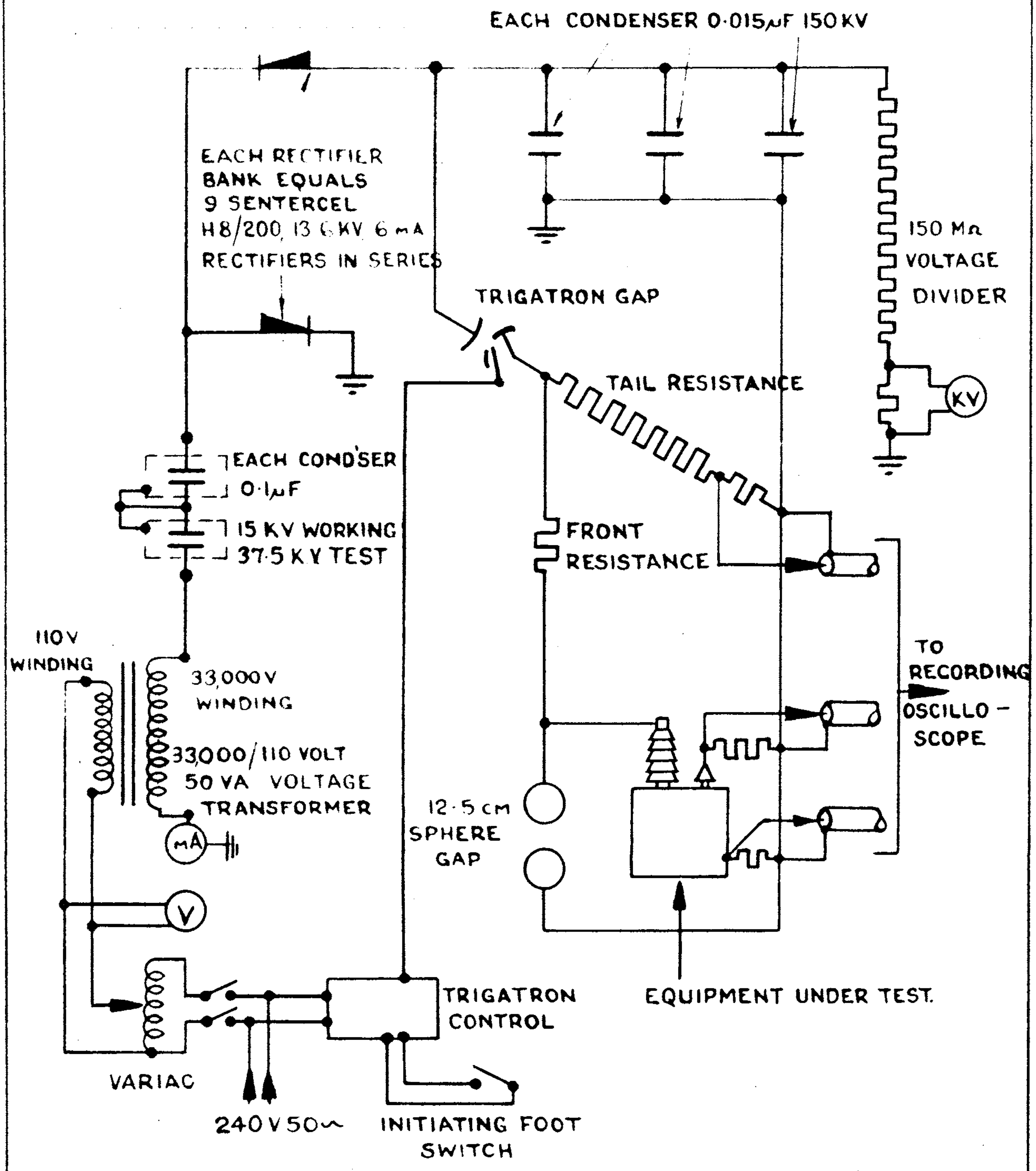


FIG: S/3 : SYDNEY COUNTY COUNCIL 100 K.V. IMPULSE GENERATOR.
DIAGRAM OF CONNECTIONS.

NOTE: SEE FIG S/4 FOR DETAILS OF TRIGATRON CONTROL CIRCUIT

(d) cont.

control electrode which was supplied from the trigatron control unit described below and the generator was fired by the foot-switch seen in the foreground.

(e) A milliammeter was connected in the earth lead of the high voltage D.C. supply unit to indicate the rate of charging of the generator.

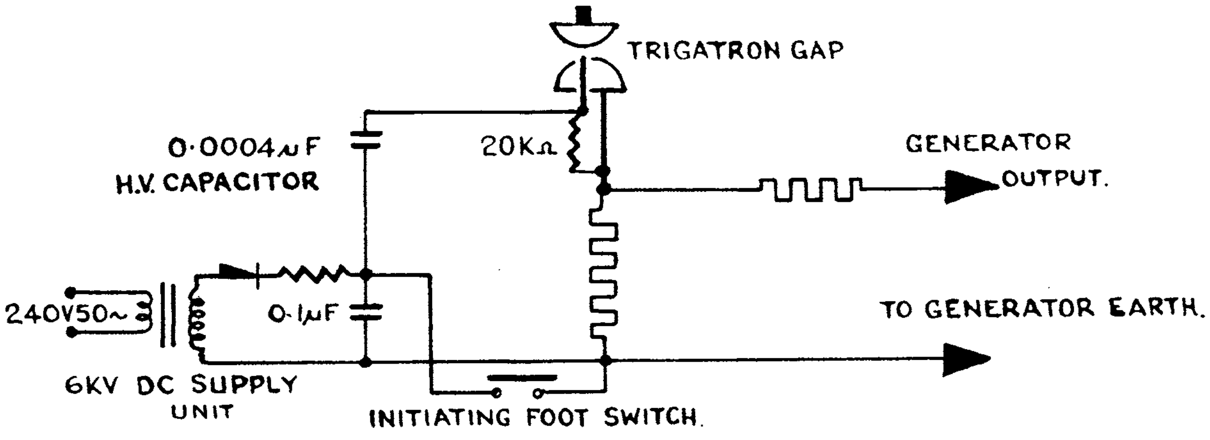
These improvements gave greater control over the operation of the impulse generator and resulted in consistent firing and satisfactory calibration of the voltage output. It was found that corona had been reduced to such a degree that a straight line relationship existed between the impulse voltage output (into a given test object capacitance) and the r.m.s. value of the voltage supplied to the 110 volt winding of the step-up transformer. This fact was established by 50/50 flashover calibration tests using the 12.5 centimetre sphere gaps, (see Fig S/1) and deriving the peak value of the impulse generator output from the sphere gap calibration given in B.S.S.358:1939, Fig. 2, page 21.

Fig S/3 shows the diagram of connections of the generator. The voltage doubler circuit used proved economical to construct and very satisfactory in operation. The two-stage voltage doubler circuit did not cause multiple firing of the generator and series charging resistances were not necessary. This also contributed to the convenient output voltage calibration mentioned above. Also several successive operations of the generator during a short period of time did not seem to overload the high voltage D.C. supply unit, presumably due to the limiting effect of the 0.05 microfarad capacitance.

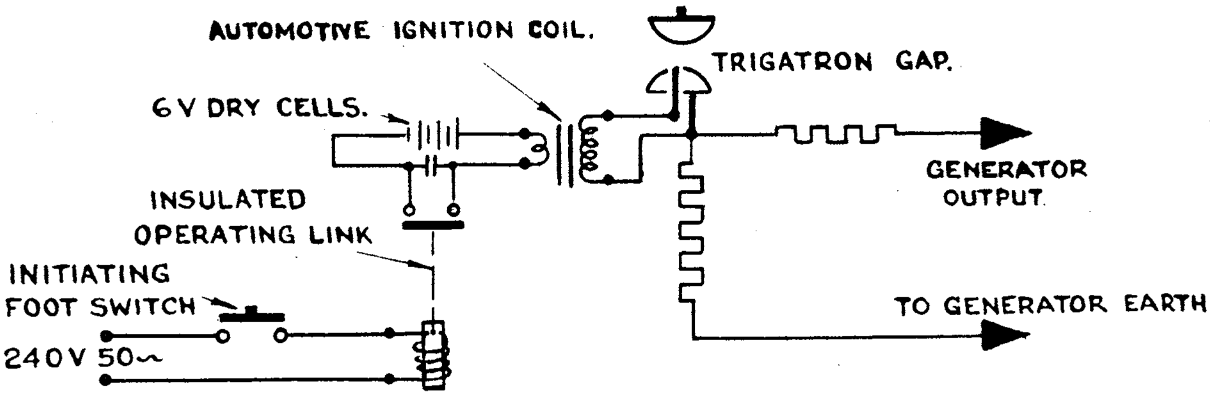
It was found that the generator capacitance was sufficiently large to allow a fixed capacitance (0.0023 microfarad) to be placed across the output so that small variations in the capacitance of the test object did not require re-adjustment of the front and tail resistances (See Section 2.5. p.77).

The trigatron gap was found to be most successful, positive firing being achieved with one gap setting for a wide variation in generator voltage. Initially the condensor discharge circuit shown in Fig. S/4 was employed. However, at high output voltages the 0.0004 microfarad capacitor failed occasionally and high voltages endangered the operator. The ignition coil circuit also shown in Fig. S/4 was then used and found very satisfactory. Control of the tripping instant was not critical since the cathode ray oscilloscope used had a four microsecond time delay line, as an integral part of its recording circuit. Oscilloscope tripping was by a voltage from a pick-up aerial.

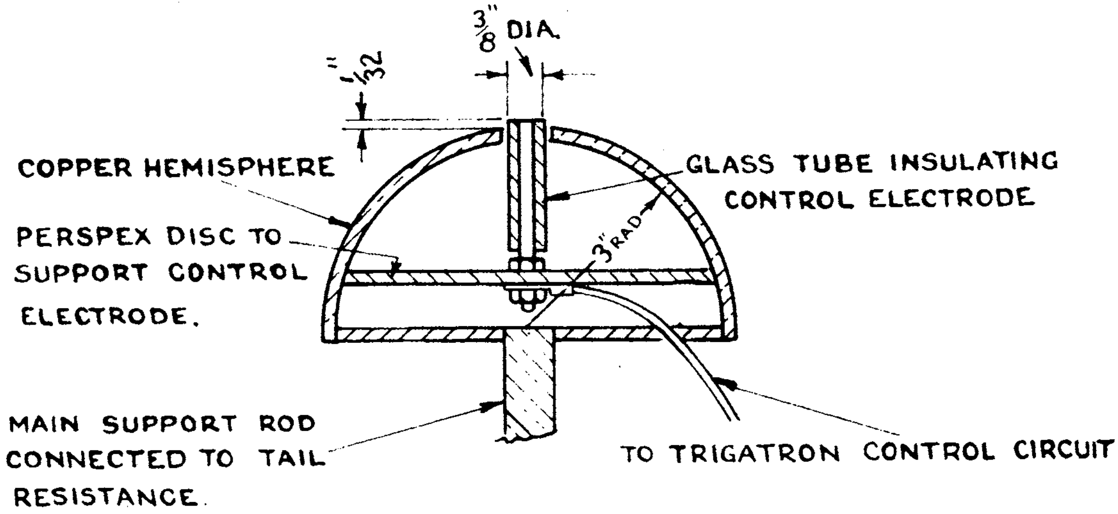
The construction of the trigatron gap electrode is also shown in Fig. S/4. It was found important to fix the glass insulating tube so that it projected slightly outside the main electrode's surface. This forced the ignition arc into the inter-electrode gap and gave positive firing.



(a) CAPACITOR DISCHARGE CIRCUIT



(b) IGNITION COIL CIRCUIT.



(c) CONSTRUCTION OF TRIGATRON GAP ELECTRODE.

FIG: S/4: SYDNEY COUNTY COUNCIL 100 K.V. IMPULSE GENERATOR.

TRIGATRON GAP FIRING ARRANGEMENTS.

The recording equipment comprised a telequipment cathode ray oscilloscope containing integral delay line and pulse brightening features. To reduce interference the recording equipment was housed in a steel framed 5 foot cube room with galvanised wire mesh covering the walls, floor and ceiling. It was supplied at 240 volt A.C. from a battery driven motor-alternator which was contained, with the batteries, in the screened recording room. The screened co-axial recording leads were the only connections to the recording room. These leads were taken through conduits under the floor to the recording shunts in the test area.

The recording room was positioned approximately fifteen feet from the impulse generator firing gap. However considerable interference occurred during the first 60 microseconds when testing transformer "B" (Section 2.5. page 76). The author feels that the open mesh screening used was not sufficiently dense and would employ a heavy gauge, low resistance mesh in future.

4.5.2 FUNDAMENTAL BEHAVIOUR OF TRANSFORMER WINDING CURRENTS DURING IMPULSE TESTING.

The experiments intended to clarify and support the author's theoretical study fall into three groups:

(a) The effects of winding parameters.

