STUDY OF TRANSFERRED SURGES ON TERTIARY OF 220 KV CLASS POWER TRANSFORMER AND ITS PROTECTION

A DISSERTATION
Submitted in partial fulfilment
of the requirements for the award of the Degree

MASTER OF ENGINEERING
in
ELECTRICAL MACHINE DESIGN

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CERTIFICATE

Certified that the dissertation entitled 'STUDY OF TRANSFERRED SURGES ON TERTIARY OF 220 KV CLASS POWER TRANSFORMER AND ITS PROTECTION' which is being submitted by Shri D.V. NARKE in partial fulfilment for the award of the degree of MASTER OF ENGINEERING (ELECTRICAL) of the University of Roorkee, Roorkee is a record of student's own work carried out by him under my guidance and supervision since May 1978 to June 1979. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

Place: ROORKEE

Dated: July 6,1979

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A C K N O W L E D G M E N T

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S Y N O P S I S

This dissertation is based on an experimental approach to the study of transferred surge phenomena on 11 kV delta connected tertiary of 220 kV Class, 3 Phase or 3 Phase bank of single phase 3 winding transformers and auto transformers using recurrent surge generator and CRO. The magnitude of transferred surges on tertiary at different terminal conditions are determined when a lightning or switching impulse wave applied either on high voltage or medium voltage terminal of 220 kV transformer. The transferred surge voltage on tertiary are found to exceed considerably the specified value of BIL for 11 kV syatem voltage when tertiary is kept unloaded or connected to high impedance circuit or one terminal of tertiary is earthed and other two are kept isolated in service. Thus while designing the insulation for this type of winding whether loaded or used for stabilising purpose in the transformer, the magnitude of transferred surges on it under unloaded conditions should be taken into account. The impulse insulation levels for 11 kV tertiary of 220 kV Auto Transformer or system step down transformer are recommended by analysing the test results of the transformers. The effect of an earthed shield placed outside the tertiary coil on the magnitude of transferred surges on tertiary has been studied. The relative advantages and disadvantages of this shield

in transformers are discussed. In the case of loaded tertiary, the clearances for tertiary bushings and associated bus bars and the BIL of tertiary load would have to be kept more than the value specified in the I.S. for 11 kV system in absence of proper protective measures at tertiary load circuit. The necessary protective measures are recommended in the dissertation depending upon the nature of associated impedance or load. Suggestions for the selection of protective levels and energy rating for the tertiary side arresters are mentioned.

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CHAPTER - I

1.0 INTRODUCTION

Stabilising windings, in the form of delta connection are provided for star/star connected transformers to reduce third harmonic voltage components and to permit the transformation of unbalanced three-phase loads. When this delta connected winding is used for supplying the station auxiliaries in power stations or for supplying synchronous condensers for power-factor improvement on long transmission lines in addition to the loads handled by the main windings, it is designated as "loaded tertiary". For 220 kV class transformers, the most common rated voltages for stabilising/ tertiary winding is 11 kV in the country. This winding is normally placed next to the core.

The tertiary winding is not directly connected to the power transmission lines. The probability of direct impact of lightning surge on tertiary is negligible being the lowest voltage winding of a transformer. Thus the impulse withstand voltage level of the tertiary will depend upon the magnitude of surge appearing at HV/LV line terminals and on transformer parameters. When a transformer winding is subjected to a lightning/switching surge, transient over-voltage are produced in the impulsed and also in all the non impulsed windings due to induction phenomena. Thus the 11 kV tertiary windings of 220/132/11 kV auto transformer or 220/66/11 kV system step down transformer generally experience over-voltages in this form. The tertiary winding may attain fairly high potentials to ground or high voltages across the winding when it is kept floating in service.

A transformer terminal is considered as 'floating' when it is :

1) isolated from gound, or

2) connected to ground through a high impedance

Typical examples of floating terminals are the unloaded tertiary winding terminals of a three winding transformer, or one tertiary terminal is grounded and other two are kept unloaded, or terminals connected only to voltage transformer or distribution/ small power transformer or to a few hundred feet of line or cable which is isolated at its further end or connected there to a high impedance. For the rational design of insulation for tertiary winding, it is essential to know the magnitude of the transferred surge on tertiary under various terminal conditions.

When a synchronous machine or static compensator or some other equipment is connected to tertiary terminals, the over-voltages are transmitted to the equipment via the transformer. It is known that the impulse withstand strength of rotating a.c. machine or dry type transformer in absence of insulating oil is considerably lower than that of a oil immersed power transformer with the same rated voltage. Similarly the age of the rotating machine has to be taken into account as ageing of the insulation may further cause a reduction in the impulse withstand strength. In order to avoid a higher voltage rating for equipment and bus bars having larger clearances for tertiary connections, a proper protective system consisting of lightning arresters/surge absorptio capacitors should be planned in their tertiary circuit.

Occasional flash overs from 11 kV unloaded tertiary terminals to ground have been noticed in service presumably due to transferred surges. To illustrate : in commercial impulse testing of high voltage windings, if the LV windings were allowed to float, the LV bushings would flashover to ground in some cases; and therefore, it is standard practice to connect the LV bushings to ground through a resistance during the test which also represents the service conditions. When lightning arresters are installed at tertiary terminals, their faiure have also been observed. Frequent failures of these arresters may damage the tertiary coils due to short circuit formation. Thus both the study of transferred surge phenomena in transformer and the selection of proper arrester rating are important. It is the object of the dissertation to determine the magnitude of the transferred surges at tertiary terminals under various tertiary terminal conditions and to recommend necessary protective measures wherever required.

2.0 COMPONENTS OF SURGE TRANSFER

In a fundamental paper (1) by K.K. Palueff and J.H. Hagenguth, published over 45 years ago, the surge voltage transferred from the HV to the LV winding terminal of a 2 winding transformer has been described as consisting of four components, shown in Fig. 1 are :

i) The electro static component

ii) The oscillatory component in the HV winding which induces a corresponding oscillation in the LV winding.

iii) A second oscillatory component produced in the LV windings.

iv) The electromagnetic component.

The transferred surge voltage which appears on tertiary terminals of a 3 winding

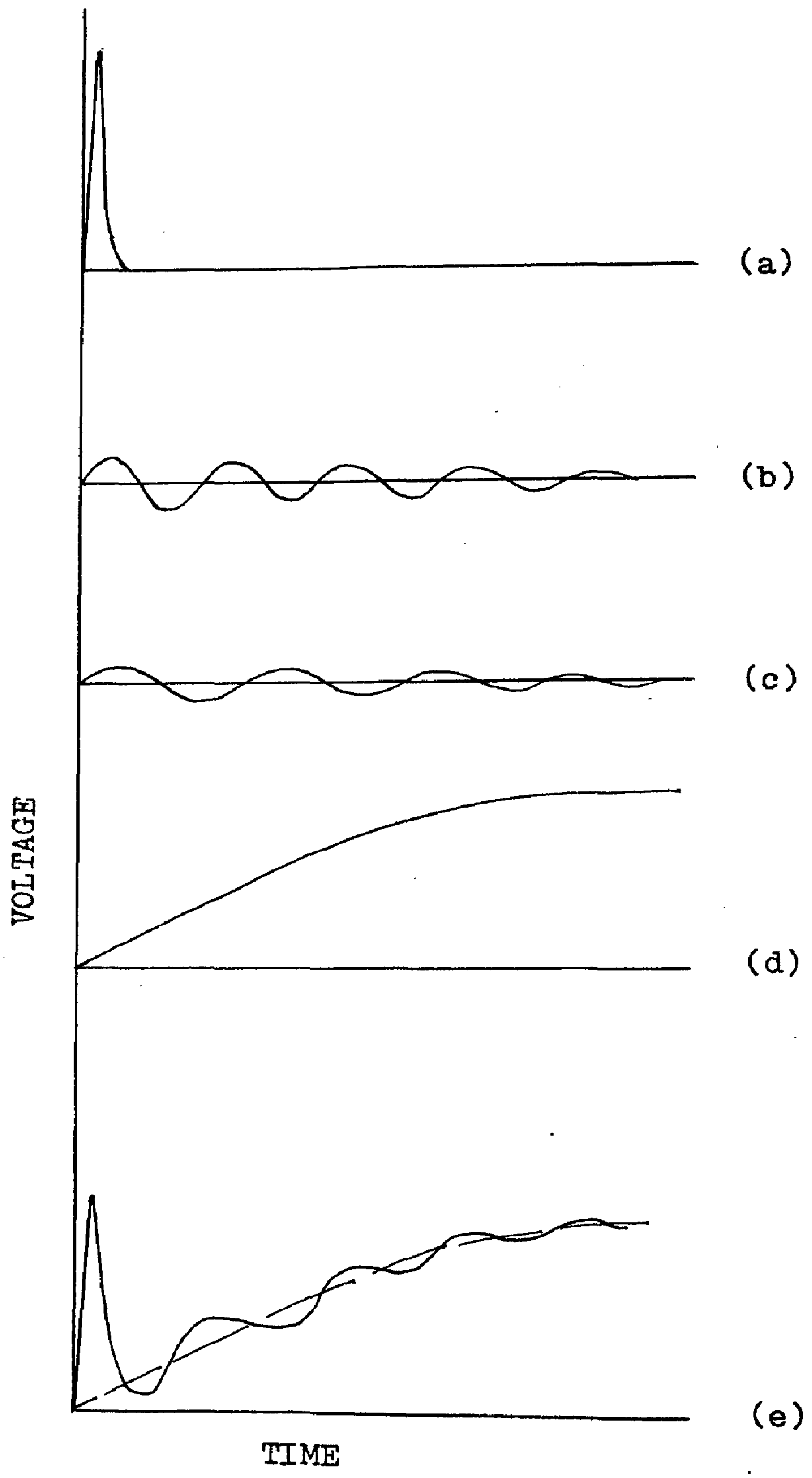


Fig.1 Composition of the surge voltage at the LV terminal of a transformer due to the impact of a surge wave on the HV terminal.

transformer or auto-transformer also consists of these four components. Itis known that when a transformer winding is disturbed from its steady state condition by an impulse voltage, either applied directly or through induction, it will return to its normal condition after a series of damped sinusoidal oscillations. The wave-shape and the frequencies of these harmonic oscillations depend upon the terminal conditions of the oscillatory winding. The amplitude of each harmonic voltage depends upon the difference of the initial and final distributions. For the free oscillations of the LV winding the transient electrostatic component represents the initial distribution and the electromagnetic component represents the final distribution.

Part (a) of Fig.1 shows the exponential electrostatic component of the transferred surge voltage at the LV terminal. The magnitude and shape of this component depends upon the front duration of the applied surge voltage, the capacitance distribution among the transformer windings and earth and the nature of the impedance connected to LV terminal. Part (b) is the free sinusoidal oscillations induced in the LV winding by a similar effect in the HV winding, which consists of a number of space harmonics; the induction is achieved throug the electrostatic and electromagnetic fields of these harmonics. The magnitude of this component depends upon the distributed constants and turns ratio of the windings. Part (c) shows the free sinusoidal oscillation in the LV winding which immediately follows the impact of the wave - the voltages produced depend upon the distributed constants of the LV winding. Part (d) is typical of the exponential unidirectional surge voltage wave produced in the LV winding by electromagnetic induction between the windings, the wave rising from zero to a certain maximum and then falling to zero. The magnitude of this component is dependent on the turns ratio, the leakage inductance, the impedances connected to the winding terminals, the wave-shape of applied surge and is independent of the distributed capacitance of the windings. Part (e) is the resultant LV Surge Voltage Wave.

The magnitude of oscillatory components are usually small compared to electrostatic and electromagnetic components. Thus the components of surge transfer usually of primary concern are electrostatic and electromagnetic components.

2.1 ELECTROSTATIC SURGE TRANSFER

Electrostatic induction becomes hazardous when the floating winding is having quite lower voltage rating than the inducing winding(for example 11 kV tertiary winding of 220/132 kV Auto transformer), because this type of induction is determined not by turn ratio but by capacitance distribution within the transformer. Often the capacitance distribution leads to higher potentials in the lower voltage windings than turn ratio would have produced.

In the symmetrical three-phase installations, the vectorial average of the normal frequency potentials of the three-phases to ground is zero, and therefore the corresponding average normal frequency potential to ground of a symmetrical three phase floating winding also will be zero. As the electro-statically induced potentials in the three secondary phases tend to neutralize each other by an exchange of small capacitance currents, the maximum local values of the electrostatically induced normal frequency potentials will be negligible. However, if for any reason the neutral of the HV winding should shift, or the potential of the HV winding should be raised, a corresponding electrostatic potential will be induced in a floating winding on the transformers. This is apt to occur under the following conditions :

1) LIGHTNING

Lightning on the HV lines is the source of maximum electrostatic induction from the HV windings to a floating lower voltage winding. Due to the rapid rise of these potentials, floating terminals may be raised to much higher potentials than the average of the winding.

Simplified expression for capacitively transferred surge voltage at LV terminal when impulse voltage is applied on a HV terminal of single phase 2 winding transformer is given below :

$$UL = UH \quad \frac{CH\text{-}L}{CH\text{-}L + CL\text{-}E}$$

Where UH = Peak value of the Surge voltage on HV terminal

CH-L = Capacitance between HV and LV windings of the transformer

CL-E = Capacitance between LV winding of the transformer and earth

The series capacitance of HV and LV windings are however not taken into account.

2) SWITCHING WITH SINGLE-POLE SWITCHES OR BLOWING OF FUSES.

In switching with single-pole air-break switches, or in the blowing of two fuses, one line may be closed and the other two open for a few seconds during which the entire HV winding will be raised to the potential of the closed line and will therefore induce an abnormal potential in a floating low-voltage winding. These voltages are less than those in case (1) but are of relatively long duration.

3) SWITCHING WITH OIL CIRCUIT BREAKER

As the three contacts of an oil circuit breaker cannot be expected to open or close exactly simultaneously, their operation also leads to the same situation as in (2) but with very much shortened duration.

4) DYNAMIC OVER VOLTAGES

Unbalanced fault conditions, even in a grounded neutral system, may cause neutral shift of the HV windings and electro-statically induce high potential in a floating winding.

2.2 ELECTROMAGNETIC SURGE TRANSFER

While electrostatic induction can produce dangerous transient voltages when the floating winding is of quite lower voltage rating than the inducing winding electromagnetic induction produces transient voltage approximately proportional to turns ratio in the floating winding. The voltages induced due to electromagnetic induction may become intensified by the oscillations occasioned by a steep front applied voltage.

As a result of mutual inductances between two non-impulsed windings, when one of the winding of a 3 winding transformer is subjected to a surge voltage, the magnitude of transferred surge in

3 winding transformer are generally slightly more in comparison to 2 winding transformer.

CHAPTER -2

LITERATURE STUDY.

2.1 In the bibiliography references of papers on surge phenomena have been given. Out of these, reference numbers 3, 4, and 7 directly deals with surge transfer in 3 winding transformers and auto-transformers.

2.2 P.A. Abetli and H.F. Davis (4) have indicated that only two components of the transferred surge have practical significance i.e. electrostatic and electromagnetic components. Analytical expressions of the terminal voltages have been obtained for both these components for various terminal conditions of the non-impulsed winding. Measurements made on electromagnetic model of a 33.33 MVA, 3 winding transformer are compared with the results of the analytical expressions. Recommendations for the tertiary terminals and apparatus connected to these terminals are made.

In the paper it is indicated that as HV windings are provided with shields, the amplitude of the free oscillations are usually small. Furthermore, in the case of tertiary windings which contain relatively few turns the frequency of oscillations may be as high as 200 KHz so that the free oscillations are damped out entirely after a few cycles, before the electromagnetic component has reached an appreciable value. The finite length of the front of the applied impulse wave (i.e. 1.2μs± 30%) further reduces the amplitude of the free oscillations as compared to the vertical front. It is also indicated that as modern power systems have HV windings connected in grounded Wye or in delta and intermediate windings (in the case of 3 winding transformer) connected to transmission lines with surge impedance 500 Ohm or below, the magnitude of forced oscillations at the tertiary terminals caused by transferred surge phenomena will also be small. Thus only the electrostatic and electromagnetic components are considered important for practical cases.

The electrostatic voltage distribution in all the three windings of a single phase transformers for unit step voltage application has been investigated in detail analytically by P.A. Abetti(3). The main implication to be drawn from this paper has been stated in the paper (4). Analytical expressions for the computation of the transferred electrostatic and electromagnetic voltage components are quite rigorous and determination of correct values for various parameters for modern large capacity EHV transformers are some-what involved.

The main conclusions drawn in the paper are given below :

1) When surges are applied to the HV winding or IV winding of single phase 3 winding transformer, both properly protected, the transferred electrostatic voltage to the tertiary may exceed 80 percent of the basic impulse level of the winding, if the tertiary line terminal is isolated, e.g. connected to a pot head or connected to a short length of cable isolated at its far end or terminated into a surge impedance greater than 100 Ohm.

2) In a 3 phase transformer, if the non-impulse winding under discussion is wye connected or if both the impulsed and the non-impulsed windings are delta-connected, the forgoing conclusions can be applied directly to it. If the non-impulsed winding is delta connected and the primary is wye connected, in effect the non-impulsed winding is grounded through a capacitance equal to its effective capacitance and thus in many cases the electrostatically transferred voltage will be reduced to below 80 percent of the BIL of the winding. These recommendations are quite general and it is suggested to compute the electrostatic and electromagnetic components for specific transformer under consideration according to the methods derived in the paper.

3) Low surge impedances of about 100 Ohm or less or capacitance of a few thousand picofarad on the non-impulsed terminals would eliminate the electrostatic transferred voltage at these terminals.

4) When one of the terminals of non-impulsed winding is isolated or grounded through capacitance or a high resistance the electromagnetic transferred voltage at this terminal may be larger than the turns ratio multiplication even for an applied wave with a 40 to 60 μs tail. In two winding transfromers the electromagnetic component is less than the turns ratio transformation.

The front length of the transferred electromagnet voltage is usually long (10 μs or more).

5) Measurements made on electromagnetic model of 33.33 MVA, 3-winding transformer are in good agreement with the result of the analysis present in this paper.

6) Protection by means of lightning arresters at the non-impulsed winding terminals may be needed when these are isolated or grounded through apparatus having high surge impedance to limit magnitude of transferred surges at these terminal below 80% of rated BIL.

2.3 A.R. Hileman 7 has derived the equivalent circuits to determine the surge voltage transferre electromagnetically through 3-winding, 3 phase, transformers. The validity of the equivalent circuits is proved by impulse tests on transformers. Knowing the transferred voltage, the required degree of lightning protection on the secondary and tertiary terminals can be evaluated

2.4 In the literature study analytical expression to determine the transferred electrostatic or electromagnetic voltages at non-impulsed terminal are given. However the expression for determinin the magnitude of these voltages across the non-impulsed windings are not given which are also quite important as the low voltage stabilising/tertiary w inding are delta connected. Also the expressions for determining the magnitude of electromagnetically transferred voltage at any point other than line terminals of non-impulsed windings are not given. The effect of chopped wave application on the magnitude of transferred surge voltage at non-impulsed terminals has not been discussed analytically. The transferred surge phenomena under switching surges have also not been studied in detail in literature. Also when lightning arresters are installed at the terminals of non-impulsed winding whether it limits the magnitude of transferred surges at these line terminals only or at other points along the non-impulsed winding also is not discussed. The basis on which the BIL of tertiary winding of the transformer should be decided is also not discussed in the literature. Certain other points such as effect of earthed shield outside the tertiary winding, requirements for lightning arresters for protecting tertiary loads are in addition to above on which further work is required.

By conducting experimental studies, some light on these problems is thrown in the dissertation.

CHAPTER - 3.

EXPERIMENTAL SET UP

3.1 DETAILS OF TESTING FACILITY

The lightning and switching impulse voltages having crest values upto 120 Volts were generated by Haefely make recurrent surge generator. The front and tail durations of the generated surge voltage can be adjusted quickly by varying built in front and tail resistors, generator and load capacitances. Provision for connecting external resistances and capacitances to control the wave-shape is also there in the generator. The amplitude of the surge voltage can be controlled by "amplitude control". The generated surge voltage can be chopped at any moment whenever required. The out put of the generator is directly fed to the transformer terminal.

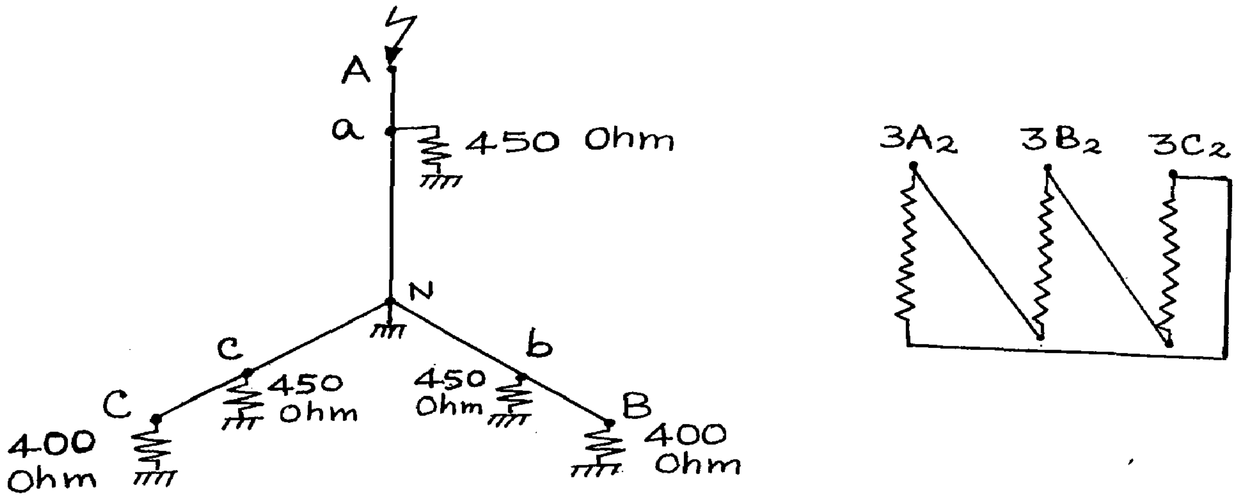
The measurements of surge voltage applied at transformer terminal and transferred voltages at non-impulsed terminals were carried over by Tektronics make precision oscilloscope (Type 507). The oscilloscope is equipped with "differential voltage measuring unit" so that the surge voltage across any two terminals of transformer can be measured. For measurement of surge voltage at non-impulsed terminal with respect to earth, one lead of the measuring unit is connected to that terminal while the other is connected to earth point of the test set up. The oscilloscope probes used for connecting the transformer terminals were having facility to compensate its stray capacitance which otherwise may introduce errors in the readings.

The common neutral of the auto transformer or HV and LV neutral terminals of the system transformer as well as the transformer tank body were connected to a common earth point of the multi-terminal board by wide copper strips. The earth terminals of the generator and oscilloscope were also connected to the earth point of this board which is used to facilitate quick measurements. This earth point is in turn connected to the nearest earth point of the testing hall. The effective resistan of the earthing system is about 0.5 Ohm. The HV, LV and tertiary terminals of the transformer were brought out by insulated leads to the terminal board points.

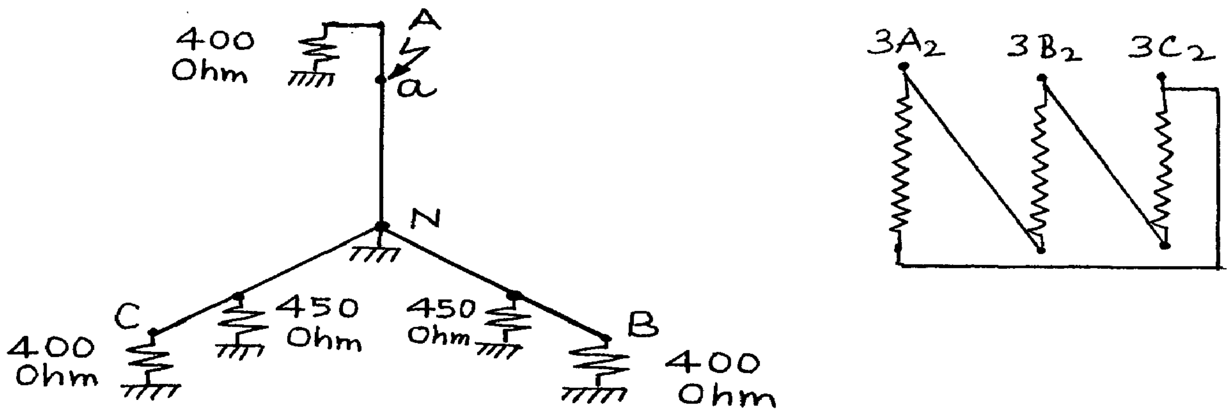
The non-impulsed terminals of 220 kV and 132 kV windings of auto-transformer during transferred surge study were earthed through the resistances of 400 and 500 Ohm. It is assumed that the surge impedance values of 220 kV, 132 kV and 66 kV transmission lines are about 400, 450 and 500 Ohm respectively. The typical test connections for the transformers under study are shown in figures 2,3, and 4 of this chapter.

Termination details for transferred surge study on 3 Phase 220/132/11 kV Auto Transformer

(a) Surge Voltage (from recurrent surge generator) applied on HV terminal 'A'.



(b) Surge voltage applied on LV terminal 'a'



Where A B and C	are	220 kV HV terminals
a b and c	are	132 kV LV terminals
$3A_2$, $3B_2$ and $3C_2$	are	11 kV tertiary terminals
N	is	Neutral terminal

450 and 400 Ohm are terminating resistances for non-impulsed HV and LV terminals respectively

Fig.2

Termination details for 3 pole surge application on 132 kV terminals of 3 Phase 220/132/11 kV Auto Transformer.