(b) The currents which flow.

(c) The voltage conditions created.

Also these groups can be dealt with separately for the two test conditions, namely,

1. Full wave tests

and

2. Chopped wave tests.

The author did not have the equipment, or the opportunity to make his own experiments concerning chopped wave tests conditions. In his analysis he relied entirely on direct discussion with, or reading of the results of, overseas experiments, notably Thomas, Rippon, Hickling and Provoost. These results are referred in detail in Section 2.3.2., p.49.

In July 1955, the author wrote to Dr.T.J.Lewis, Queen Mary College, London University, concerning the mathematical derivation of the neutral current.due to the application of unit function voltage, i.e. full wave test, (Ref.9). Dr. Lewis replied that he was not now working on the subject, and found it difficult to formulate an up-to-date reply to queries regarding the derivation of the neutral current, and the equivalent self-inductance paramater. However, he was kind enough to contact a colleague, Mr.A.W. Hough-Grassby, of the Electrical Research Association, who indicated the general approach to the solution of the neutral current solution. He indicated that the solution would be a summation of sinusoidal components similar to the voltage equation derived by Lewis (Section 1.2,p.9). The author could not readily solve this mathematical problem even though he sought the assistance of others, and, in any case, it was now obvious that an expression of this type would not yield qualitative or quantitative values of fault sensitivities. Therefore, greater emphasis was placed on obtaining experimental results, analysing them and comparing them with observations of others working along similar lines.

Study of Dr. Ganger's work as presented to the 1954 C.I.G.R.E. at Paris (Ref.27; Section 1.3, p.15) showed the author the value of developing an empirical theory of the transient behaviour of transformer winding currents, using as tools the recurrent surge generator and an experimental winding stack comprising three components, namely, a stack of coils, a metallic surface to simulate the tank and a stalloy core.

In August 1956, the author designed and had built, such an experimental winding, using bobbin type coils from a damaged 200kVA distribution transformer. The design of this equipment is described in detail in the thesis (Section 2.2,p.32). During August 1956 he carried out preliminary experiments on several loose bobbin coils using the experimental recurrent surge generator at a Sydney County Council Testing Laboratory. These experiments indicated the main requirements to be met by the final design.

In September 1956 the 2kV recurrent surge generator was finally commissioned, and the author employed it for experiments on the experimental winding stack at the Sydney County Council Testing Laboratory. These experiments continued into October 1956, when the author started using a neon gap to simulate insulation breakdown. These artificial "sparking" faults were found to demonstrate the propagation of voltage stresses through the winding and the sensitivity of the tank current to this type of fault.

Two experiments to clarify the effect of the inductive parameters were carried out in 1957, namely:

<u>August 1957</u> - 100 cycle per second impedance test on a 200kVA three phase transformer with and without one shorted turn. (Section 2.3.1, p.46 refers).

<u>October 1957</u> - 1000 cycle per second measurements of the inductance of portions of the experimental winding using a G-R bridge (Section 2.3.1, p.35 refers).

These experiments, which are described in detail in the thesis, were particularly relevant to:

(a) The effect of frequency upon mutual coupling between portions of the winding.

(b) The empirical relationship used by Abetti and Maginnis (Ref.13,35) in their approach to the mathematical derivation of the transient behaviour of the transformer winding.

Also during 1957, the author continued recurrent surge experiments with the three components of the experimental winding stack. These experiments were eventually narrowed down into a programme, the oscillographic results of which supported the author's empirical theory of the fundamental behaviour of transformer winding currents. This programme of experiments is described in detail in Section 2.3.1, p.35 and the diagram of connections is shown in Fig.14. These experiments were to form the main portion of a recurrent surge demonstration at a meeting before the Institution of Engineers, Australia-Sydney Division, on 26th March 1958. The demonstration equipment is shown in Fig.12 of the thesis. During the discussion on the paper, it was acknowledged that the demonstration had been effective in illustrating the basic relationship concerning transformer winding currents under full wave test conditions. Further details of the demonstration are given later in Section 4.5.4 of this appendix.

The author also studied the results obtained by overseas experimenters, as they applied to the full wave test behaviour, notably Ganger (Ref.27) and Waldvogel and Rouxel (Ref.37).

The voltage conditions created in the winding due to the application of a full wave impulse voltage are primarily a matter for transformer designers. However, the test engineer requires an appreciation of the voltage conditions in order that he may employ the correct test connections and fault detection methods.

The author measured voltages at various points in the experimental winding during the 1957 programme mentioned above.

The voltages had to be connected directly to the cathode ray plates so that the effects of additional shunt capacitance were minimised. The method and the results are described in Section 2.3.1, p.47.

Further voltage distribution experiments were conducted in July 1958 on a 11000/110 volt 3 phase voltage transformer (transformer "B") and a 10,000/415 volt 200kVA distribution transformer. However, since the results of these experiments were used mainly in that portion of the thesis dealing with "Test Connexions" (Section 2.4,p.58), the details of the experiments are given below in Section 4.5.3 of this appendix.

The results did show good correlation with the theoretical analysis of Part 1 of the thesis, which was based mainly on the work of Lewis (Ref.9) and Norris (Ref.17). The intercoil voltages determined for transformer "B" are given oscillygraphically in Appendix 4.4 and show the progression of the peak value through the winding.

The intercoil voltages of transformer "B", which were determined by the recurrent surge experiment carried out before the full scale tests, revealed a design weakness in the prototype transformer. A rearrangement of winding leads and connections was made to reduce the possibility of flashovers across the first bobbin coil.

4.5.3 TEST CONNECTIONS

During 1950 whilst working at the B.T.H. works, England, under Mr.D.Wadland, the author learnt the importance of the correct test connections. At that time he was only aware of two aspects, namely:

(a) The need to check that the voltages transferred to windings not under test will not be excessive during the full scale impulse test.

(b) That the maximum fault detection sensitivity is obtained having regard to (a) above and the need to simulate service conditions as closely as possible.

Later in his work, the author realised that two other factors could affect the voltage conditions in the winding under test, namely:

(c) Whether or not the remote terminal is connected to earth.

(d) Whether or not other windings are short-circuted or shunted by a loading resistance.

The author made a practice of measuring the transferred voltage, whenever it was possible, during fault detection experiments made in Sydney from 1954 to 1958. The details of these experiments and the experimental connections used are described in Section 4.5.4 of this Appendix. It will be seen that oscillographic records were obtained using recurrent surge techniques. The transferred voltage was connected to a Cossor Oscilloscope, either directly to the vertical deflection plates or via a voltage divider. The results obtained are summarised and analysed in Section 2.4 of the thesis (Table 2,p.60).

The magnitude of the transferred voltage in each case was determined by measurement of the applied voltage and transferred voltage oscillograms and making due allowance for the ratios of the respective voltage dividers. The transferred voltage was then expressed as a percentage of the applied voltage.

In November 1956, the author carried out recurrent surge experiments on transformer "R", a 500 kVA, 10,000/415 volt distribution transformer to determine the effect, on fault detection sensitivity, of short-circuiting other windings. The connections used are as shown in Fig.B (See Section 4.5.4 of this Appendix), except for the value of theneutral current shunt. The experiments were conducted at the S.C.C. transformer overhaul depot, Pyrmont.

The core and windings were standing in air for the experiments. Composition resistors were used for the neutral current shunts which were:

200 ohm for LVLwinding not shorted.

50 ohm for L.V. " shorted.

Due allowance was made in the calibration of the vertical current scales of the oscillograms, which are shown in Fig.21 (a). An artificial single turn solid fault was made, at X = 5% from the line terminal, by wrapping a turn of conductor around the winding stack and shorting it as required.

A double exposure was used so that the "no-fault" and "solid single-turn fault" neutral current waveforms appeared superimposed on the one oscillogram (see Fig.21(a)).

The results of these experiments are analysed in Section 2.4 of the thesis, p.65.

During his revision of the impulse testing specification used by the Sydney County Council (see Section 2.5, p.71) the author had to consider the reasons for earthing the remote terminal of the winding under test. Study of the mathematical analysis of the effects of short circuits between turns, which was made by Heller, Hlava and Veverka (Ref.40), also indicated the continental practice may allow full scale tests with the remote terminal not earthed (see Section 1.4,p.23). The author's transformer design experience indicated that the voltage conditions would then be less onerous and to prove this he carried out voltage distribution experiments on transformer "M", a 200 kVA, 10,000/415 volt, delta-star transformer in July 1958.

The experiments were conducted at the S.C.C. transformer overhaul depot with the core and windings out of oil. The 2kV recurrent surge generator was used and the test connections were as shown in Fig.U.

The output of the recurrent surge generator was reduced to approximately 140 volts so that the voltage appearing at various points in the winding could be directly connected to the vertical deflection plates of the oscilloscope. This kept the shunt capacitance due to the measuring equipment to a low value. Multiple exposures of the oscilloscope camera produced a composite oscillogram of the voltage conditions in the winding (see Section 2.4, page 58).

The same technique was employed in the experiments made on transformers "B" and "M" to determine intercoil voltages and the effect of shunting other windings (Section 2.4,page 62). The experiments were made in July 1958.

The oscillograms were enlarged so that quantitative

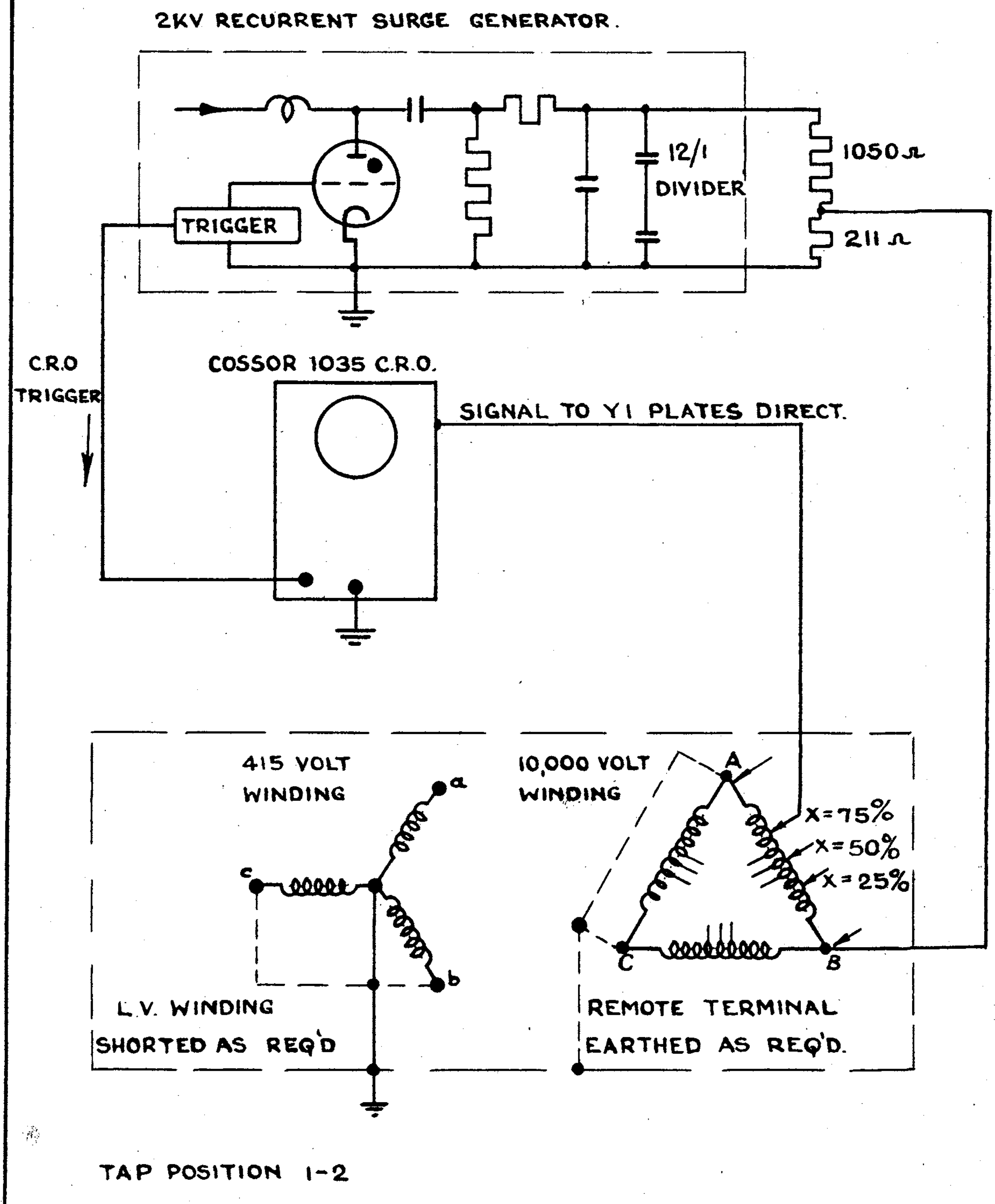


FIG. U:- VOLTAGE DISTRIBUTION EXPERIMENTS ON TRANSFORMER "M" — DIAGRAM OF CONNECTIONS —

measurements could be made. The intercoil waveforms given in Appendix 4.4 were derived in this manner.