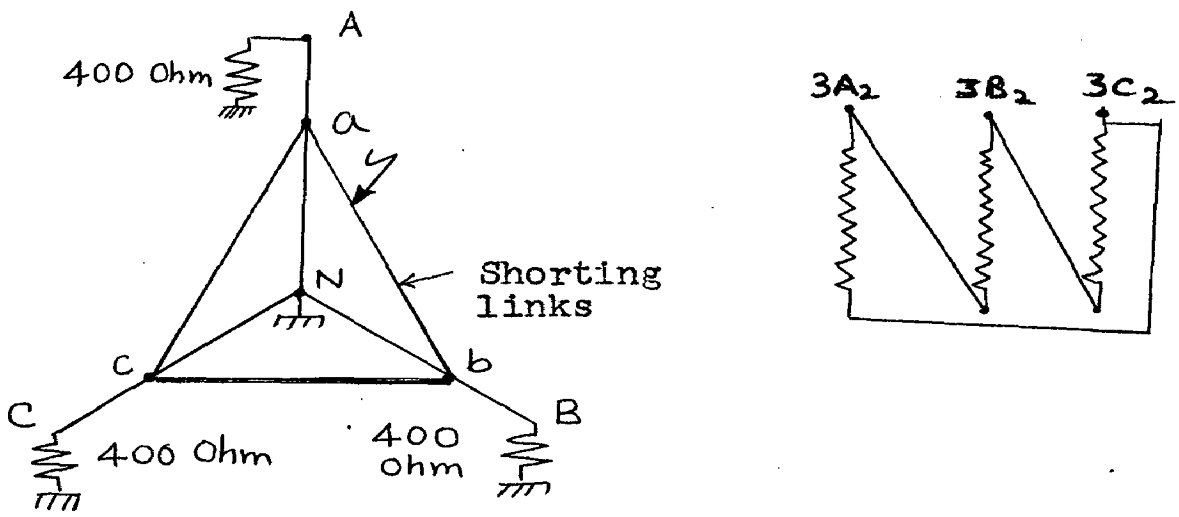
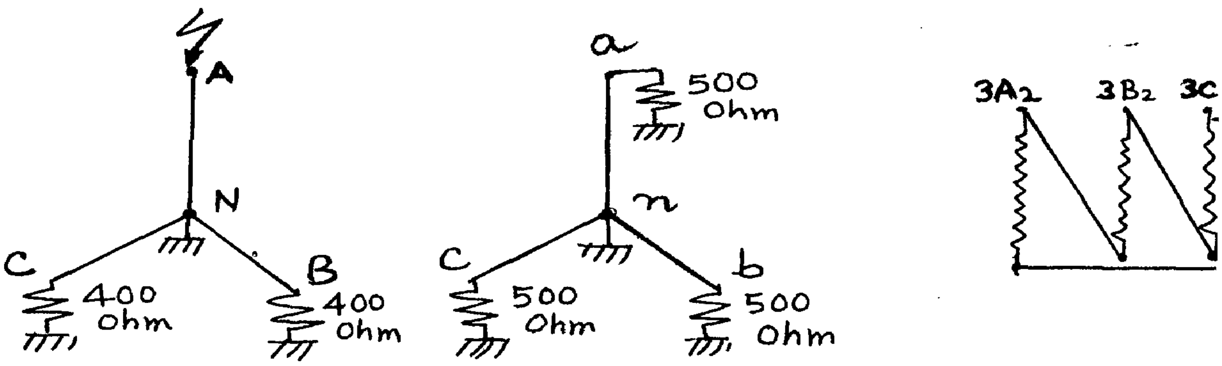


Fig.3

Termination details for transferred surge study on 3 Phase 220/66/11 kV step down system transforme

Surge voltage applied on HV terminal A



Where	A B and C	are	220 kV terminals
	a b and c	are	66 kV terminals
	N and n are		220 kV and 66 kV winding neutrals
	$3A_2$, $3B_2$ and	are	11 kV tertiary terminals

Fig. 4

3.2 PRECAUTIONS OBSERVED

The transformer under study were placed near to the earthing point of the test hall. 60 mm wide copper strips (to have low resistance and inductance) were used for earthing connections. Earthing contacts were made firm by using nuts and bolts. The distance between the transformer, terminal board, measuring equipments and earth point were kept as minimum as possible.

The oscilloscope was calibrated before starting the actual measurements. Also after every two hours interval its calibration was checked.

The values of resistances were measured by avometer before using them. The values of the capacitors employed during experimental study were also checked.

3.3 DETAILS OF THE TRANSFORMERS USED FOR EXPERIMENTAL STUDY.

220 kV class auto-transformers having different percentage impedance values, voltage and MVA ratings, BIL levels and having either loaded tertiary or stabilising windings were selected for experimental studies to have the over all idea. It is seen that in some transformers electrical clearances between various coils are less as compared to others (e.g. refer page Nos.30 and 62). These clearances depend upon the specified test levels, percentage impedance values between pair of windings, cooli considerations etc. 3 Phase 220/66/11 kV step

down system transformers were also studied. The transferred surge study on 50 MVA system transformer is only considered in the dissertation as the magnitude of transferred surge on it were slightly higher than found in the case of 67 MVA transformer. The details of the transformers are given below. All the auto-transformers have star auto/delta winding connections with vector relationship HV-LV: Yyo, HV-TV: Yd 11. These transformers (except serial number 5) are equipped with on load tapchangers at LV line end for ± 10% variation in 16 equal steps of LV side voltage. All percentage impedance voltage values between pair of windings mentioned are based on rated MVA of the transformers.

1. 3 Phase, 50 Hz, 50 MVA, 220/132/11 kV Auto-transformer with percentage impedance values between HV-LV, HV-TV and LV-TV 9.75, 33 and 21.7 respectively. Rated Tertiary rating: 15 MVAr, HV and LV BILs 900 and 500 kVp.
2. 3 Phase, 50 Hz, 100 MVA, 220/132/11 kV Auto-transformer with percentage impedance values between HV-LV, HV-TV and LV-TV 15, 54.5 and 36 respectively. Tertiary rating: 30 MVAr, HV and LV BILs 900 and 550 KVp.
3. 3 Phase, 50 Hz, 100 MVA, 220/132/11 kV Auto transformer with percentage impedance values between HV-LV, HV-SV and LV-SV 10.5, 36 and 24

respectively. 11 kV delta winding designed for stabilising purpose. HV and LV BILs: 900 and 550 KVp.

4. 3 Phase, 50 Hz, 100 MVA, 220/110/11 kV Auto-transformer with percentage impedance values between HV-LV, HV-TV and LV-TV 15.2, 41.3 and 23 respectively. Tertiary rating: 30 MVAr, HV and LV BILs: 900 and 450 KVp.

5. 3 Phase bank formed using 3 numbers single phase $\frac{220}{\sqrt{3}}$ / $\frac{110}{\sqrt{3}}$ / 11 kV Auto transformers with off circuit tap switch at LV line end for $-1\frac{1}{2}$ to $+ 7\frac{1}{2}$ LV voltage variation in steps of $2\frac{1}{2}$%. Percentage impedance values between HV-LV, HV-SV and LV-SV 10, 30 and 18 respectively. 11 kV delta windings are designed for stabilising purpose. HV and LV BILs: 1050 and 550 KVp.

6. 3 Phase, 50 Hz, 50 MVA, 220/66/11 kV star/star/delta connected step down system transformer with percentage impedance values between HV-LV, HV-TV and LV-TV:15, 22.6 and 4.9 respectively. HV and LV BILs: 900 and 325 KVp.

For HV and LV of the above transformers shielded layer type winding and reverse section disc type winding (with static rings at both the ends) are used. Interwound helical or interwound spiral coils are used for tapping winding, former is used when current rating is high. For loaded tertiary/stabilising windings, helical/spiral type coils have been used. These types of windings are commonly used by the transformer manufacturers. A few manufacturers use inter-leaved disc type winding for 220 kV rating. The reduction of the oscillations in the HV winding as the result of interleaved design will cause reduction in the forced oscillatory component of the transferred voltage on LV or tertiary windings. Also the transient voltage distribution in tertiary coils will slightly improve a uniform impulse voltage distribution is obtained in inter-leaved disc type winding. Figures 5 and 6 indicate the general arrangement of windings in 220 kV class auto and 3 winding transformers.

3.4 DETAILS OF MEASUREMENTS

When impulse voltage applied on a transformer terminal (either HV or LV) the transferred surge voltage at all non-impulsed terminals with respect to earth were noted. In the case of tertiary, the transferred surge voltage across the coils were also measured. As the magnitude of transferred surges on tertiary exceed the rated BIL for 11 kV system, detailed study is made.

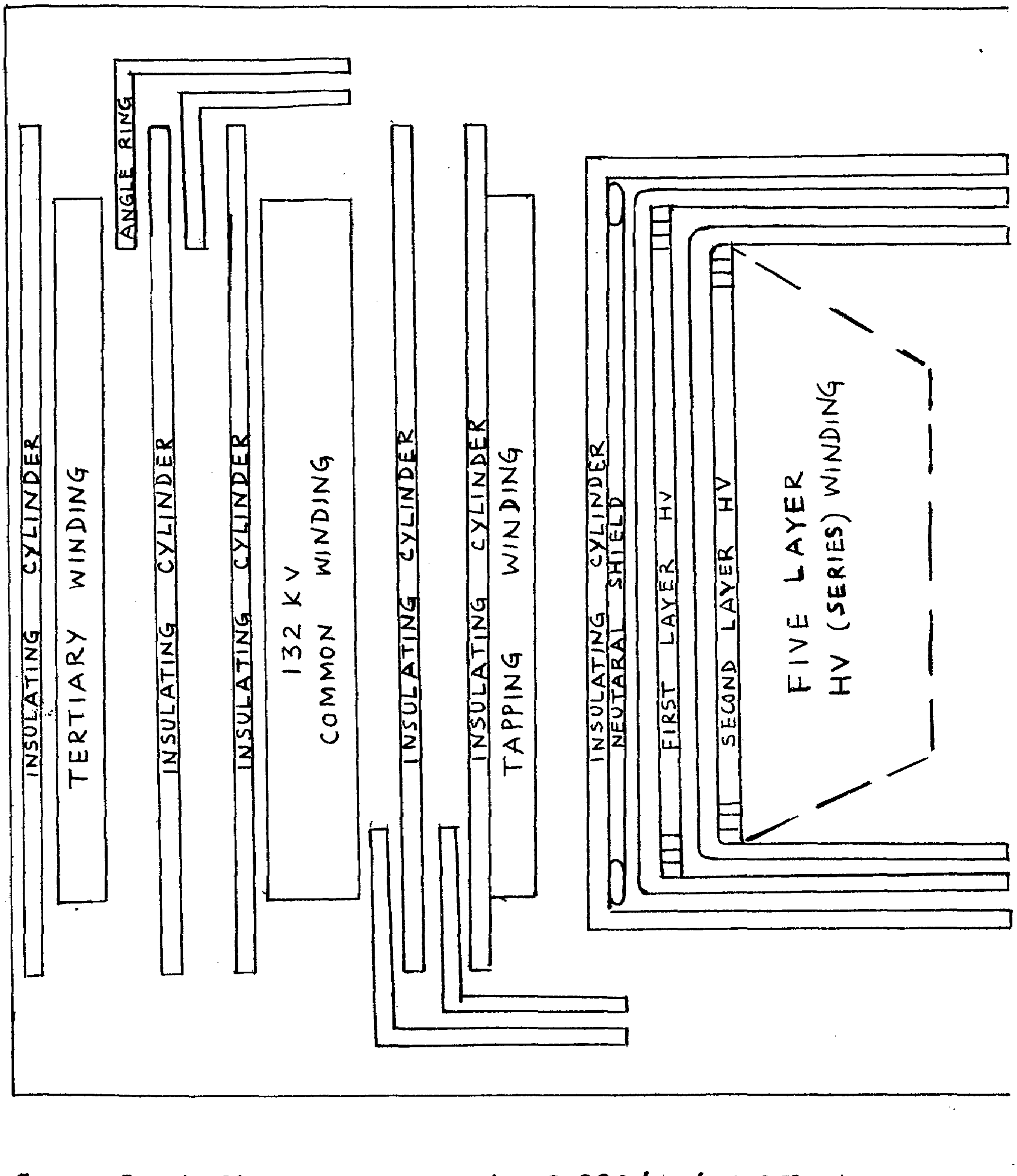
The magnitude of transferred surge voltage measured on tertiary at following different terminal conditions :

i) Tertiary terminals kept unloaded

ii) One tertiary terminal earthed and other two kept floated.

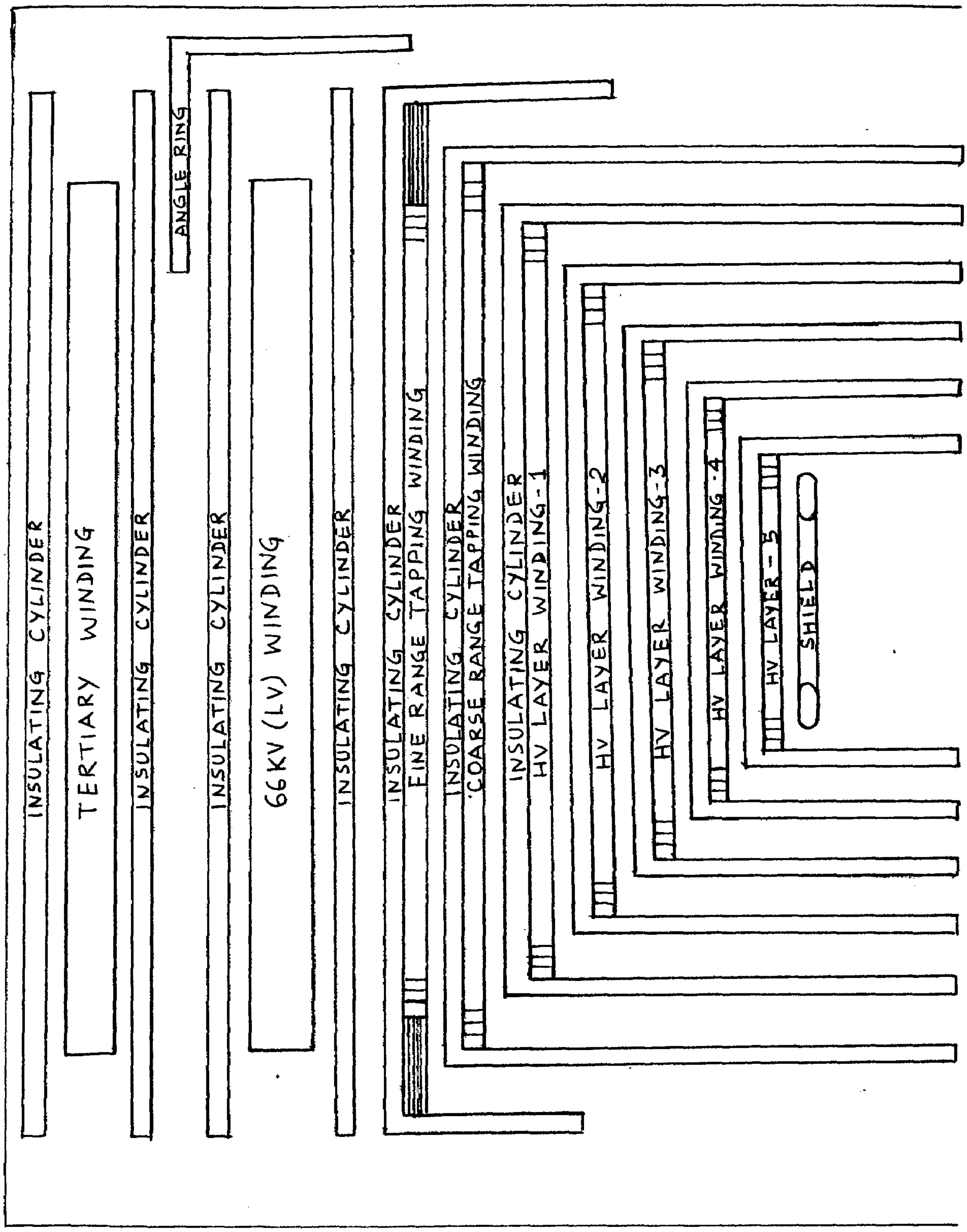
iii) Terminals earthed through capacitors

iv) Terminals earthed through resistors and



General winding arrangement of 220/132/11 kV step down Auto transformer

Fig. 5



General winding arrangement of 220/66/11 kV
Step down system transformer.

Fig. 6

v) Terminals earthed through reactors.

As there was very little change in the magnitude of the surges transferred from HV to LV terminal or vice versa due to different tertiary terminations, these measurements were not repeated in all the cases.

The effect of chopped impulse voltage applicatio on transferred surges were also studied. The magnitude of applied full wave impulse voltage or chopped impulse voltage were kept same as it is recommended in IS 2026. The effect on transferred surges due to the application of 0.7/100μS impulse voltage, switching surges, 2 and 3-pole surges were also studied. The test results are tabulated in Chapter 5. The values indicated in the table are the peak magnitude of transferred surges at different non-impulsed terminals considering when rated impulse voltage is applied on a terminal (e.g. 900 KVp on HV terminal). Typical photographs of the transferred surges are also shown in chapter 5.

The crest values of the transferred surge voltag (e.g. the highest amplitude when transferred surge is oscillatory in nature) is noted. Whenever required the crest values of electromagnetic and electrostatic components of the transferred surge are also separately noted.

4.1 TRANSFORMER SERIAL NUMBER 1

3 Phase, 50 MVA, 220/132/11 kV Auto transformer

GENERAL PARTICULARS

Impulse voltage levevel

HV	900 KVp
LV	550 KVp

Percentage impedance voltage at rated MVA

% Z H-L	9.75
% Z H-T	33.0
%Z L-T	21.7

Core details:

Diameter	550 mm
Length	2360 mm

Electrical clearances:

Core - TV	20 mm
TV - LV	58 mm
LV - TAPS	54 mm
TAPS - HV	48 mm

Coil thickness:

TV	37 mm
LV	78 mm
TAPS	19 mm
HV	57.5 mm (excluding 88 mm interlayer clearances)

CHAPTER - 4

EXPERIMENTAL RESULTS

I. 1.1/48 microsecond impulse voltage applied on HV terminal A

Magnitude of applied impulse voltage considered: 900 KVp

Transferred surge voltage at (i) LV terminal 'a' : 262.5 KVp (29%)
(ii) LV terminal 'B' & 'C' : 54.5 KVp
(iii) HV terminal 'B' & 'C' : 52.5 KVp

Tertiary terminal	Transferred surge peak magnitude (KVp) on tertiary terminals						
	Case 1 unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminal $3B_2$ earthed	Case 4 terminal $3C_2$ earthed	Case 5 terminals earthed by R=500 Ohm	Case 6 terminals earthed by c= 0.1 μF	Case 7 terminals earthed by c = 0.25 μF
$3A_2$-Earth	70	Zero	60.8	60.5	48	7.5	6
$3B_2$ - Earth	60	-52.5	Zero	-52.5	±38.8	Nil	Nil
$3C_2$ - Earth	-58	-61.5	-56.3	Zero	40	-7.5	-6
$3A_2$ - $3B_2$	-40	52.5	60.8	-40	24	7.5	6
$3B_2$ - $3C_2$	54.5	54.5	56.3	-52.5	29	7.5	6
$3C_2$ - $3A_2$	-27	-61.5	-28	-60.5	-12.5	-15	-12

II. Chopped Impulse Voltage applied on <u>HV terminal A</u> (Chopped at 1.5 μs)

Magnitude considered : 900 KVp

Transferred surge voltage at LV terminal 'a' : 343 KVp (38.1%)

Tertiary terminals	Transferred surge peak magnitude (KVp) on tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by R=500 Ohm	Case 4 terminals earthed by C= 0.1 μF
$3A_2$ - Earth	-144	Zero	-113	5
$3B_2$ - Earth	124	124	97	3
$3C_2$ - Earth	-144	-145	-113	-5
$3A_2$ - $3B_2$	-75	-124	- 48	-5.5
$3B_2$ - $3C_2$	-116	116	- 47.6	-6
$3C_2$ - $3A_2$	± 25	-145	- 17	-7.5

III. Impulse Voltage (0.7/100 micro second) applied on <u>HV terminal</u>)

Magnitude considered : 900 KVp

Transferred surge voltage at LV terminal 'a' : 306 KVp (34%)

Tertiary terminals	Transferred surge peak magnitude (KVp) on tertiary terminals			
	Case 1 unloaded terminal	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by R=500 Ohm	Case 4 terminals earthed by C= 0.1 μF
$3A_2$ - Earth	76.5	Zero	55	9
$3B_2$ - Earth	-66	-58	-41	Nil
$3C_2$ - Earth	65	-65	46	-9
$3A_2$ - $3B_2$	42	58	26	9
$3B_2$ - $3C_2$	55	54	30	9
$3C_2$ - $3A_2$	-27	-65	-15	-18

IV. 1.1/50 micro second impulse voltage applied on <u>LV terminal 'a'</u>

(Magnitude considered : 550 KVp)

Transferred surge voltage at (i) HV terminal 'A' : 193 KVp (35%)
(ii) HV terminal 'B' and 'C' : -55 KVp
(iii) LV terminals 'b' and 'c' : -51.3KVp

Tertiary terminals	Transferred surge peak magnitude (KVp) on tertiary terminals						
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminal $3B_2$ earthed	Case 4 terminal $3C_2$ earthed	Case 5 terminals earthed by R=500 Ohm	Case 6 terminals earthed by C=0.1μF	Case 7 termin earthe by C=C
$3A_2$ - Earth	103.5	Zero	103	103	70	43	41.0
$3B_2$ - Earth	101	-126	Zero	77.4	-40	nil	nil
$3C_2$ - Earth	73.3	-106	-86	zero	52	-43	-41.0
$3A_2$ - $3B_2$	92	126	102	94	50	43	41.0
$3B_2$ - $3C_2$	132	135	86	102	72	43	41.0
$3C_2$ - $3A_2$	-75	-106	-76	75.4	-55	-86	82

V. Impulse voltage chopped at 3 μS applied on LV terminal 'a'

(Magnitude considered : 550 KVp)

Transferred surge peak magnitude at HV terminal 'A' : -256.8 KVp (46.7 %)

Tertiary terminals	Transferred surge peak magnitude (KVp) on tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$earthed	Case 3 terminals earthed by R=500 Ohm	Case 4 terminals earthed by C = 0.1 μF
3A2 - Earth	103.5	Zero	82.5	8
$3B_2$ - Earth	146	- 128	90	Nil
$3C_2$ - Earth	-125	- 175	-102.5	-8
$3A_2$ - $3B_2$	-154	128	-81	8
$3B_2$ - $3C_2$	178	180	104	8
$3C_2$ - $3A_2$	- 38	- 175	-25	-16

VI. 0.7/100 micro second impulse voltage applied on LV terminal

(Magnitude considered : 550 KVp

Transferred surge peak magnitude at HV terminal 'A' : 223 KVp (40.6%)

Tertiary terminals	Transferred surge peak magnitude (KVp) on tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by R = 500 Ohm	Case 4 terminals earthed by C = 0.1 μS
$3A_2$ - Earth	113.6	Zero	79.6	45
$3B_2$ - Earth	110	-130	- 44.5	Nil
$3C_2$ - Earth	78	-112	58	-45
$3A_2$ - $3B_2$	93	130	51	45
$3B_2$ - $3C_2$	132	136	76	45
$3C_2$ - $3A_2$	-73.5	-112	-56.5	-90

VII. Switching Surge Voltage applied on <u>HV terminal 'A'</u>

Wave Shape : 180/2000μs, Switching impulse level : 750 KVp

Transferred surge peak magnitude at LV terminal 'a' : 438.8 KVp (58.6%)

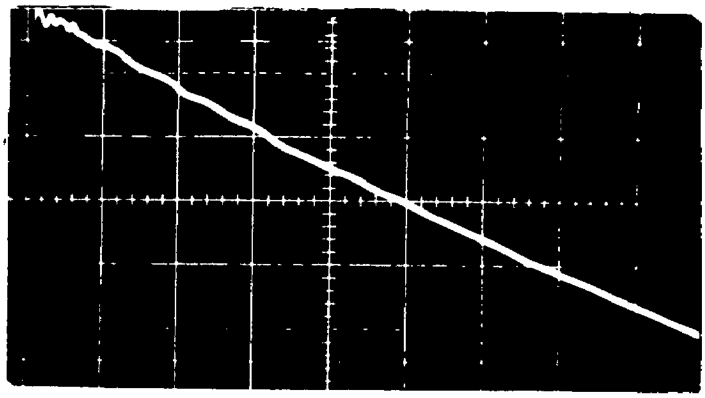
Tertiary terminals	Transferred surge peak magnitude (KVp) on tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthedby R = 500 Ohm	Case 4 terminals earthed by C = 0.25μF
$3A_2$ - Earth	40	Zero	23.5	23.5
$3B_2$ - Earth	18	-23.5	Negligible	Negligible
$3C_2$ - Earth	-9	-47	-23.5	-23.5
$3C_2$ - 3A2	47	-47	-47	-47

VIII. Switching surge voltage applied on <u>LV terminal 'a'</u>

Wave shape : 180/2000 μs , Switching impulse level considered : 460 KVp

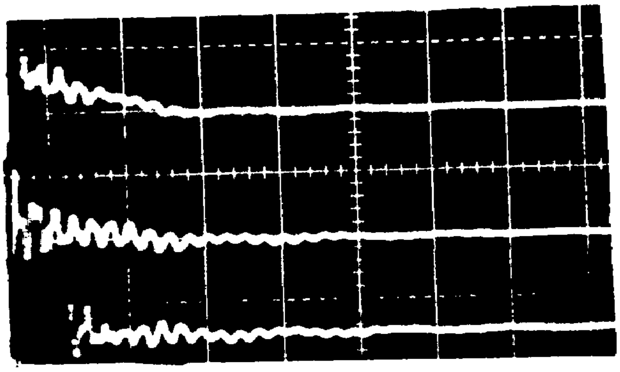
Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by R= 500 Ohm	Case 4 terminals earthed by C= 0.25 μF
$3A_2$ - Earth	46	Zero	25	25
$3B_2$ - Earth	23	-25	Negligible	Negligible
$3C_2$ - Earth	-16	-50	-25	-25
$3C_2$ - $3A_2$	50	-50	-50	-50

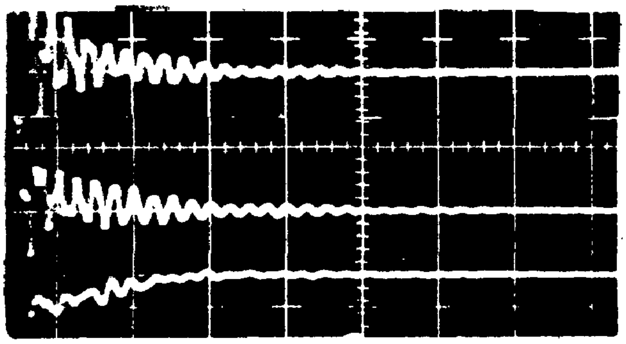
I. Surge Oscillograms when 132 kV winding terminals of auto transformer impulsed (non-impulsed terminals of 220 kV and 132 kV windings earthed by respective surge impedance).