4.5.4 EXPERIMENTS ON VOLTAGE, DISTRIBUTION AND POWER TRANSFORMERS.

This section of the Appendix describes, in a chronological order, the experiments not already described in Sections 4.5.1, 4.5.2 and 4.5.3

In Part 2 of the thesis experiments have been described in general terms without details of procedure, time or location. Only sufficient information has been given for the full significance of the results to be appreciated in the light of the detailed analysis given by the author for each experiment. This log of experiments provides details of procedure and technique equipment used, and the time and location of the experiment, but does not present again or analyse the results which are given in Part 2 of the thesis. A cross-reference is given to those results in each case.

1950

The first work by the author in this field was carried out in 1950, whilst he was serving a graduate apprenticeship to the British Thomson-Houston Company Limited, Rugby, England. At the time he was in the Transformer Design Department, working under Messrs. H.L. Thomas and D.McDonald on the impulse strength of transformers. He studied various methods of determing the initial voltage distribution in a transformer winding when unit function voltage is applied. These methods included

(a) derivation of the equivalent capacitance network (see Appendix 4.2), and subsequent analysis on a resistance type analogue computer,

(b) electrolytic tank analysis of transformer winding models using the wedge-shaped electrolyte method. The author assisted Mr.D.McDonald in the commissioning of a large electrolytic tank for this work.

The author's observations concerning the impulse strength design of transformer windings were fully described later, in a paper before the Institution of Engineers, Australia (see "1952").

The full-scale and recurrent surge impulse testing required for checking impulse strength design calculations was carried out by Mr.D.Wadland of the B.T.H. Transformer Department. Whilst the author was assisting Mr.Wadland, experiments were made on transformers "C" (220kV voltage transformer) and "X" (40,000kVA 67/22kV transformer).

The experiment on transformer "C" is described in Part 2 of the thesis, Section 2.5,p.83. The single phase 220,000/110 volts voltage transformer had two identical low voltage windings. Mr. Wadland was investigating the possibility of using a transferred voltage record for fault detection, and all records taken were only of the line and transferred voltages. Good correlation was proved between the full scale and the recurrent surge oscillograms.

Although the full scale records were obtained by direct connection from a suitable voltage divider to the 1000 volts continuously evacuated oscillograph, an amplifer was used before applying the corresponding recurrent surge quantity to the recurrent surge oscilloscope. This amplifer, which was normally set for a gain of 200, is shown in Fig.V which relates to the experiments on transformer "X".

The experiment on transformer "X" is fully described in Part 2 of the thesis, Section 2.7, p.121.

This transformer was to be stripped following an insulation failure in service. This meant that a wide range of artificial faults could be applied and the oscillographic indications studied with the aid of the 250 volt recurrent surge generator. The author assisted Mr.Wadland in these experiments.

Fig. V gives a schematic diagram of the connections used in this experiment. All recording leads were shielded. The output surge of the recurrent surge oscilloscope had a peak value of 250 volts.

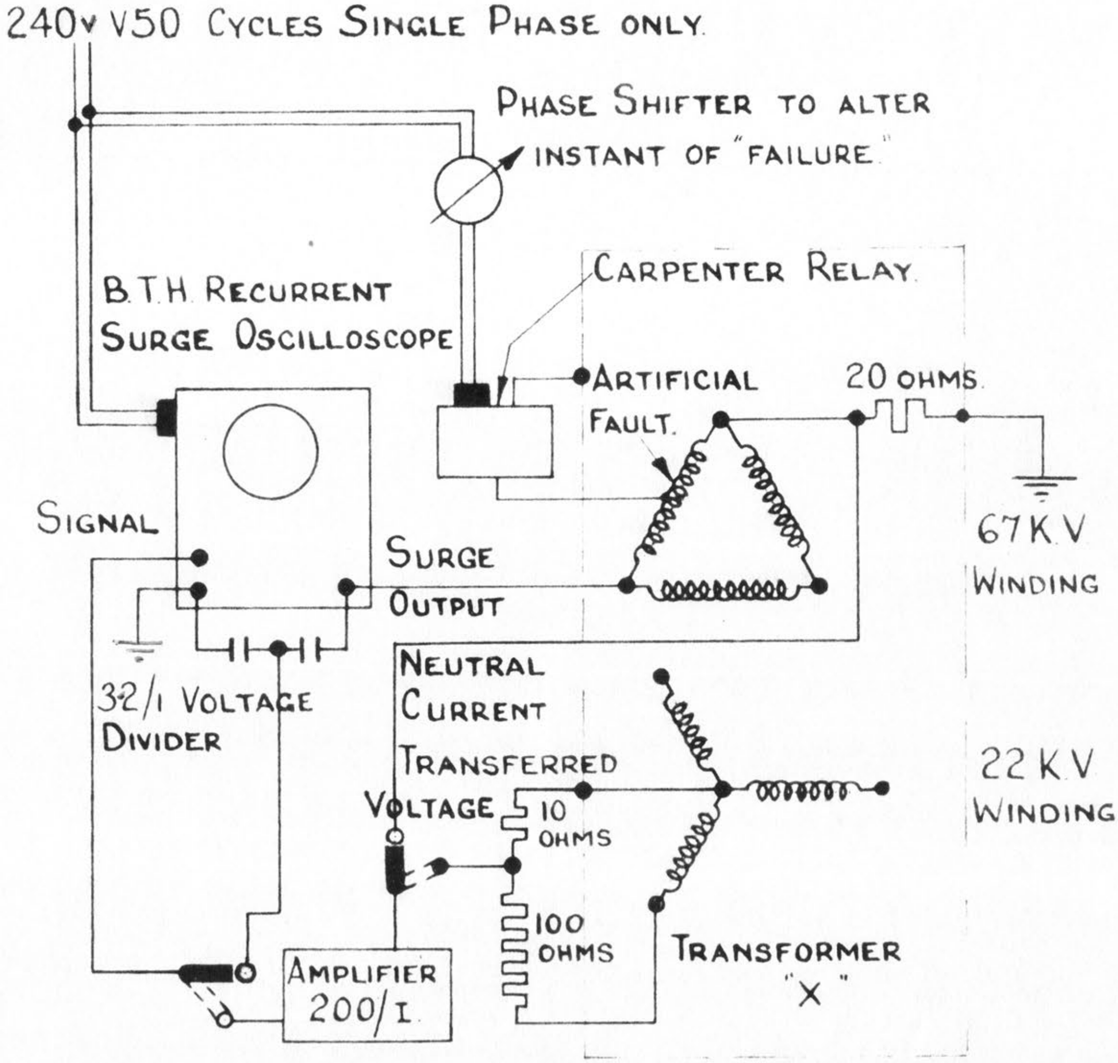


FIG."V".

SCHEMATIC CIRCUIT OF FAULT DETECTION EXPERIMENTS ON 40 MVA 67/22 KV. TRANSFORMER ("X") AT B.T.H. WORKS. ENG.

NOTE: WHEN THE 22 K.V WINDING WAS SHORTED THROUGH 5 OHMS. THE RESISTANCE OF THE NEUTRAL CURRENT SHUNT HAD TO BE REDUCED TO 2·5 OHMS.

DATE OF EXPERIMENT
21·4·50.

1951

During the first few months of 1951, the author was working in the Power System Engineer's Department under Dr.J.R.Mortlock, at the British Thomson-Houston Switchgear works, Willesden, London NW10. This work included mathematical and experimental investigations of transient phenomena. One experiment dealt with the transient voltage distribution over cascaded transformers to be employed at a short circuit testing station. Electrical models of the transformers were employed and measurements made with both the recurrent surge oscilloscope, and the restriking voltage indicator. The latter instrument operates on a similar principle to the recurrent surge oscilloscope except that it injects a current surge of linearly increasing magnitude. By the principle of superposition this simulates current interruption and the transient voltage appearing at the point of injection is the restriking voltage component.

Surge reflection analyses were also made using a lattice model with coloured lines (actually wires between pins) for clarity. The work under Dr. Mortlock provided further experience for the author to draw upon when he started to carry out the investigation described in this thesis. The author also inspected the 1400kV, 17.5kW Sec. ladder type impulse generator used at the works for switchgear insulation testing.

For the greater portion of 1951, the author was employed as a junior design engineer by A.Reyrolle and Company, Hebburn-on-Tyne, England. He was principally concerned with the design of high voltage switchgear up to 275KV air blast types. An opportunity presented itself to carry out further work using the electrolytic tank technique for the analysis of electrostatic fields. This work is fully described in an article in the "Electrical Times" dated 24th January 1952, and entitled "Electrolytic Field Analysis".

During this year the author had the opportunity of discussing fault detection problems with Messrs. E.C. Rippon and G.H. Hickling at the Heaton Works of C.A. Parsons Company Limited. Mr. Rippon informed the author of possible developments in chopped wave impulse testing and supplied the oscillograms shown in Fig.17 of the thesis and discussed in Section 2.3.2 - "Behaviour under chopped Wave Test Conditions" (p.49).

A 2250 kV 14 kw-sec. column type impulse generator was erected at the Hebburn works of A. Reyrolle and Company during this year, but the author did not have time to make a close study of its construction and operation. Experience gained by the author in the short-circuit testing station and the power-frequency high voltage laboratory proved of value later. The short-circuit testing techniques are similar to those employed in impulse testing due to the short duration of the test, the need for accurate interpretation of the oscillographic records, and the possibility of a failure which cannot be conveniently repeated.

The author also visited the Ferranti works at Hollinwood, and the English Electric works at Stafford during this year. At each place he was afforded every assistance to study developments in high voltage transformer design and to inspect the impulse testing laboratories.

1952

Just prior to leaving England early in 1952, the author again visited Ferranti, Metropolitan-Vickers and the British Thomson-Houston Company, and discussed developments in transformer design and inspected the impulse testing installations. At the time the author was preparing a paper for presentation before the Institution of Engineers, Australia, on his return to Australia.

On arrival in Melbourne in April, 1952, the author took the opportunity to visit the impulse testing laboratory of the State Electricity Commission of Victoria. The author had previously visited this laboratory in 1949, but with his overseas experience he was now in a better position to appreciate developments at this laboratory.

The author took up duties again with the Sydney County Council in April, and carried out system analysis work for the greater part of the year.

In August he inspected the high voltage testing facilities available at the University of Sydney.

During the year the final work was done on a paper, entitled "Developments in British Transformer Design and Manufacture", which the author then submitted to the Institution of Engineers, Australia.

1953

In May and October of this year, the author presented his paper "Developments in British Transformer Design and Manufacture" before the Sydney and Melbourne Divisions respectively, of the Institution of Engineers, Australia. Approximately one hundred copies of the paper were circulated before each meeting, and copies of the discussions were later forwarded to the British transformer manufacturers who had assisted the author to prepare the paper.

Four sections of the paper were to prove very relevant to the present work. These sections were:

"ELECTROLYTIC FIELD ANALYSIS"

An introduction to and description of the technique and its application to design of high voltage equipment.

"INSULATION STRENGTH DESIGN"

This section dealt with "Power Frequency Voltage Stresses" abd "Impulse Voltage Stresses" separately.

The latter subsection was divided into:

Theoretical Basis.

Methods of Stress Analysis.

Methods of Providing Impulse Strength.

The author dealt thoroughly with the various aspects of this subsection, and this work proved of great value to him when he was preparing this present thesis.

"INCREASE IN TEST PLANT CAPACITY"

In this section the author dealt with Impulse Generators, Power Frequency Test Plant, and Special Testing Arrangements. The subsection dealing with impulse generators described the general trends in generator design and the reasons for these trends. Even at this stage, the author was able to confidently state the need for recurrent surge facilities at every transformer impulse testing installation.