(1) Applied impulse voltage on 'a' phase LV terminal
Magnitude: 20V/unit, Time base: 10 μs/unit

1.1 Tertiary kept unloaded



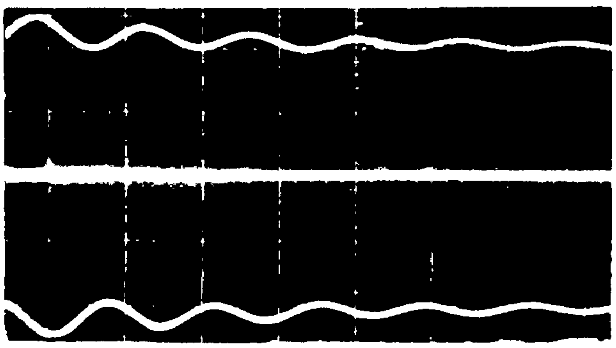


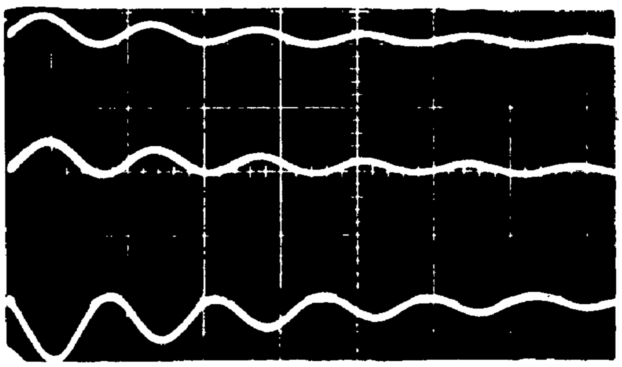
(2) Surges at tertiary terminals $3A_2$, $3B_2$, $3C_2$

(3) Surges across terminals $3A_2 - 3B_2$, $3B_2 - 3C_2$, $3C_2 - 3A_2$

Magnitude: 20V/unit, Time base: 50μs/unit

1.2 Tertiary earthed through C = 0.1 μF



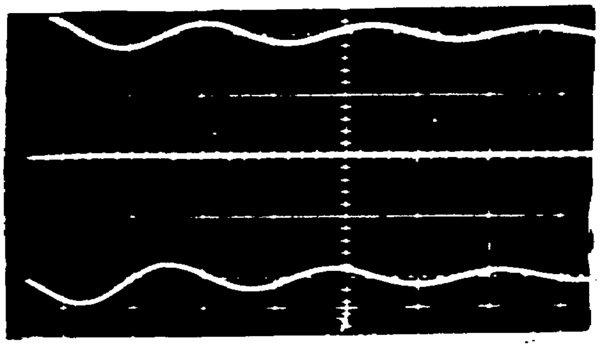


(4) Surges at tertiary terminals

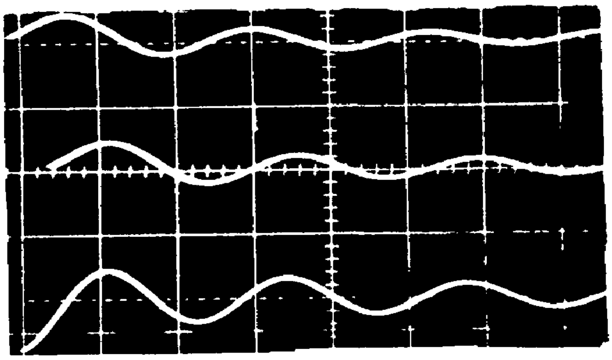
(5) Surges across terminals $3A_2$-$3B_2$, $3B_2$-$3C_2$, $3C_2$-$3A_2$

Magnitude: 20V/Unit, Time base: 50 μs/unit

1.3 Tertiary earthed through C = 0.25 μF



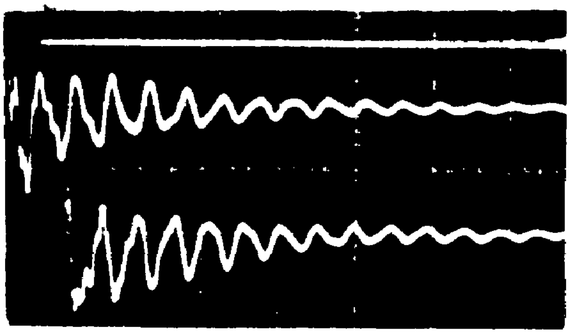
(6) Surges at tertiary terminals $3A_2$, $3B_2$, $3C_2$



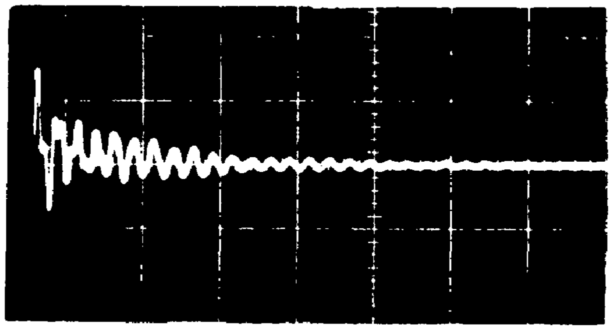
(7) Surges across terminals $3A_2$-$3B_2$, $3B_2$-$3C_2$, $3C_2$-$3A_2$

Magnitude: 20V/unit, Time base: 20 μs/unit

1.4 Tertiary terminal $3A_2$ earthed, remaining unloaded



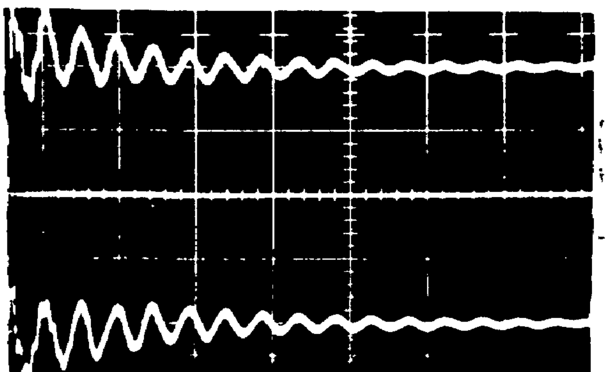
(8) Surges at tertiary terminals $3A_2$, $3B_2$, $3C_2$



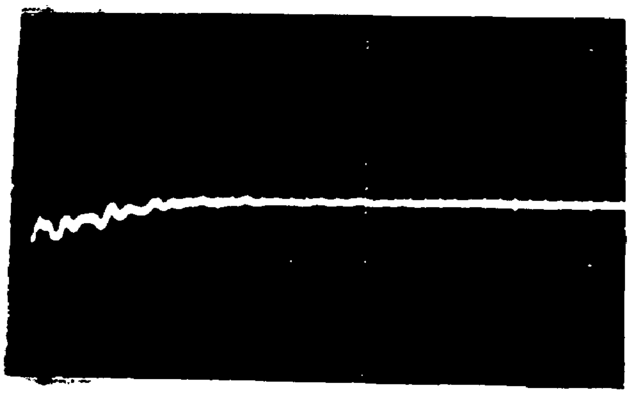
(9) Surges across terminals $3B_2$-$3C_2$.

Magnitude: 20V/unit, Time base: 20 μs /unit (LHS)
50 μs/unit (RHS

1.5 Tertiary terminal $3B_2$ earthed, remaining unloaded



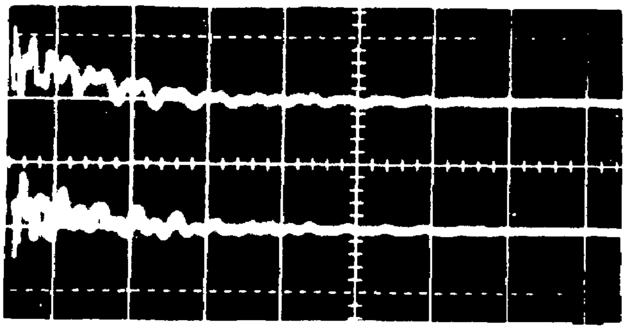
(10) Surges at tertiary terminals 3A2, $3B_2$ and $3C_2$

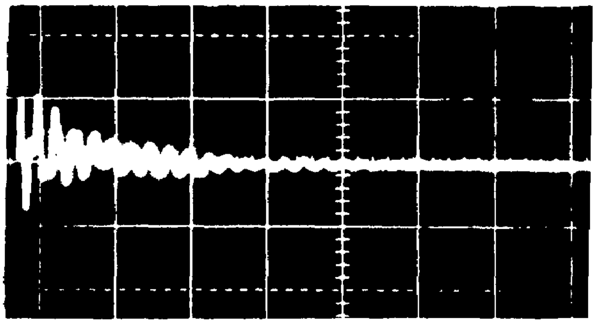


(11) Surges across terminals 3C2-$3A_2$.

Magnitude: 20V/Unit. Time base: 20 μs/unit(LHS).50 μs/u

1.6 Tertiary terminal $3C_2$ earthed, remaining unloaded



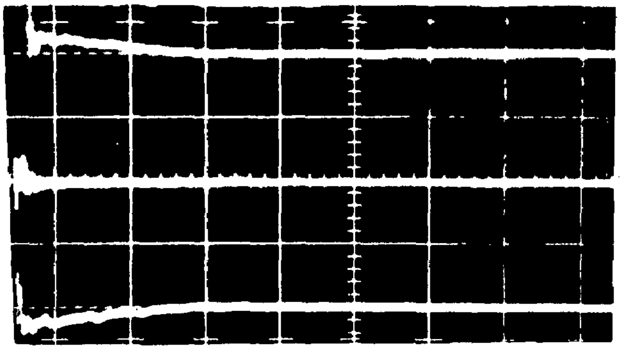


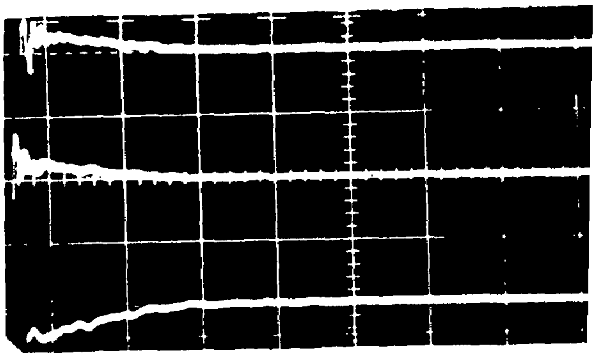
(12) Surges at tertiary terminals $3A_2$, $3B_2$,

(13) Surges across terminals $3A_2$-$3B_2$,

Magnitude: 20V/unit, Time base: 50 μs/unit

1.7 Tertiary earthed through 500 Ohm resistors



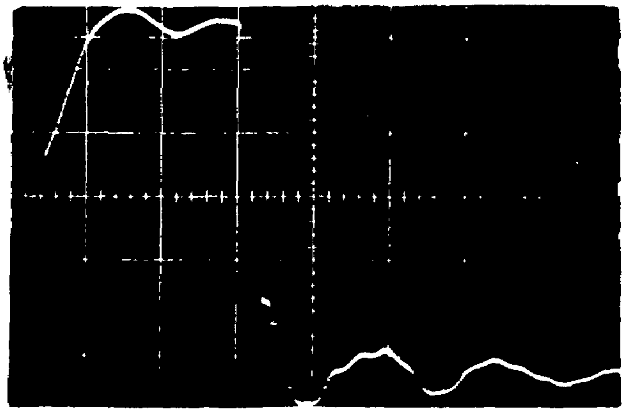


(14) Surges at tertiary terminals $3A_2$, $3B_2$ and $3C_2$

(15) Surges across terminals $3A_2$-$3B_2$, $3B_2$-$3C_2$, $3C_2$-$3A_2$

Magnitude: 20 V/unit, Time base: 50 μs/unit

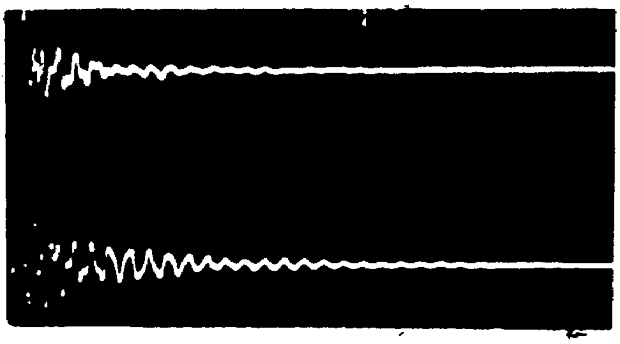
1.8 Chopped impulse voltage application



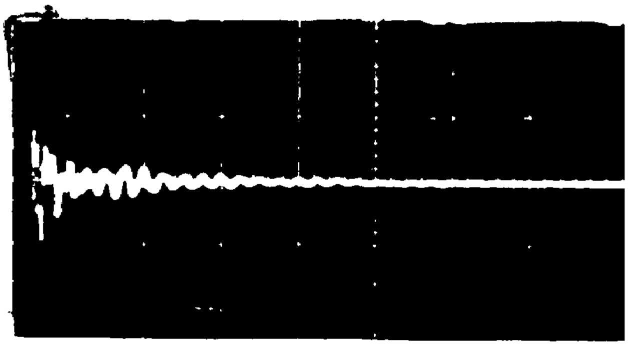
(16) Applied impulse oscillogram at LV 'a' phase