"IMPULSE TESTING AND FAILURE DETECTION"

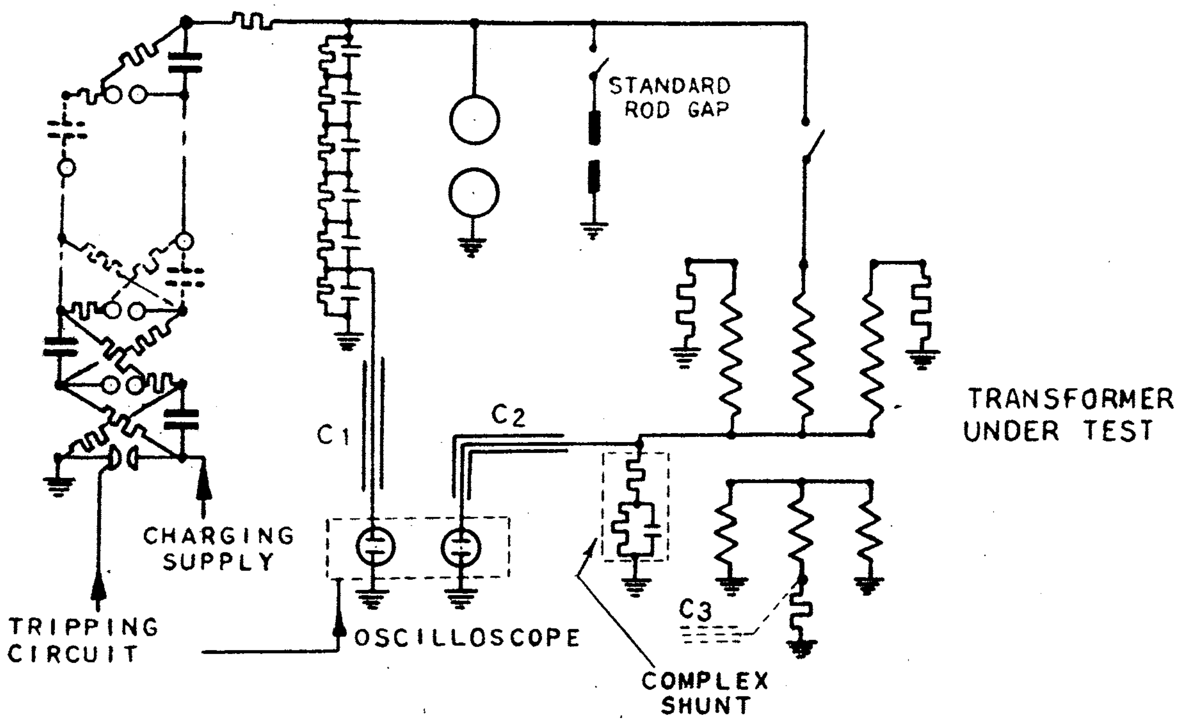
Once again an overall picture of British practice was given and Fig.15 of the paper showed the correlation between the high voltage testing arrangement, and the corresponding arrangement for recurrent surge application. This illustration is reproduced herein as Fig.W.

General indications of failure as recorded on oscillograms of applied voltage, neutral current and transferred voltage, were summarised.

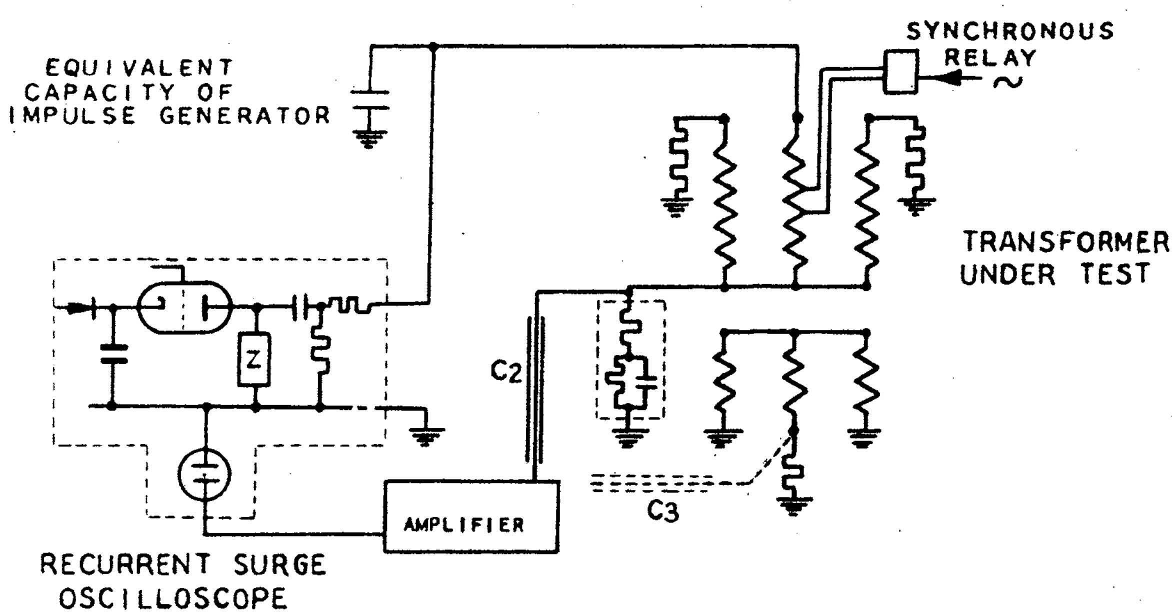
This present thesis is basically an amplification of this section of the author's 1952 paper. It does not try to cover also the wide field of impulse strength design of transformer windings, or even the design of impulse generators and accessories.

Early in the year the author was appointed second-in-charge of the Heavy Engineering Section of the Sydney County Council Testing Branch. His responsibilities now included the high voltage testing of switchgear, cables and transformers.

In August the author inspected the impulse generator operating at that time, at 210KV peak at the University of



(a)



(b)

FIG. W TRANSFORMER IMPULSE TESTING AND OSCILLOGRAPHIC FAILURE DETECTION TECHNIQUES.

(a) HIGH VOLTAGE IMPULSE TESTING ARRANGEMENT

(b) CORRESPONDING ARRANGEMENT FOR RECURRENT-SURGE APPLICATION

Queensland. Discussions were held with Professor Prentice and Dr. Parnell.

In October the author once again visited the impulse testing laboratory of the S.E.C.(Vic) at Yarraville and discussed various aspects with Mr. Saunders.

In November the author was registered as a part-time candidate for a Master of Engineering degree of the University of Technology and, with the permission of the General Manager of the Sydney County Council, he commenced the investigation described herein. The work was mainly done outside normal hours with equipment on loan from the University or The Sydney County Council.

1954

The major portion of this year was occupied by the author constructing the experimental recurrent surge generator and preparing a specification to assist Mr. Dewscrap in the design of the final 2KV recurrent surge generator. This work has been described earlier in the log (Section 4.5.1).

In April the author attended a demonstration of the recurrent surge oscilloscope experiments being made at the B.G.E.(E.P.M.) works at Waterloo, Sydney, for transformer impulse strength design purposes.

In October the author carried out his first independent experiment, on transformer "P", a 500 kVA 10,000/415 volt delta/star, bobbin/layer transformer, using the experimental recurrent surge generator. The experiment was made at the Tyree Electrical Works, Kingsgrove. Fig. X shows circuit used for the experiment. The Oscillographic results were recorded using the 35mm fixed focus camera. Severe halation occurred at the start of each trace, since no trace brightenings facility had yet been provided/ The results are analysed thoroughly in the thesis - section 2.6, page 95.

The experiment was restricted due to the fact that the core and windings could not be removed from the tank, and artificial faults had to be applied to the tapping leads. Nevertheless the experiment confirmed the author's overseas experience, indicated the need for improved recording technique, and provided the first portion of the large amount of experimental data needed.

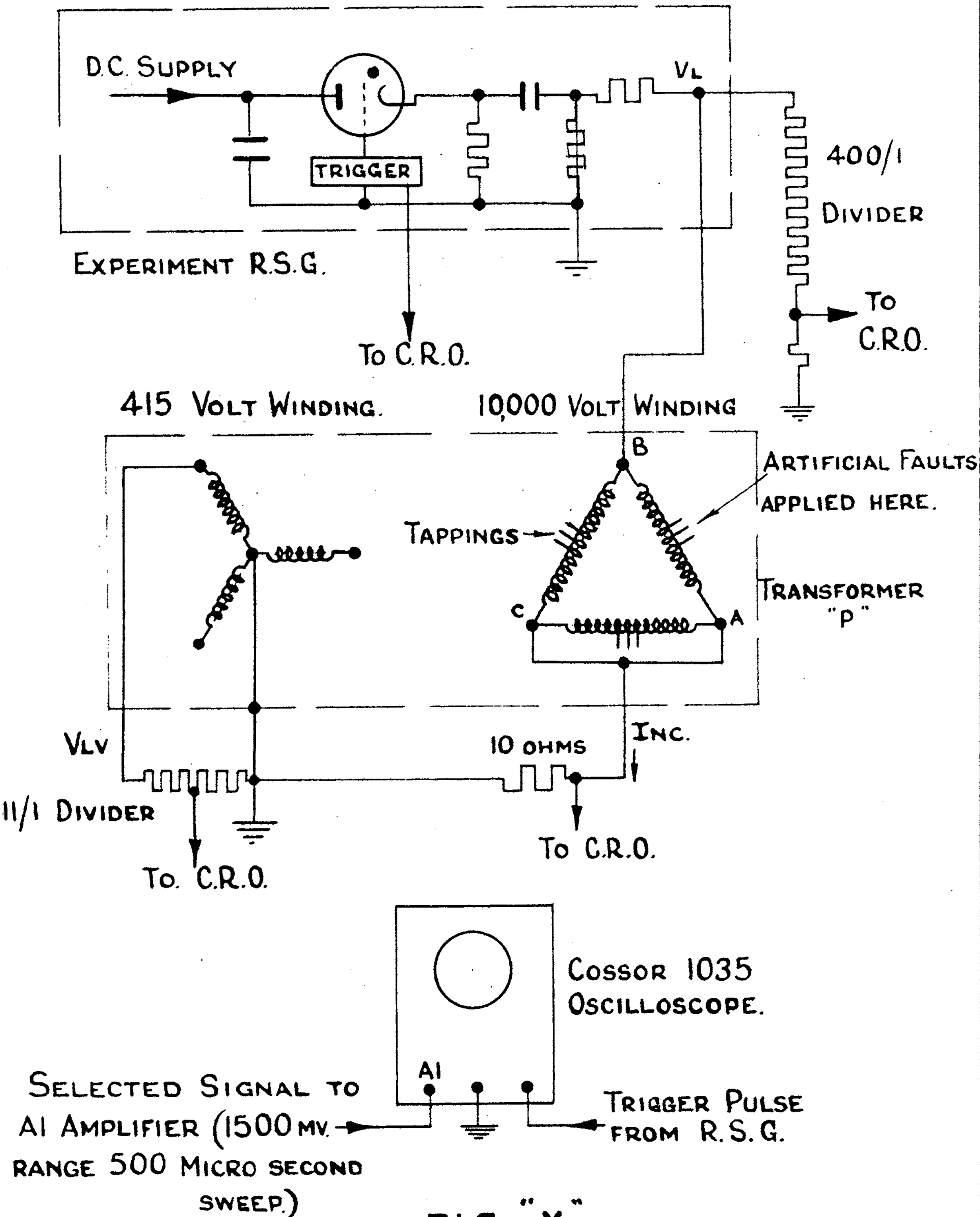


FIG. "X".

CIRCUIT USED FOR EXPERIMENT ON TRANSFORMER "P".

In November and December the author had another opportunity to carry out valuable experiments at the Tyree Electrical Works. The experiments were made on transformer "Q". a 500 kVA, 10/0.415 KV delta-star, disc-layer unit.

The experiments were made using the experimental recurrent surge generator. Initially the test connections were as shown in Fig. Y(a), but these were later changed to those shown in Fig. Y(b) so that measurements of line current could be made. The transformer was placed on wooden blocks to insulate the tank from earth.

The results of the experiments are given, and analysed in Section 2.6 of the thesis, page 99. At this stage the author was checking, for himself, the value of recording transferred voltage and line current, quantities favoured at that time by Mr. Wadland, B.T.H. and Stenkvist (Ref.6) respectively.

These results also assisted the author in his study of the basic behaviour of transformer winding currents although at this time he was not able to completely analyse the oscillograms.

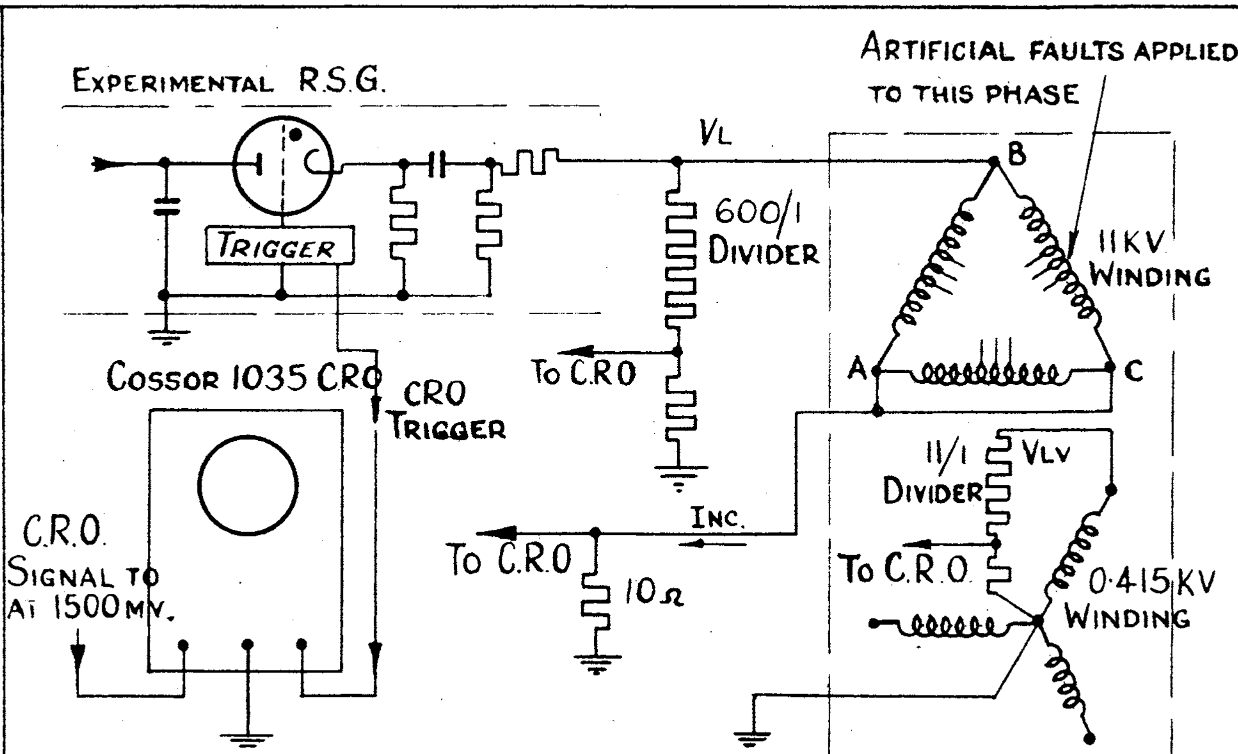


FIG. Y. (a)

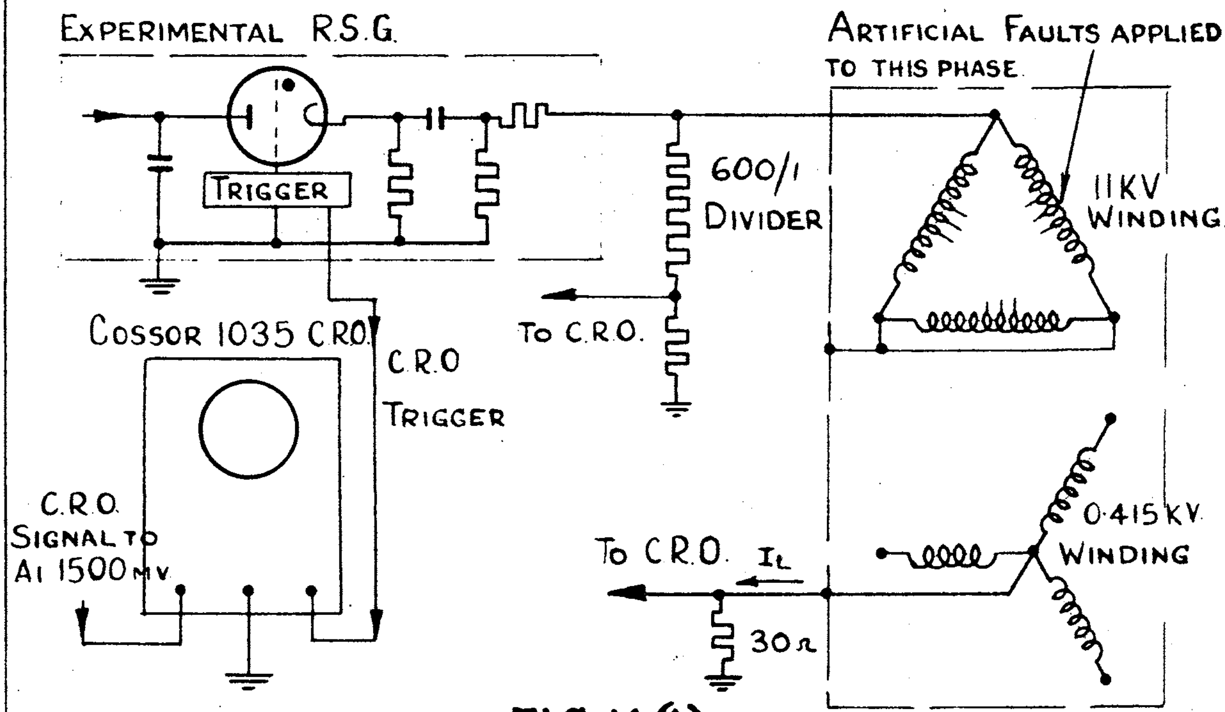


FIG. Y. (b)

FIG. Y.

EXPERIMENTS ON TRANSFORMER "Q" AT TYREE ELECTRICAL WORKS DEC. 1954.

TEST CONNECTIONS FOR :-

(a) NEUTRAL CURRENT & TRANSFERRED VOLTAGE RECORDS

(b) LINE CURRENT.

1955

The intensive study of the theoretical aspects of the subject continued during this year. Some of the questions facing the author at this time, and which he logged in his 1st Term, 1954, progress report to Professor Vowells, were:

(a) When impulse testing delta-connected windings what is the best method of connection if only two transient recorder channels are available?

(i) The method must indicate what type of fault has occurred and in which phase.

(b) Why does the neutral current reverse sign when flash-over to earth occurs?

(c) Why does the line current retain the same polarity under similar conditions?

(d) Does the magnitude of the line current tell where a flash-over to earth has occurred?

(e) What change occurs in the sensitivity of the Neutral Current or Line Current method when the low voltage windings of a distribution transformer is shorted instead of being left open.

In July of this year the author was priviliged to have a discussion with Dr. Parnell at Queensland University where some distribution transformers had been subjected to full scale tests. These transformers were rated at less than 50kVA and the fault indications, even for quite severe faults, were not as great as the author had obtained with larger transformers. Dr. Parnell had some interesting indications of the location of a severe fault, from oscillations appearing superimposed on the applied voltage waveform. However, the magnitude of these indications is dependent on the impedance of the impulse generator, and the author did not find this type of indication sensitive enough to be reliable (See Section 2.9, p.136).

Difficulties encountered concerning access to suitable transformers restricted the author's recurrent surge experiments to a single comprehensive series on transformer "N", a 200 KVA, 33/11KV, delta-star, bobbin-layer unit. These experiments were carried out in August at the Tyree Electrical Works before the transformer was shipped to Queensland University for full scale design tests. A large number of records were taken and arranged in such a way that they could be used in setting up for the full-scale tests.

The test connections for:

(a) Surge applied to 33KV winding

and

(b) Surge applied to 11KV winding

are shown in Fig. Z(a) and Fig.Z(b) respectively. The experiments were conducted with the core and windings in the tank under oil.

A full description of the experiments is given in Section 2.6, p.88 and the results analysed. This description also refers briefly to the two faults which occurred during the full scale tests, at test voltages greater than the acceptance

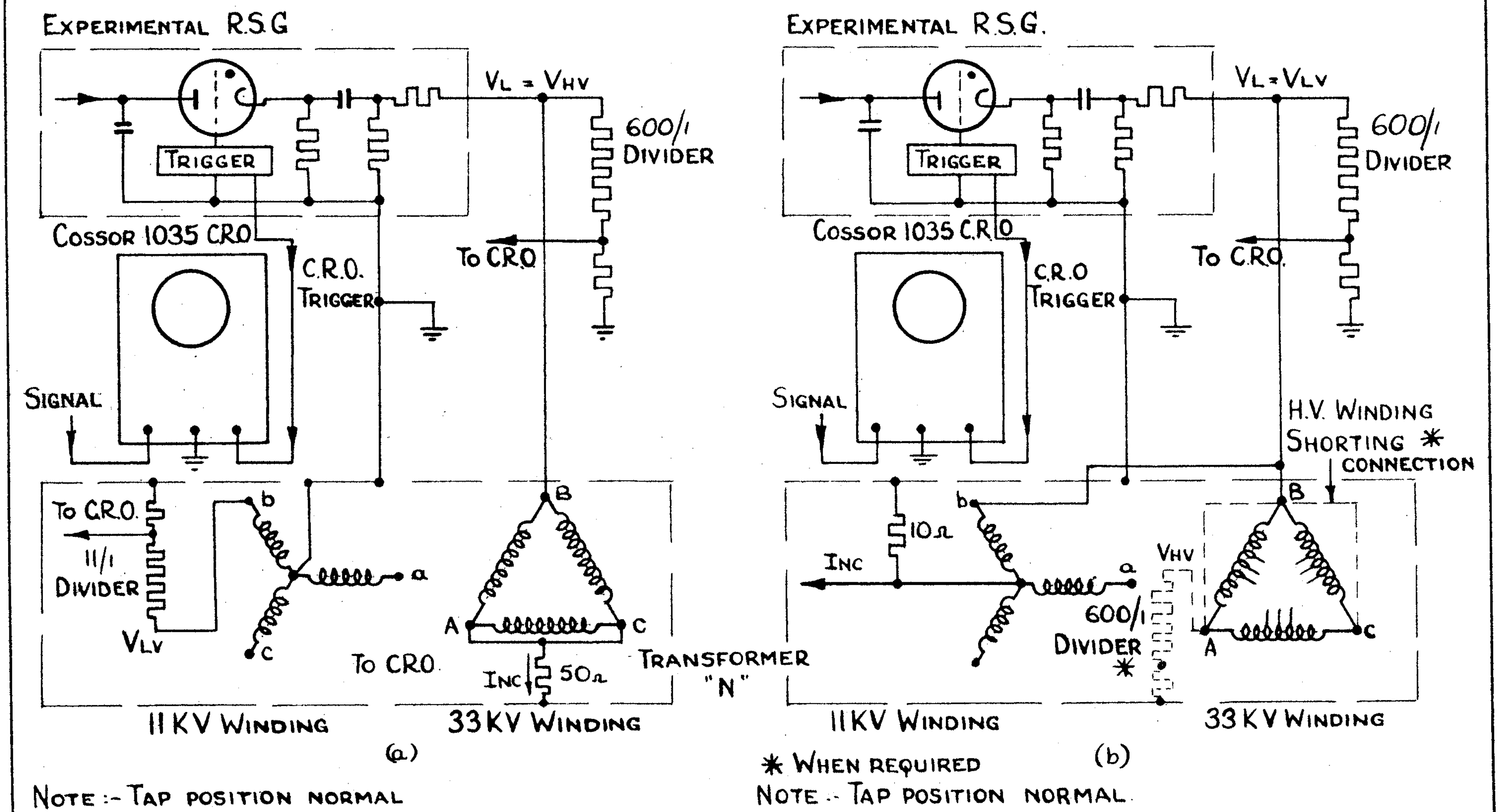


FIG. Z. CONNECTION DIAGRAMS-RECURRENT SURGE EXPERIMENTS MADE ON TRANSFORMER "N" AT TYREE ELECTRICAL WORKS

1955

levels.

When the unit was returned to the Tyree Electrical Works, the author attempted to determine the location of the faults using the full scale records and by fault simulation under recurrent surge conditions. Unfortunately, however, the full scale test records had disappeared off the screen when the fault occurred, and the author could only use the "time to failure" as a guide. These attempts at fault location were unsuccessful as were power frequancy tests made under the author's direction. The author was now more convinced than ever that every possible piece of oscillographic evidence should be properly recorded during full scale tests, particularly those for design investigations.

During 1955 the author studied the literature, particularly with reference to the fundamental behaviour of transformer winding currents. Also, initial preparation of a joint paper with Mr.G.C.Dewsnap, for submission to the Institution of Engineers, Australia, was commenced.

1956

The 2KV recurrent surge generator was available in October and was employed for experiments on transformer "O", a 400KVA 10,000/415 volt unit.

Transformer "O" was fully assembled in its tank and readings were limited to "no fault" conditions. The test connections were as shown in Fig.A. The transformer was placed on wooden blocks to insulate it from earth.