Magnitude: 20V/unit, Time base: 1 μs/unit

1.9 Tertiary kept unloaded

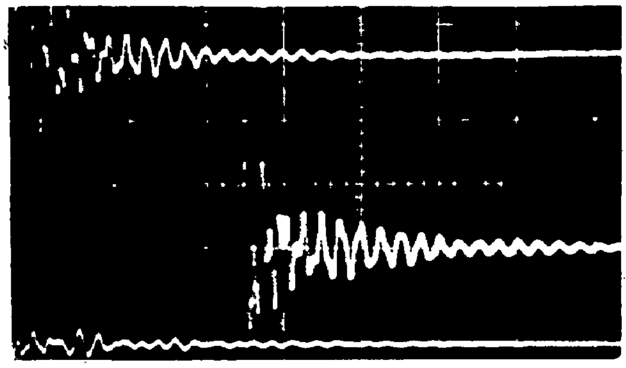


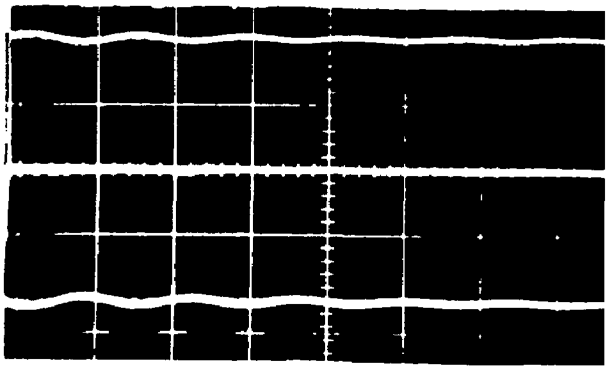
(17) Surges at terminals $3A_2$ & $3B_2$



(18) Surge at terminal $3C_2$

Magnitude: 20V/unit, Time base: 50μs/unit





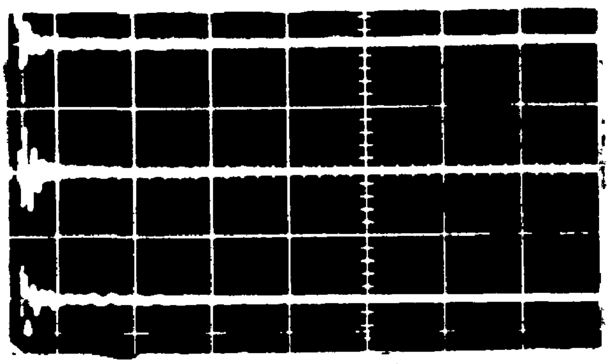
Surges across terminal $3A_2$-$3B_2$, $3B_2$-$3C_2$, $3C_2$-$3A_2$

(19) terminals unloaded

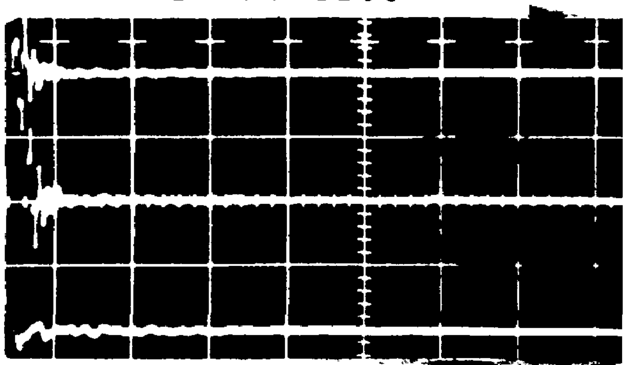
(20) terminals earthed by c = 0.1μF

Magnitude: 20V/Unit, Time base: 50μs/unit

1.10 Tertiary earthed through 500 Ohm resistors.



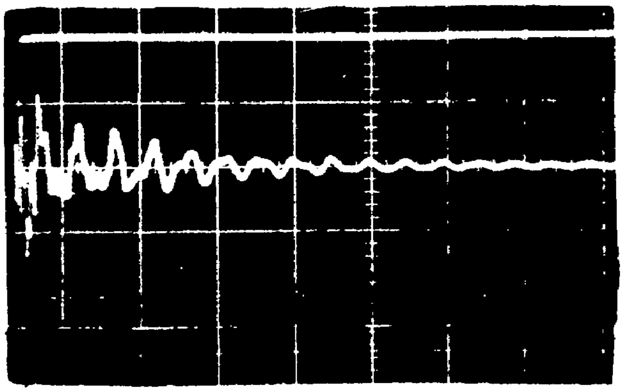
(21) Surges at tertiary terminals $3A_2$, $3B_2$, $3C_2$

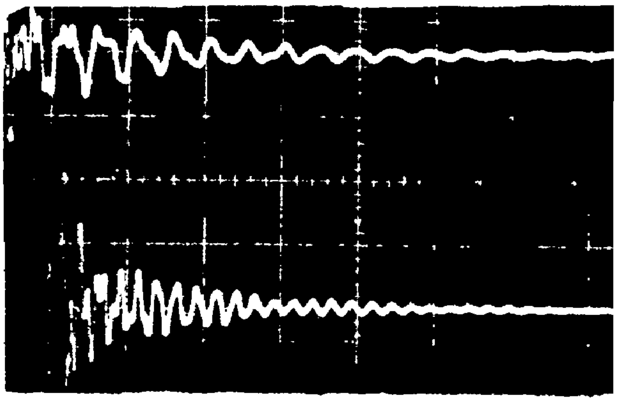


(22) Surges across terminals $3A_2$-$3B_2$, $3B_2$-$3C_2$, $3C_2$-$3B$[illegible]

Magnitude: 20V/unit, Time base: 50μs/unit

1.11 Tertiary terminal $3A_2$ earthed, remaining unloaded



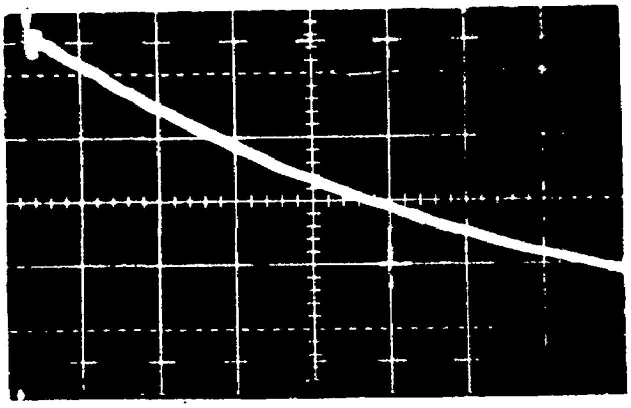


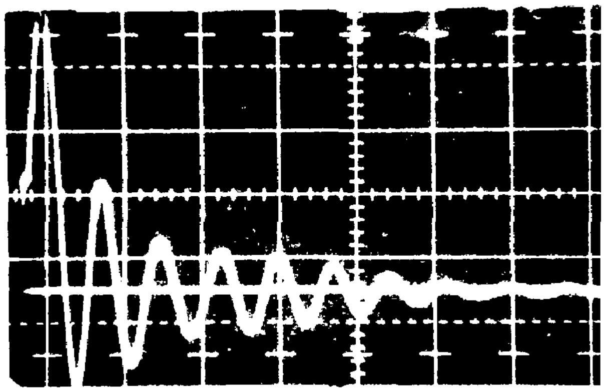
(23) Surges at terminals $3A_2$ and $3B_2$

(24) Surge at terminal $3C_2$ and across $3B_2$-$3C_2$

Magnitude: 20V/unit, Time base: 20μs/unit

II. HV non-impulsed terminals kept unloaded.

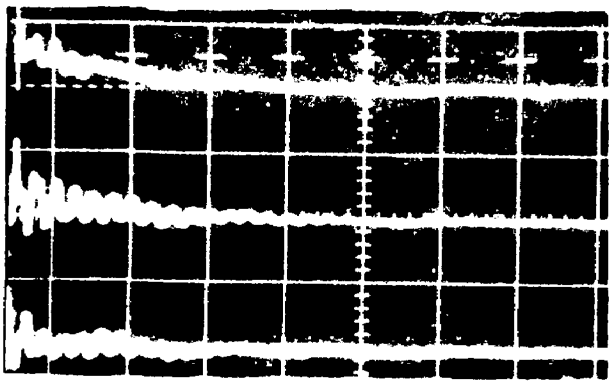


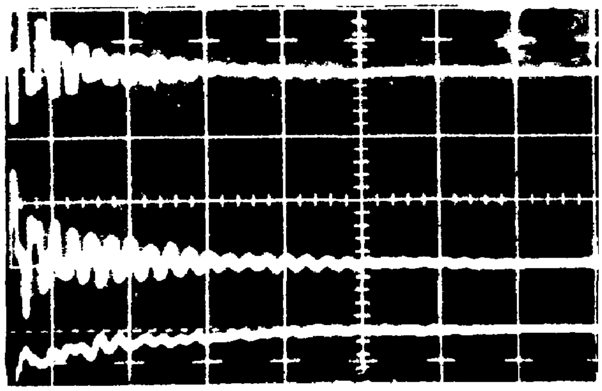


(25) Applied impulse at LV 'a'
Magnitude: 10V/unit
Time base: 10μs/unit

(26) Surge at HV terminal 'A'
Magnitude: 20V /unit
Time base: 200μs/unit

2.1 Tertiary kept unloaded.



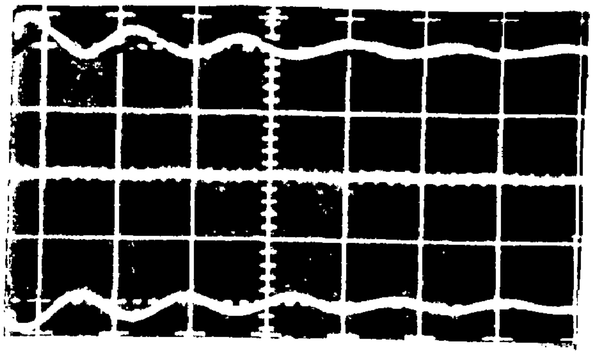


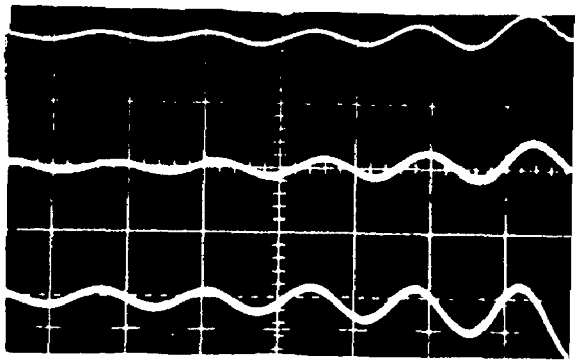
(27) Surges at tertiary terminals
$3A_2$, $3B_2$, $3C_2$

(28) Surge across terminals
$3A_2$-$3B_2$, $3B_2$-$3C_2$, $3C_2$-$3A_2$

Magnitude: 10V/unit, Time base: 50μs/unit

2.2 Tertiary earthed through $C = 0.1 \mu F$





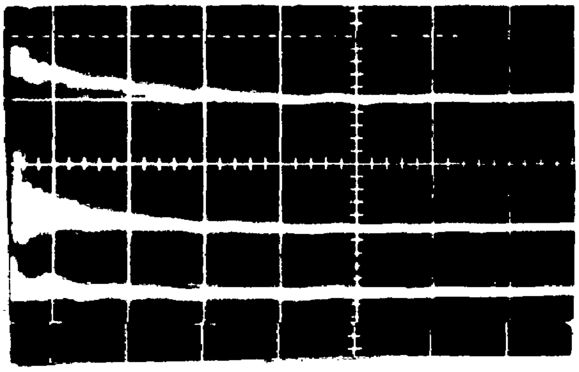
(29) Surges at tertiary terminal $3A_2, 3B_2, 3C_2$

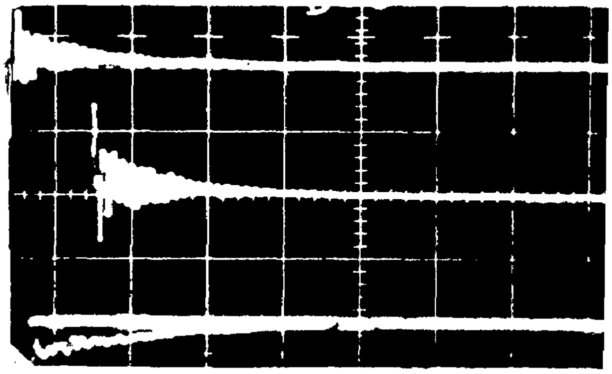
(30) Surges across terminals $3A_2-3B_2$, $3B_2-3C_2$, $3C_2-3A_2$

Magnitude: 10V/unit, Time base: 50μs/unit

I. 0.7/100μs Impulse Voltage applied on <u>LV terminal</u> 'a', remaining condition same as in I, (Magnitude: 120 Volts

3.1 Tertiary kept unloaded.



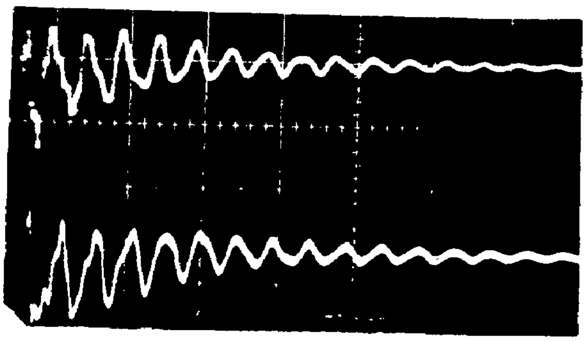


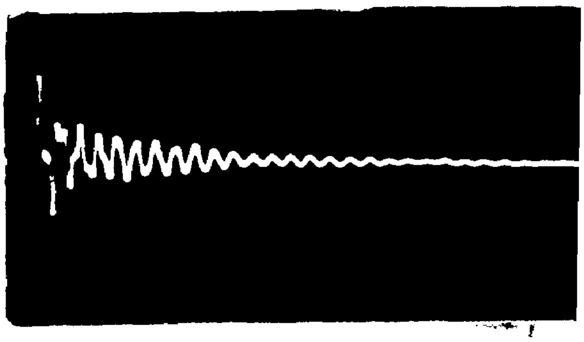
(31) Surges at tertiary terminals $3A_2, 3B_2, 3C_2$