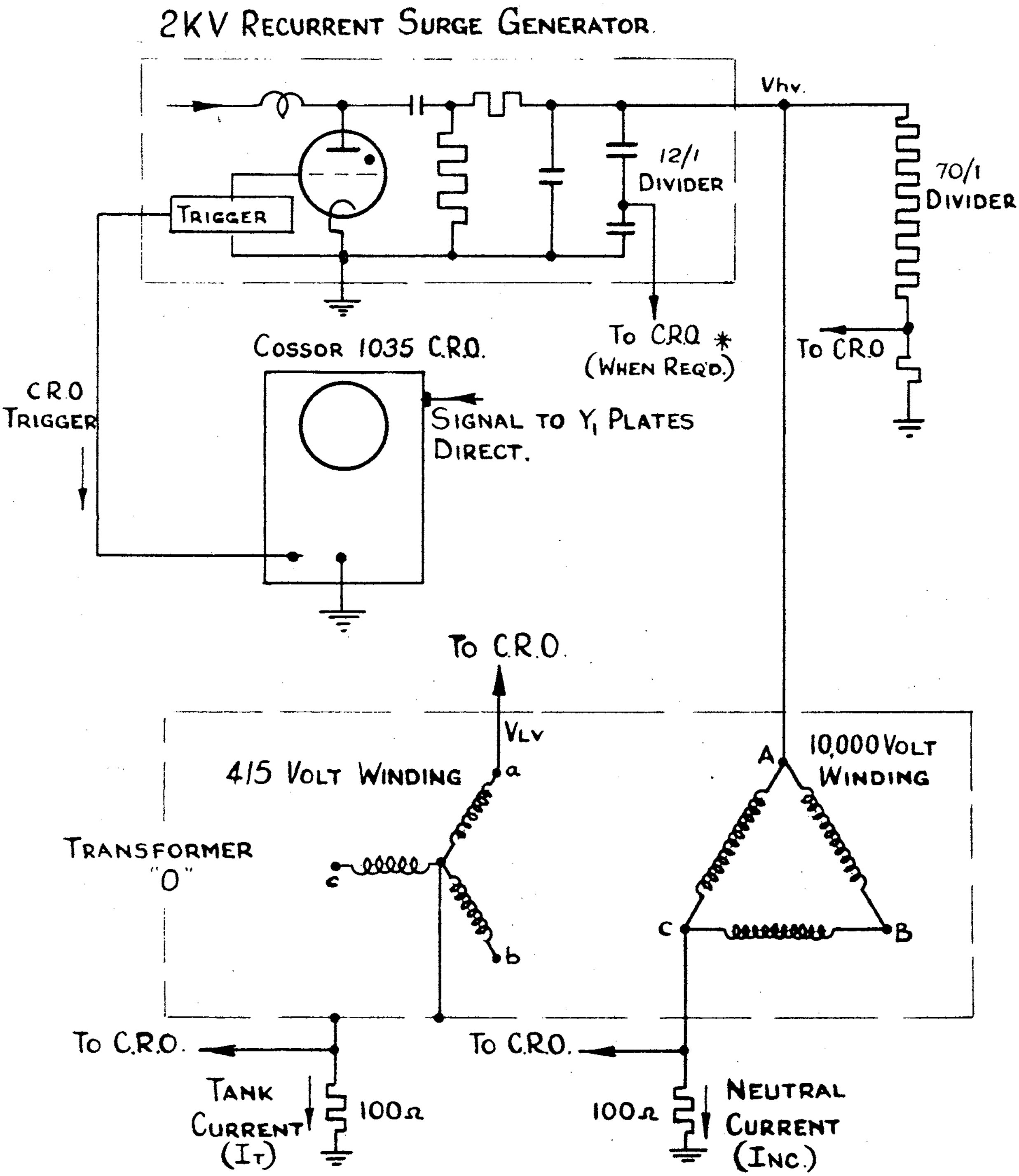
During these experiments, it was found that the 250 ohm section of a decade resistance box, which was initially employed as the neutral current shunt, was inductive. Composition type resistance shunts were employed for the remainder of the experiments, and for all subsequent experiments.

The results of the experiments on transformer "O" are given in Section 2.6, p.95.

The author conducted a series of recurrent surge experiments on transformer "R", a 500 KVA, 10,000/415 volt, unit in October. These experiments were made at the Sydney County Council transformer overhaul depot at Pyrmont.

The 2KV recurrent surge generator was employed, the experimental connections being as shown in Fig .B. The results are given and analysed in Section 2.4,p.65 and Section 2.6,p.102. These deal with the optimum test connections, and the fault detection aspects respectively.

During this experiment the author developed a winding continuity check method which he always employed subsequently



* Not used in these experiments

FIG. A.

EXPERIMENTS ON TRANSFORMER "O" AT S.C.C. LABORATORY IN SEPTEMBER 1956 DIAGRAM OF CONNECTIONS.

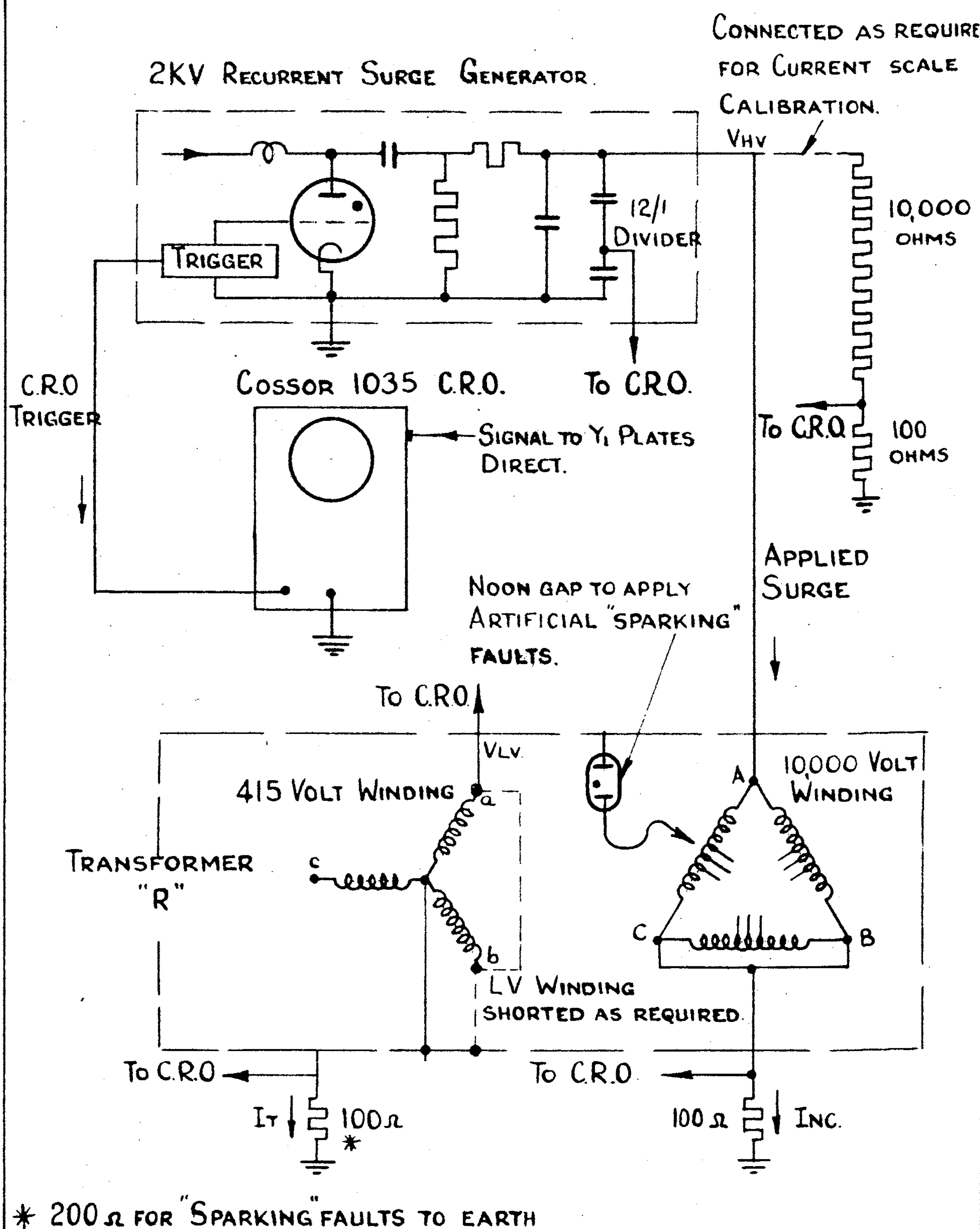


FIG. B.

EXPERIMENTS ON TRANSFORMER "R" AT S.G.C. TRANSFORMER DEPOT IN OCTOBER 1955 DIAGRAM OF CONNECTIONS.

before commencing oscillogram recording. He had found that faulty tapping switch contacts or connections could cause high resistance points in series with the winding under test. These resistance values would not affect the "no-fault" neutral current records but when faults were applied the correct "Electro-magnetic" indication would not occur. The author's check was to short out a substantial section of the winding under test, or a winding not under test, and to check visually that the electro-magnetic component increased in a positive direction by the usual amount. The placing of an artificial fault to earth from some point near the centre of the winding under test was another quick check applied. This check ensured that the electromagnetic component of the neutral current became negative thus showing that the recording lead polarities were correct.

This was the first time the author had attempted to establish a current scale on the oscillographic records so that others could calculate the shunt impedances necessary to match the sensitivities of their own recording equipment. The current scales were derived for a nominal 100 KV peak value of applied surge. The actual surge applied from the recurrent surge generator was 1280 volts (peak). The 10,000 ohms plus 100 ohm loading resistance shown at the top of Fig. B was connected to the surge output and the resultant current flow (equivalent to approximately 10 amps for a 100 KV peak surge) recorded oscillographically, then measured from the film in millimetres and the current scale in amperes per millimetres calculated. If the recording shunt was different from 100ohms due allowance was made. Current scales derived in this manner appear in Figures 21 and 25.

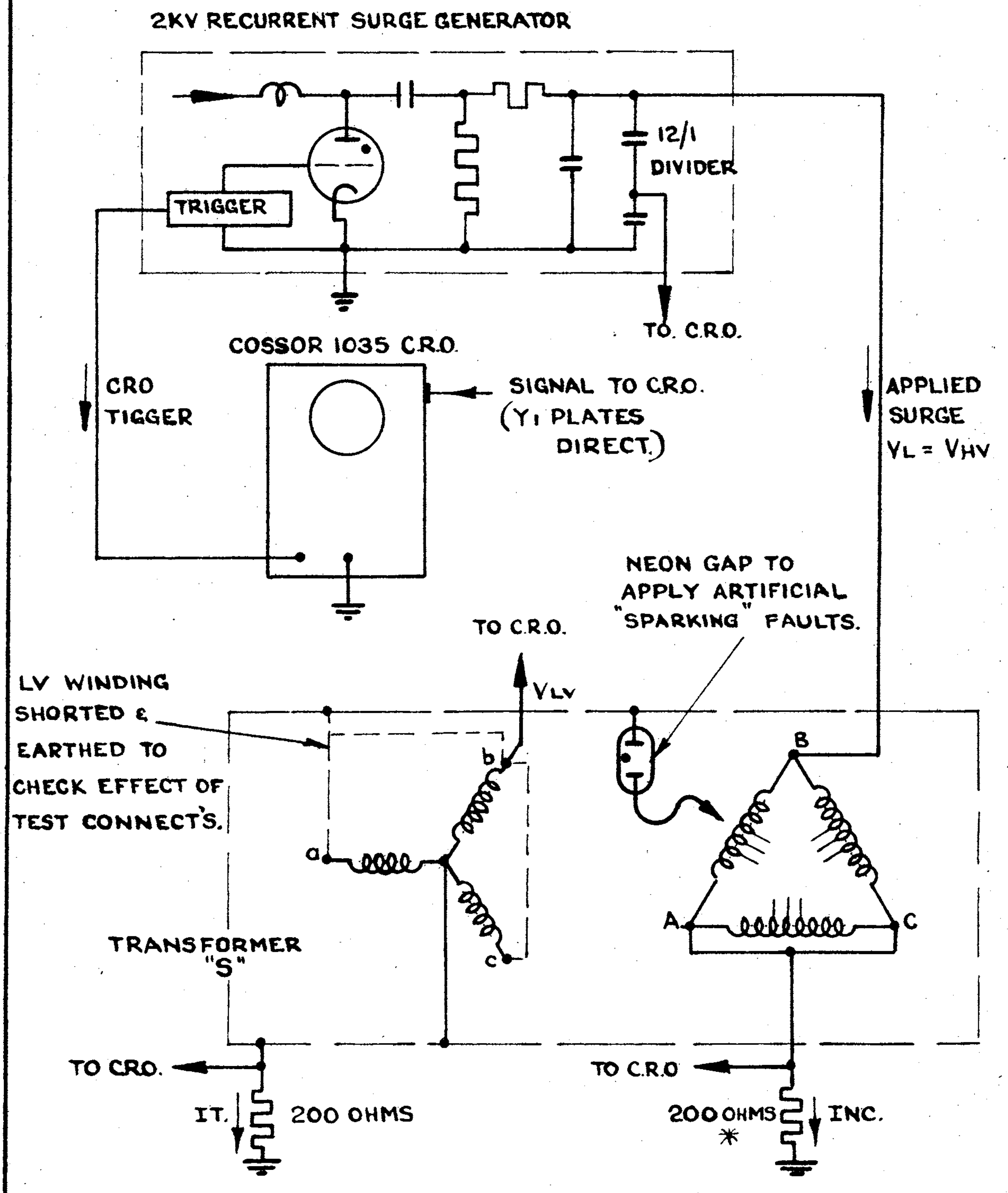
In November the author carried out a few experiments on a prototype 11KV layer winding intended for one phase of transformer "T", a 250 KVA, 11/0.433 KV, delta-star, layer-layer, unit. Only one single phase winding stack, comprising the 11,000 volt and 433 volt windings, was available. The experiments, which were carried out using the 2KV recurrent surge generator at the Tyree Electric Company's works at Kingsgrove, are described in Section 2.6, page 91.

Also during November experiments were carried out by the author on a Transformer "S", a 500 KVA, 10/0.415 KV, delta-star, bobbin-layer distributon transformer. The experiments, which were carried out at the Sydney County Council Transformer Depot using the 2KV recurrent surge generator, are described in Section 2.6, page 107.

The connections used for the author's experiments are shown in Fig.C. The author had now gained sufficient experience to know what oscillographic evidence was required for the purposes of this investigation and the experimental results shown in Fig.26 of the thesis, were comprehensive.

Current scales for the oscillograms were derived in the same manner as that described for the experiments on Transformer "B".

Faults involing only a few turns were simulated by winding turns of wire around the coil stack at a given point, and then



* 25 OHMS WHEN L.V. WINDING SHORTED

FIG. C: EXPERIMENTS ON TRANSFORMER "S" AT S.C.C. TRANSFORMER DEPOT IN NOVEMBER 1956

—DIAGRAM OF CONNECTIONS—

lowering the core and windings back into the coil. Artificial faults of twelve turns could be produced by shorting connections across the off-load tapping leads.

Trace brightening was applied to the Cossor 1035 oscilloscope during this month and resulted in improved oscillograms. The modification required has been previously described in this Appendix (Section 4.5.1.2., p.5).

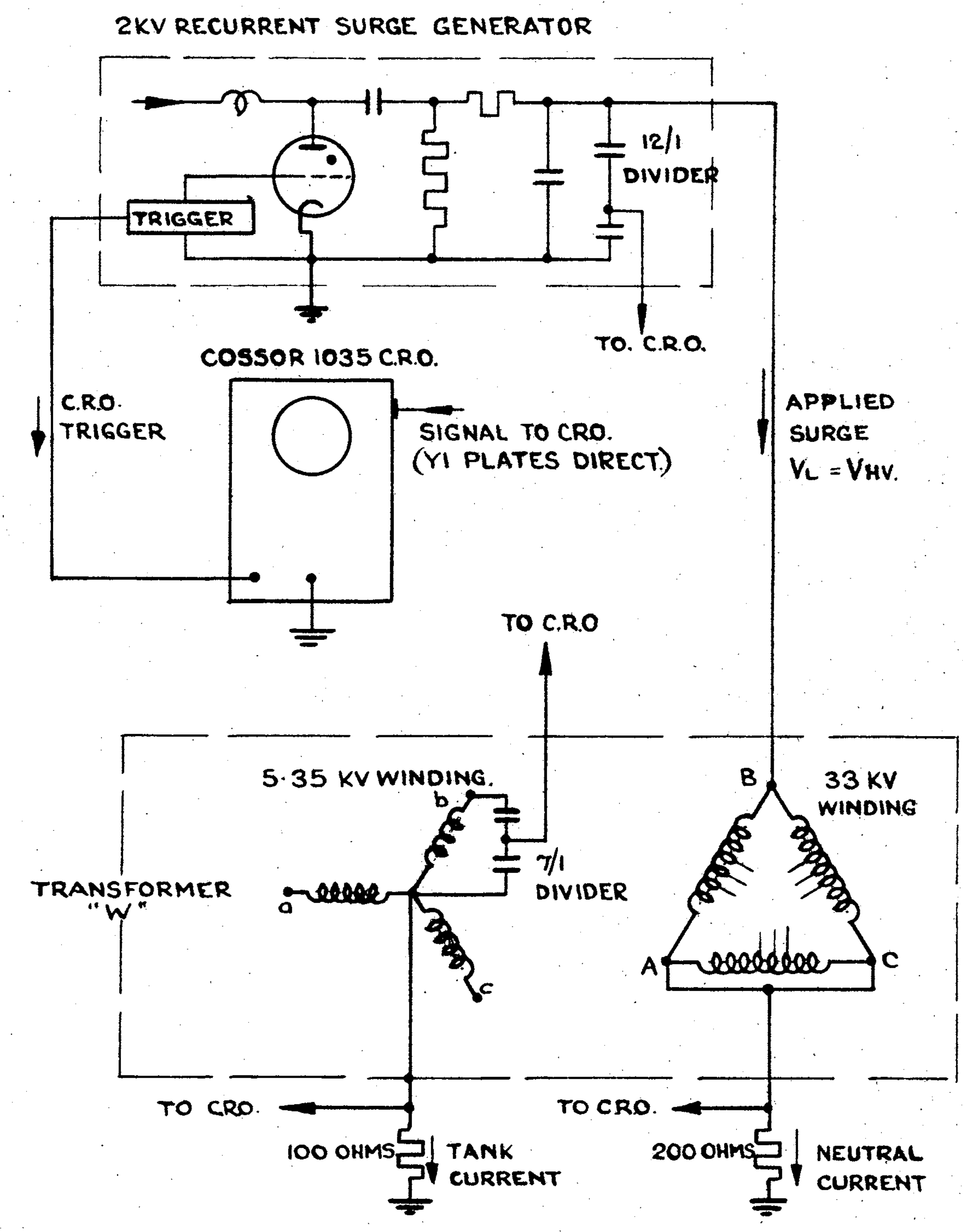
1957

During the early part of this year further experiments were conducted with the experimental winding stack, to assist the author in preparing an empirical theory of the fundamental behaviour of transformer winding currents.

In April a programme of experiments was carried out on Transformer "W", a 13,500 KVA 33/5.35KV, delta-star, disc-layer, power transformer, at the Botany substation of the Sydney County Council. Due to the size of this unit, special care, and attention to detail, had to be exercised by the author so as not to disturb the overhaul programme for the transformer. The experiments were made during the few hours when the transformer was under the crane, the core and windings having been lowered into the tank under oil, and the lid had not yet been fitted. It was necessary for the transformer to be under the crane so that artificisl faults could be applied and removed by lifting the core and windings clear of the oil.

The test connections used are shown in Fig.D. The results of the experiments are given in Section 2.7, page 116, and then analysed. The equivalent voltage and current scales were calculated using oscilloscope vertical deflection constants previously derived. Time scales were derived from an oscillogram of the 20 Kilocycle timing wave displayed with a 500 microsecond oscilloscope sweep time.

In May the author commissioned a 100 KV 0.15 KW-sec. impulse generator for the Sydney County Council at Camperdown substation. Construction of this generator has been described earlier in



NOTE: CORE & WINDING IN OIL. FULL 33KV WINDING IN CIRCUIT.

FIG. D: EXPERIMENTS ON TRANSFORMER "W" AT S.C.C. SUBSTATION AT BOTANY IN APRIL 1957

— DIAGRAM OF CONNECTIONS. —

Section 4.5.1.5. The author carried out impulse tests on 11KV cable terminations using this generator, although it suffered from the serious disabilities described previously.

In August an experiment was conducted on a 200KVA, 11,000/415 Volt, 50 Cycles per second distribution transformer to check the effect of frequency and the presence of the core on mutual coupling between sections of a winding. The method used and the results of the experiment are given in full in Section 2.3.1, page 45.

The joint paper - "Investigation of Fault Detection Methods for the Impulse Testing of Transformers" - by G.C. Dewsnap and the author was published in the December 1957 issue of the Journal of the Institution of Engineers, Australia, Vo.29, No.12, page 311. Section 2 of this paper, dealing with "Development and Construction of Recurrent Surge Generators" is due to Dewsnap. The balance of the paper, sections 3 to 6 inclusive, are the work of the author of this thesis. The paper was published, and later presented, as a progress report on the work completed to that time in connection with this thesis.

1958

The preparation of a demonstration, using the author's experimental equipment for the presentation of the joint paper referred to above, occupied the first term of 1958. On the 26th March 1958, the paper was presented before the Sydney Division of the Institution of Engineers, Australia, at Science House, Sydney. Fig.12 of the thesis shows the demonstration equipment set up in Science House. The equipment is fully described in Section 2.2., p.32 and the diagram of connections is given in Fig.14. The normal oscilloscopé display was supplemented by a Telequipment oscilloscope the display of which was magnified by a closed television link to a 21 inch television receiver.

This method of displaying the recurrent surge waveforms proved very successful, even members of the audience in the back of the hall being able to follow the experiment. The author conducted the experiment with the help of two assistants, who inserted artificial faults, assembled the experimental core and windings and so on, and Mr.G.C. Dewsnap who supervised the television link. The demonstration covered the fundamental behaviour of transformer winding currents (Section 2.3.1, p.34) and the recurrent surge waveforms of Fig.13 were displayed. During the discussion on the p aper it was acknowledged that the demonstration had been very effective.

In June the author carried out voltage distribution experiments on an 11,000/110 volt voltage transformer ("B") and a 250KVA 10,000/415 volt distribution transformer ("M"). The experiments are described in Section 4.5.3 of this Appendix. Fault detection experiments were also conducted on the voltage transformer ("B") using the 2KV recurrent surge generator. The experimental procedure and the diagrams of connections are given in Section 2.5, page 72, of the thesis.

Also during June the author was engaged in the re-erection of the Sydney County Council 100KV Impulse Generator at Waverley Substation (see Section 4.5.1.5 of this Appendix). When this generator was ready it was employed for full scale tests on the 11,000/110 volt voltage transformer ("B"). These tests continued intermittently from June to August.

These full scale impulse tests and the associated power frequency tests are described dully in Section 2.5, page 75, of the thesis. The recording arrangements shown in the diagram of connections Fig.23(d) were the best that could be employed at the time. The "Telequipment" oscilloscope was used because of its excellent trace brightening facility.

To reduce pick-up in the recording circuits, the following precautions were taken:

(a) The oscilloscope was placed in a recording room made of angle iron and screened with chicken wire mesh. The recording room was 15 feet from the test area.

(b) An independent battery driven motor generator was placed in the same room to supply the oscilloscope.

(c) The co-axial leads were taken under the floor of the test area at points close to the recording shunts, and run through a duct to the recording room.

(d) A Co-Axial neutral current shunt was made from a copper tube and co-axial conductor arrangement.

Despite these precautions excessive inductive interference occurred during the early part of each oscillogram. The author feels that the galvanised wire mesh was too open and of too high a resitance to effectively shield the recording room. A heavy gauge bronze mesh may have been more effective particularly if soldered at all joints and bonded to a copper strap network.

The author could not employ the optimum procedure for these tests due to lack of facilities. However, the test results were quite useful and the operating experience of great value to the author and the testing staff assisting him.

In September the author completed his experimental work.

Recommended Procedures for Transformer-Impulse Tests.

These recommendations are made by the author after careful analysis of his own experimental results, study of theoretical aspects of surge phenomena in transformer windings and critical reading of the findings of overseas testing authorities. It is assumed that the high-voltage testing laboratory is equipped with the necessary testing plant and the fault detection facilities specified at the end of the thesis (Section 2.9, page 140).

Three test procedures are recommended below, one for each of the following categories:-

(a) Voltage transformers and distribution transformers to 50kVA.

(b) Distribution transformers to 1000 k VA.

(c) Power transformers.

The author has not had any experience of the effect of special tapping windings and connections, such as are found in large power transformers, and only limited experience of layer type windings.

The procedures recommended are for tests intended to prove that a certain transformer complies with a purchaser's specification, i.e. acceptance tests, not design tests which are usually made to check a manufacturer's design and to ascertain design margins.

RECOMMENDED PROCEDURE FOR THE IMPULSE TESTING OF VOLTAGE AND DISTRIBUTION TRANSFORMERS TO 50kVA.

1. Determine, by recurrent surge measurements, the magnitude of the voltage which will be transferred to the other winding(s). If the transferred voltage is excessive, shunt the other winding(s) with suitable high voltage resistors to reduce it to a safe value. Earth the other winding(s) at one point only. These connections must be employed for all the recurrent surge and full scale tests specified below.

2. Remove the core and windings from the tank and, employing the test connections specified in the contract and in instruction No. 1 above, carry out recurrent surge fault detection experiments so that the nature of the indication for various types of faults is known.