(32) Surges across terminals $3A_2-3B_2$, $3B_2-3C_2$, $3C_2-3A_2$

Magnitude: 20V/unit, Time base: 20μs/unit

3.2 Tertiary terminal $3A_2$ earthed, remaining unloaded.



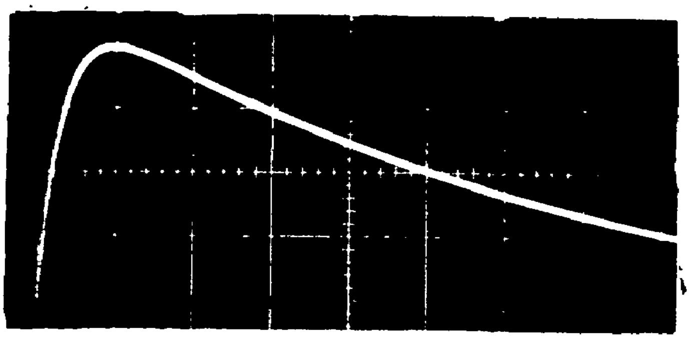


(33) Surges at tertiary terminals $3A_2$, $3B_2$, $3C_2$

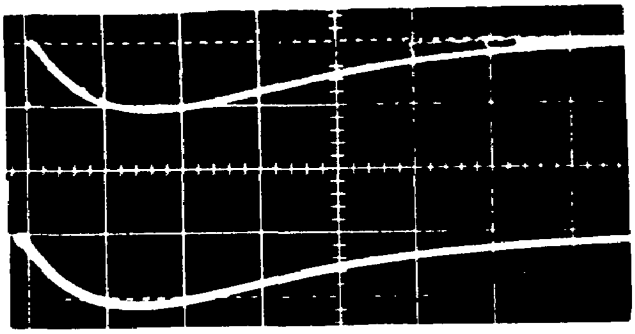
(34) Surges across terminal $3B_2-3C_2$

Magnitude: 20V/unit, Time base: 20μs/unit

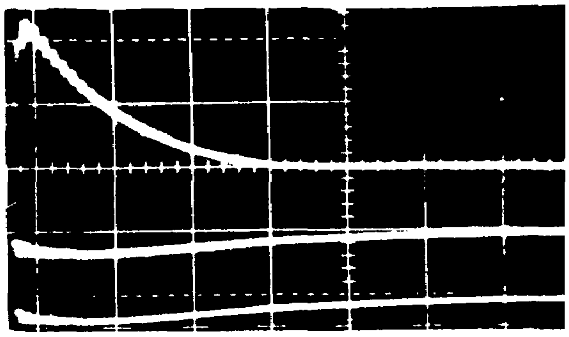
IV. Oscillograms of transferred switching surges when 220 kV HV, 'A' Phase terminal impulsed (non-impulsed terminals of LV kept unloaded)



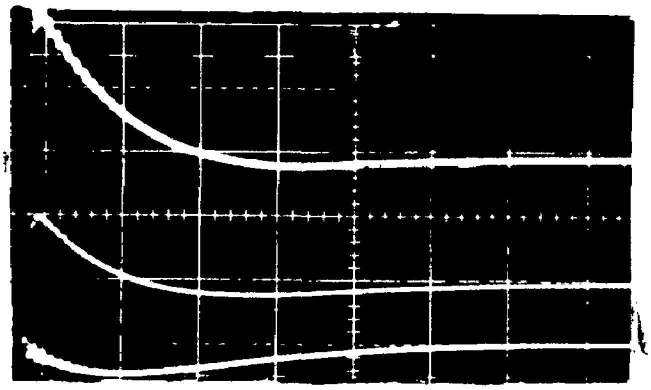
(35) Applied 220/1000μs Switching impulse at HV terminal 'A', Magnitude: 20V/unit, Time base: 200μs/unit



(36) Surges at HV terminals B and C
Magnitude: 10V/unit
Time base: 1000μs/unit



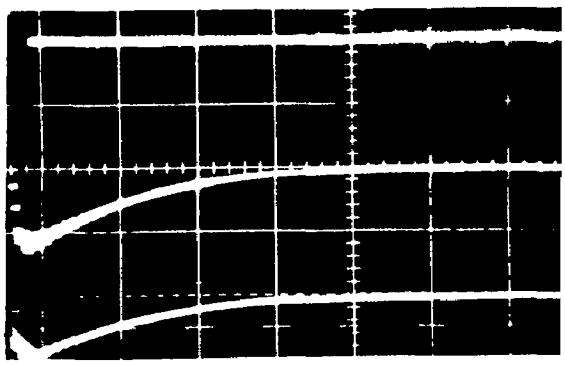
(37) Surges at terminals a, b and c
Magnitude: 20V/unit
Time base: 1000μs/unit



(38) Surges at unloaded tertiary terminal $3A_2$, $3B_2$, $3C_2$

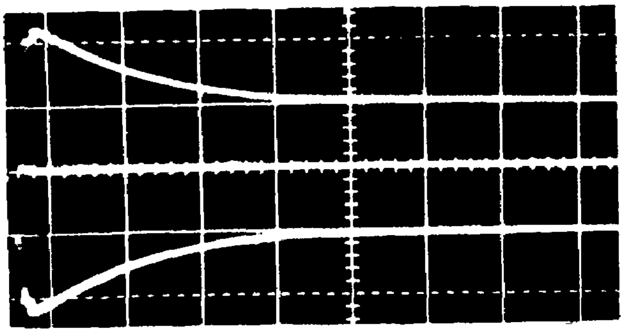
Magnitude: 2V/unit

Time Base: 1000μs/unit



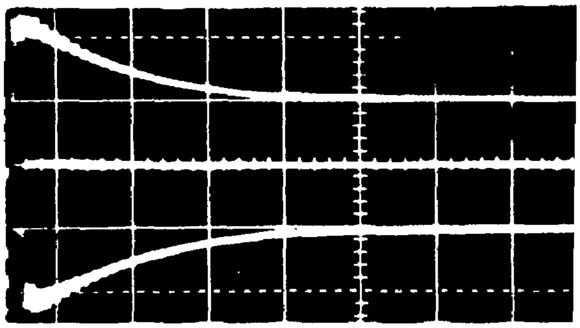
(39) Surges at terminal $3A_2$, $3B_2$, $3C_2$ when $3A_2$ earthed.

Magnitude: 2V/Unit(excep
for $3C_2$ it is 5V/unit
Time base: 1000μs/unit



(40) Surges at $3A_2$, $3B_2$, $3C_2$

when tertiary earthed by 500 Ohm

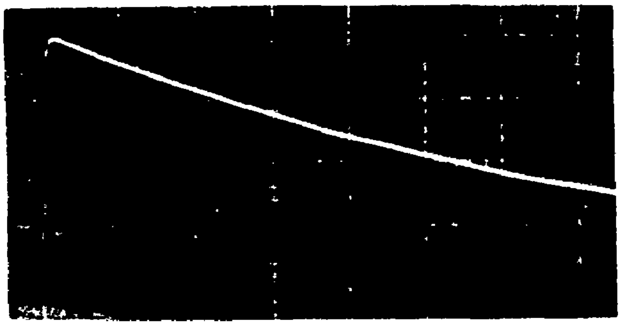


(41) Surges at $3A_2$, $3B_2$, $3C_2$

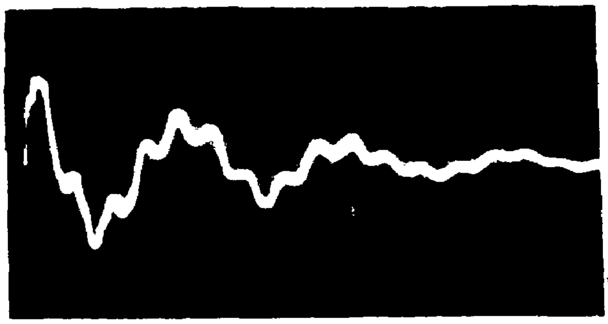
when tertiary earthed b
$C = 0.1 \mu F$

Magnitude: 2V/unit, Time base: 1000μs /unit

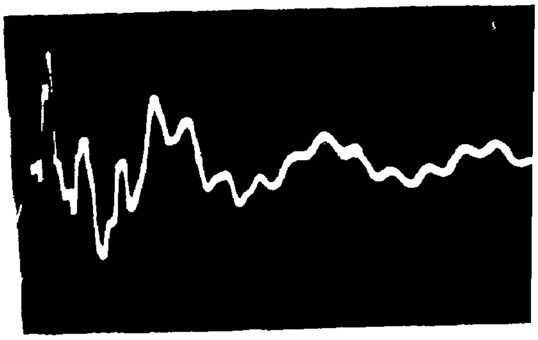
Transferred surge oscillogram for 3 phase bank of 100 MVA 220/132/33 kV Auto Transformer (33 kV tertiai with ± 5% off circuit taps to centre).



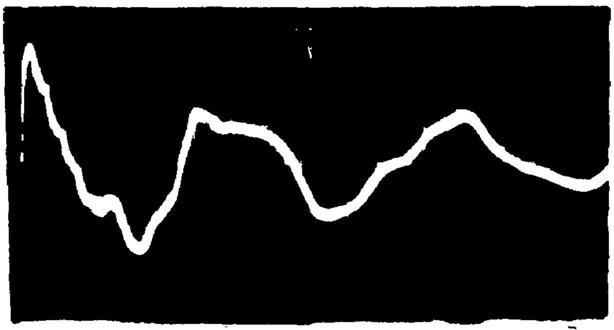
(1) Applied impulse voltage on LV terminal 'a'
Magnitude 20V/Unit, Time base: 10 μs/Unit.



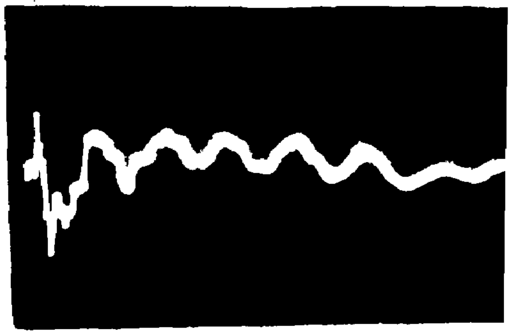
(2) Surge at terminal $3B_2$
Magnitude: 10V/Unit
Time base: 50 μs /Unit



(3) Surge at terminal $3C_2$
Magnitude: 5V/Unit
Time base: 50 μs/Unit



(4) Surge at centre point of tertiary coil C.
Magnitude: 10V/Unit
Time base: 20 μs /Unit



(5) Surge across 2½% turns of coil C
Magnitude: 2 V/Unit
Time base: 20 μs/Uni

4.2 TRANSFORMER SERIAL NUMBER 2

3 Phase, 100 MVA, 220/132/11 kV Auto Transformer

GENERAL PARTICULARS

Impulse voltage level

HV	900 KVp
LV	550 KVp

Percentage imedance voltage at rated MVA

% Z	H–L	14.8
% Z	H–T	52.5
% Z	L–T	33.5

Core details

Diameter	540 mm
Length	2360 mm

Coil thickness

TV	55 mm
LV	106.5 mm
TAPS	20.5 mm
HV	58.5 mm (excluding 88 mm inter-layer clearances)

Electrical clearances

Core – TV	20 mm
TV – LV	59 mm
LV – TAP	58 mm
TAP – HV	50 mm

I. 1.1/46 micro second impulse voltage applied on <u>HV terminal 'A'</u>

Magnitude of applied impulse voltage considered : 900 KVp

Transferred surge voltage at LV terminal 'a' : 310 KVp (34.5%)

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by R = 500 Ohm	Case 4 terminals earthed by C = 0.1 μF
$3A_2$ - Earth	76.5 (8.5%) at 0.5 μs	Zero	60	8
$3B_2$ - Earth	67.5 at 0.5 μs	-61	56	Nil
$3C_2$ - Earth	67 at 0.5 μs	± 56.6	48	-7
$3A_2$ - $3B_2$	-46	61	-47	8
$3B_2$ - $3C_2$	62 at 5.5 μs	62	49.5	7
$3C_2$ - $3A_2$	-32	56.3	-30	-15 at 70 μs

II. Impulse voltage chopped at 2.9 micro second applied at <u>HV terminal 'A'</u>

Magnitude considered : 900 KVp

Transferred surge peak magnitude at LV terminal 'a' : 495 KVp (55%)

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by R=500 Ohm	Case 4 terminals earthed by C=0.1 μF
$3A_2$ - Earth	-140 at 4.6 μs	Zero	- 110	7.7
$3B_2$ - Earth	145 (16.1%) at 4.8 μs	126 at 4 μs	- 107	-6.3
$3C_2$ - Earth	-134 at 4.3 μs	- 147 (16.3%)	- 90	6.4
$3A_2$ - $3B_2$	110	-126	42	8
$3B_2$ - $3C_2$	-96	- 96	- 98.5	-5
$3C_2$ - $3A_2$	40	-147	35.8	-6.8

Magnitude of applied impulse voltage considered : 550 KVp

Transferred surge voltage at HV terminal 'A' : 220 KVp (40% at 1μS)