Only neutral current and tank current records need be taken. Care must be taken to determine from these recurrent surge experiments, not only the fault detection sensitivities which will be possible, but also the optimum oscillograph sweep speeds to be employed. Voltage transformers can have long fundamental times and the current records must be made for at least one fundamental time, preferably two (see Section 2.5.). It will probably be found that the tank current records provide the most sensitive fault indication.

3. Replace the core and windings in the tank under oil.* Check the general condition of the major insulation.

* Oil should meet the dielectric requirements of B.S.S. 148-1952.

3 cont.

by insulation resistance, dielectric loss angle or dielectric dispersion measurements.

Acceptable values for a 33,000 volt winding are:-

Insulation resistance - 10,000 Megohms.

Dielectric loss angle - 30 Milliradians.

4. Measure the resistance of each winding on the tapping position (x) to be used in the impulse test.

5. Apply power frequency high voltage tests, both "applied voltage" and "induced voltage" to check the major and interturn insulation strengths respectively.

6. Place the transformer in position in the impulse test area so that it is electrostatically and acoustically screened from the impulse generator.

7. Fit the oil pressure detector under oil in the tank near the axial mid-point of the winding but well clear of the electrostatic field which will result under impulse conditions. A tap on the side of the tank should register on the oil pressure detector oscillograph.

8. The lid of the transformer tank should be left off so that any disturbance in the oil can be observed. The normal electrostatic field may have to be preserved by the temporary addition of metal or metallised surfaces at certain points.

9. Connect up the recording circuits using the same test connections as were employed in the recurrent surge

x If tappings are provided.

9. cont.

measurements (see instruction No. 2 above). Oscillographic records of line voltage and tank current must be taken, and neutral current if possible. Shunt values and sweep times should be based on the results of the recurrent surge measurements. The neutral current should be recorded using a long duration sweep time, say 100 microseconds, whereas the tank current time sweep should only be long enough to record one or two passages of the surge phenomena through the winding.

10. A calibration full wave impulse test at approximately 75% of the specified test level should now be carried out. Observations and records should show no sign of failure, loose connections or excessive interference in the recording circuits. The voltage waveform should also be checked at this stage and the generator output voltage measured and related to the generator charging voltage.

11. Two chopped wave tests at 115% of the specified test level should now be made. The controlled chopping gap should be set to chop after three microseconds. Line voltage and neutral current records, only, should be made. A short sweep time should be used. Careful observation of the transformer and of the chopping gap should be made owing to the possibility of failure of the major insulation during the first three microseconds. The oscillograph records must be carefully analysed after each test to check that no failure of the major insulation has occurred.

If sufficient acoustic isolation has been achieved,

11. cont.

it will be possible to employ the oil pressure detector without interference from the generator or chopping gaps. This record can be very valuable and may justify special acoustic baffling of the chopping gap which has to be mounted closely to the transformer under test.

Interturn faults involving small portions of the winding could remain undetected at the conclusion of the chopped wave tests and the full wave tests should now be carried out as soon as possible.

12. Two full wave tests at 100% of the specified test level should now be made. No change in the test connections should be made before the tests, except:-

(a) Reconnection of tank current recording shunt and oscillograph channel.

(b) Adjustment, as necessary, of the voltage divider and current shunt values, the oscillograph sensitivities and the oil pressure detector sensitivity.

After each test the voltage, current and oil pressure detector records should be carefully analysed by an experienced engineer or technician, for any indication of failure.

13. If no failure has been detected the transformer should be tested again with power frequency high voltage, as in No. 3 above, and, if it passes these tests, placed into service.

14. If failure has occurred the recurrent surge records, obtained as specified in instruction No. 2 above, should, by

14. cont.

comparison, indicate the nature and possibly, the location of the fault. Further tests, both full-scale and recurrent surge, may be necessary to determine the nature and location of the fault. As much information as possible must be obtained before stripping the winding.

APPENDIX 4.6.2.

RECOMMENDED PROCEDURE FOR THE IMPULSE TESTING OF DISTRIBUTION TRANSFORMERS TO 1,000 k VA.

1. Determine by recurrent surge measurements, the magnitude of the voltage which will be transferred to other winding(s). If the transferred voltage is excessive, shunt the other winding(s) with suitable high voltage resistors to reduce it to a safe value. Earth the other winding(s) at one point only. These connections must be employed for all the recurrent surge and full scale tests specified below.

2. Remove the core and windings from the tank and, employing the test connections specified in the contract and in instruction No. 1 above, carry out recurrent surge fault detection experiments so that the nature of the indication for various types of faults is known.

It will be found that, in addition to the line voltage record, the following records must be made:-

Layer type winding.

(a) Neutral current with fairly low current deflection sensitivity and a long sweep time, say 5 to 10 times the fundamental time of the winding. This record will indicate the nature and location of major faults.

(b) Neutral current with a high current deflection sensitivity and a sweep time not greater than one or two times the fundamental time of the winding. This record will indicate the presence and possible location of minor faults by variations in the electrostatic components.

2. cont.

Bobbin type winding.

(a) Neutral current with a sweep time approximately three times the fundamental time of the winding under test. This record should provide electromagnetic and possibly electrostatic indication of faults. However the current deflection sensitivity should allow for the indication of the type and location of major faults.

(b) Tank current with a sweep time of one to two times the fundamental time. This will provide an electrostatic indication of interturn faults.

Disc type winding.

Normally a single record of neutral current will be sufficient. If not, a record of tank current may also be used as specified for the bobbin-type winding. (See Section 2.6).

3. Check the general condition of the major insulation by insulation resistance, dielectric loss angle or dielectric dispersion measurements.

Acceptable values for an 33,000 volt winding are:-

Insulation resistance - 4,000 Megohms at 20 ^{o}C.

Dielectric loss angle - 30 Milliradians at 20 ^{o}C.

The oil should satisfy the dielectric requirements of B.S.S. 148:1952.

4. Measure the resistance of each winding on the tapping position to be used in the impulse test.

5. Apply power frequency high voltage tests, both

5. cont.

"applied voltage" and "induced voltage" to check the major and interturn insulation strengths respectively.

6. Place the transformer in position in the impulse test area so that it is electrostatically and acoustically screened from the impulse generator.

7. Fit the oil pressure detector under oil in the tank near the axial mid-point of the winding but well clear of the electrostatic field which will result under impulse conditions. A tap on the side of the tank should register on the oil pressure detector oscillograph.

8. The lid of the transformer tank or a suitable inspection cover should be left off so that any disturbance in the oil can be observed. The normal electrostatic field may have to be preserved by the temporary addition of metal or metallised surfaces at certain points.

9. Connect up the recording circuits using the same test connections as were employed in the recurrent surge measurements (see instruction No. 2 above). Sweep times and adjustment of oscillograph sensitivities should be based on the results of the latter measurements.

10. A calibration full wave impulse test at approximately 75% of the specified test level should now be carried out. Observations and oscillograph records should indicate no failure, loose connections or excessive interference in the recording circuits. The voltage waveform should be checked and the generator output voltage measured, and related to the generator charging voltage.

11. Two chopped wave tests at 115% of the specified test level should now be made. The controlled chopping gap should be set to chop after three microseconds. Line voltage and neutral current records, only, should be made. A short sweep time should be used. Careful observation of the transformer and of the chopping gap should be made due to the possibility of failure of the major insulation during the first three microseconds.

The oscillograph records must be carefully analysed after each test to check that no failure of the major insulation has occurred.

The size of the unit will probably preclude adequate acoustic screening but, if the chopping gap can be acoustically baffled, it should be possible to use the oil pressure detector satisfactorily.

12. Two full wave tests at 100% of the specified test level should now be made. No change in the test connections should be made before the tests, except:-

(a) Reconnection of tank current recording shunt and oscillograph channel.

(b) Adjustment, as necessary, of the voltage divider and current shunt values, the oscillograph sensitivities and the oil pressure detector sensitivity.

After each test the voltage, current and oil pressure detector records should be carefully analysed by an experienced engineer or technician, for any indication of failure.

13. If no failure has occurred the transformer is ready for service.

14. If failure has occurred the recurrent surge records, obtained as specified in instruction No. 2 above, should, by comparison, indicate the nature and possibly, the location of the fault. Further tests, both full-scale and recurrent surge, may be necessary to determine the nature and location of the fault. As much information as possible must be obtained before stripping the winding.

RECOMMENDED PROCEDURES FOR THE IMPULSE TESTING OF POWER TRANSFORMERS.

1. Determine by recurrent surge measurements, the magnitude of the voltage which will be transferred to other winding(s). If the transferred voltage is excessive, shunt the other winding(s) with suitable high voltage resistors to reduce it to a safe value. Earth the other winding(s) at one point only. These connections must be employed for all the recurrent surge and full scale tests specified below.

2. Using the test connections specified in the contract and in instruction No. 1 above, carry out recurrent surge fault detection experiments so that the nature of the indication for various types of faults is known. The difficulty of access to the core and windings of large units may limit the types of artificial faults that can be applied.

It will be found that, in addition to the line voltage record, the following records must be made:-

Layer type winding.

(a) Neutral current with fairly low current deflection sensitivity and a long sweep time, say 5 times the fundamental time of the winding. This record will indicate the nature and location of major faults.

(b) Neutral current with a high current deflection sensitivity and a sweep time not greater than one or two times the fundamental time of the winding. This record will indicate the presence and possible location of minor faults by variations in the electrostatic components.

Disc type winding.

(a) Neutral current record with a compromise current sensitivity and sweep time so that electromagnetic and electrostatic fault indications are possible. However if a winding not under test has to be shorted, or if complicated tapping arrangements are present, it is essential that the neutral current record be supplemented by:

(b) Tank Current or L.V. Capacitance Current record with a sweep time of one to two times the fundamental time. This will provide an electrostatic indication of failure. The L.V. Capacitance Current record is to be preferred in the case of large units since the shielding of the tank presents a problem (see Section 2.7, page 126).

3. Check the general condition of the major insulation by insulation resistance, dielectric loss angle or dielectric dispersion measurements.

Acceptable values for an 33,000 volt winding are:-

Insulation resistance - 1,000 Megohms at 20° C.

Dielectric loss angle - 30 Milliradians at 20° C.

The oil should meet the dielectric requirements of B.S.S. 148:1952.

4. Measure the resistance of each winding on the tapping position to be used in the impulse test.

5. Apply power frequency high voltage tests, both "applied voltage" and "induced voltage" to check the major and interturn insulation strengths respectively.

6. Place the transformer in position in the the test area and make a solid earth connection to it.

7. Fit the oil pressure detector under oil in the tank near the axial mid-point of the winding but well clear of the electrostatic field which will result under impulse conditions. A tap on the side of the tank should register on the oil pressure detector oscillograph.

8. An inspection cover should be removed so that the oil surface can be observed. The conservator must normally be left off for impulse tests.

9. Connect up the recording circuits using the same test connections as were employed in the recurrent surge measurements (see instruction No. 2 above). Sweep times and adjustment of oscillograph sensitivities should be based on the results of the latter measurements.

10. A calibration impulse test at approximately 75% of the specified test level should now be carried out. Observations and oscillograph records should indicate no failure, loose connections or excessive interference in the recording circuits. The voltage waveform should be checked and the generator output voltage measured, and related to the generator charging voltage.

11. Two chopped wave tests at 115% of the specified test level should now be made. The controlled chopping gap should be set to chop after three microseconds. Line voltage and neutral current records, only, should be made. A short sweep time should be used. Careful observation of

11. cont.

the transformer and of the chopping gap should be made due to the possibility of failure of the major insulation during the first three microseconds.

The oscillograph records must be carefully analysed after each test to check that no failure of the major insulation has occurred.

The size of the unit will probably preclude adequate acoustic screening but, if the chopping gap can be acoustically baffled, it should be possible to use the oil pressure detector satisfactorily.

12. Two full wave tests at 100% of the specified test level should now be made. No change in the test connections should be made before the tests, except:-

(a) Reconnection of tank current recording shunt and oscillograph channel.

(b) Adjustment, as necessary, of the voltage divider and current shunt values, the oscillograph sensitivities and the oil pressure detector sensitivity.

After each test the voltage, current and oil pressure detector records should be carefully analysed by an experienced engineer or technician, for any indication of failure.

13. If no failure has occurred the transformer is ready for service.

14. If failure has occurred the recurrent surge records, obtained as specified in instruction No. 2 above, should, by comparison, indicate the nature and possibly, the location of the fault. Further tests, both full-scale and recurrent surge, may be necessary to determine the nature and location of the fault. As much information as possible must be obtained before stripping the winding.

There seems no reason why "sparking" and "solid" faults should not be located fairly accurately from the neutral and LV Capacitance current records provided that they occur consistently. A transient "sparking" fault which does not recur, cannot be said to have affected the service life of the transformer.

5.0 INDEX.

I N D E X (Cont'd)

I N D E X (Cont'd).