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminals earthed by reactor	Case 3 terminals earthed by reactors and C = 0.1μF in parallel	Case 4 terminals earthed by C = 0.1μF alone
$3A_2$ - Earth	110 (20%) at 2.3μS	85 (14.5%) at 3μS	33.5 (6.1%)	43
$3B_2$ - Earth	105 at 6.5μS	63 at 5μS	7.0	nil
$3C_2$ - Earth	76 at 6μS	-80 at 7μS	-32.5	-43
$3A_2$ - $3B_2$	92 at 3μS	-73.4	31	43
$3B_2$ - $3C_2$	140 (25.5%) at 2.3μS	109 (19.8%) at 3μS	35	43
$3C_2$ - $3A_2$	-79.5 at 5.2μS	-46	-66 (12%)	86

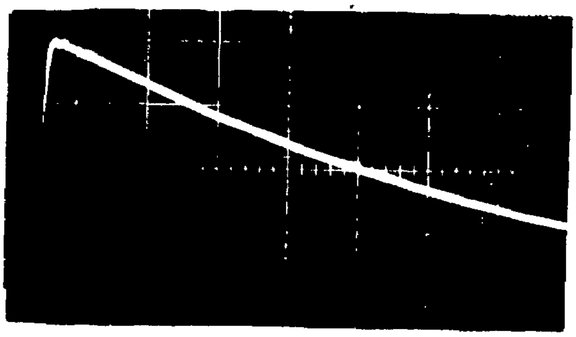
IV. Impulse Voltage Chopped at 3.3μs applied on LV terminal 'a'

Magnitude considered : 550 KVp

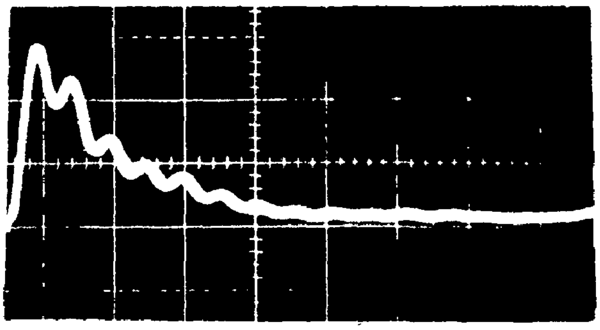
Transferred surge voltage at HV terminal 'A' : -260.5 (47.2%)

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals		
	Case 1 unloaded tertiary	Case 2 terminals earthed by reactor	Case 3 terminals earthed by reactor and C=0.1μF in parallel
$3A_2$ - Earth	110 at 2.3μs	97	10
$3B_2$ - Earth	154 (28%) at 6.5μs	130(23.6%)	-2.8
$3C_2$ - Earth	-124 at 5μs	-114	-10.5
$3A_2$ - $3B_2$	-160 at 6.5μs	-137	11
$3B_2$ - $3C_2$	180 (32.7%) at 6.5μs	150 (27.3%)	12
$3C_2$ - $3A_2$	-49.5	-41.4	-20

I. Oscillogram of surges when HV terminal impulsed.



(1) Applied impulse voltage on HV terminal 'A'
Magnitude: 20V/unit
Time base: 10 μs/unit

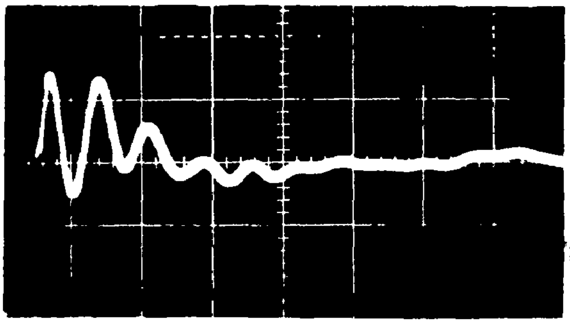


(2) Transferred surge at LV terminal 'a'
Magnitude: 10 V/unit
Time base: 2 μs/unit

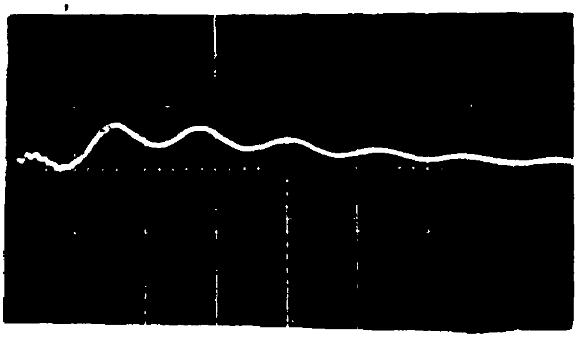
Oscillograms of transferred surges on tertiary.

Tertiary kept unloaded

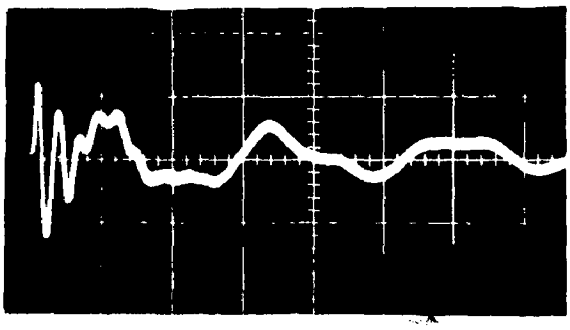
Tertiary with C = 0.1 μF



(3) Surge at terminal $3A_2$
Magnitude: 5V/unit
Time base: 2 μs/unit



(4) Surge at terminal $3B_2$
Magnitude: 1V/unit
Time base: 50 μs/unit

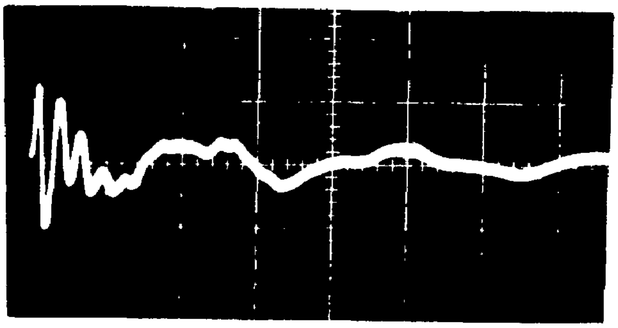


(5) Surge at terminal $3B_2$
Magnitude: 5 V/unit
Time base: 5 μs/unit

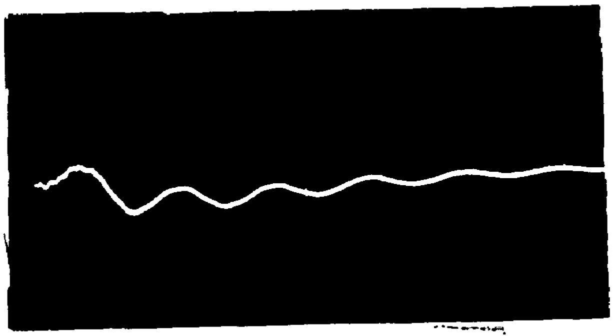
(6) Surge at terminal $3B_2$
Magnitude: 1 V /unit
Time base: 50 μs/unit

Tertiary kept unloaded

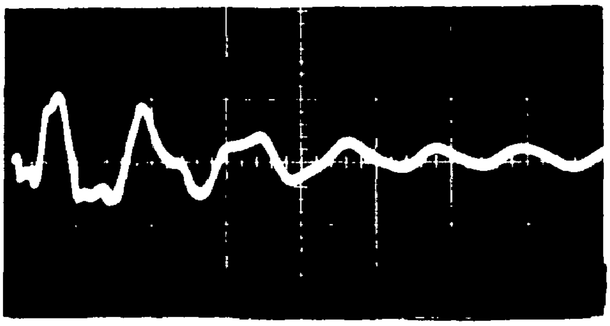
Tertiary with C= 0.1μF



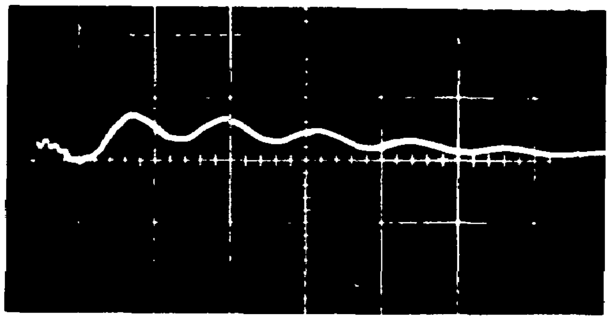
(7) Surge at terminal $3C_2$
Magnitude: 5V /unit
Time base: 5μs/unit



(8) Surge at terminal $3C_2$
Magnitude: 1 V /unit
Time base: 50μs/unit

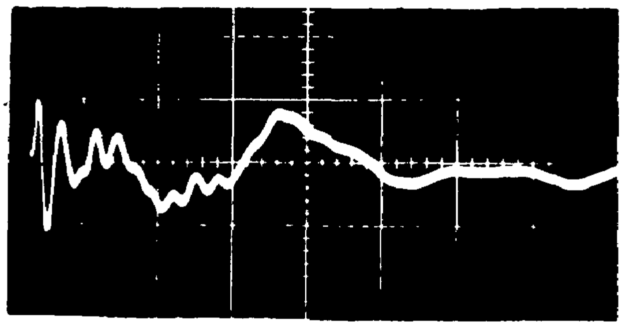


(9) Surge across terminal $3B_2$ - 3 C_2
Magnitude: 5 V /unit
Time base: 10μs/unit

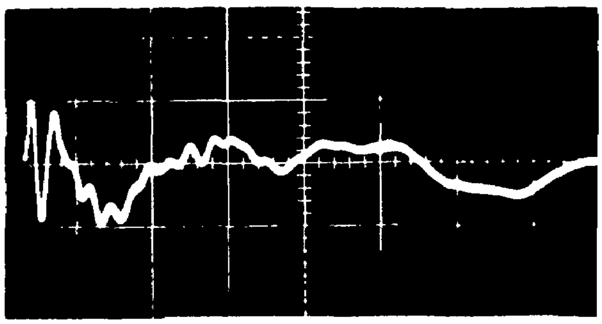


(10) Surge across terminals $3B_2$ - $3C_2$
Magnitude: 1 V /unit
Time base: 50μs/unit

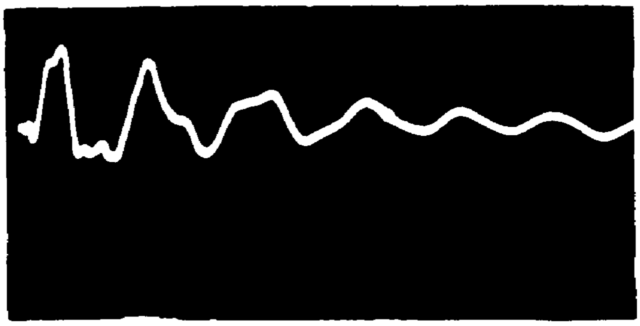
Tertiary terminal $3A_2$ earthed, remaining isolated.

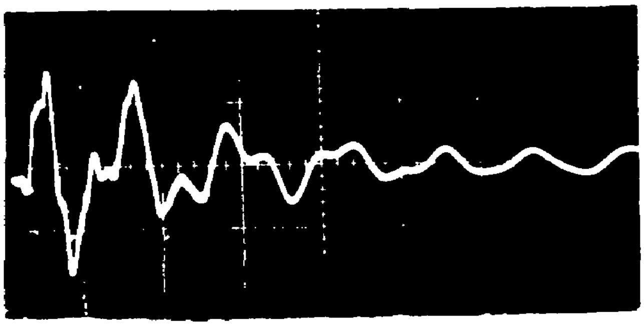


(11) Surge at terminal $3B_2$
Magnitude: 5 V/unit
Time base: 5μs/unit



(12) Surge at terminal $3C_2$
Magnitude: 5V /unit
Time base: 5μs/unit

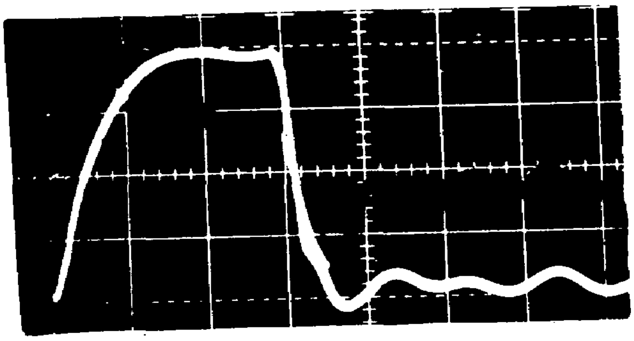


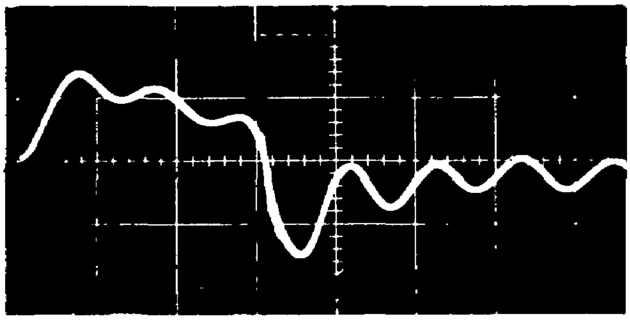


(13) Surge across terminals $3B_2 - 3C_2$
Magnitude: 5 V/unit
Time base: 10 μs/unit

(14) Surge across $3B_2 - 3C_2$
Under chopped impulse
Magnitude: 5 V/unit
Time base: 10 μs/unit

Chopped impulse voltage application





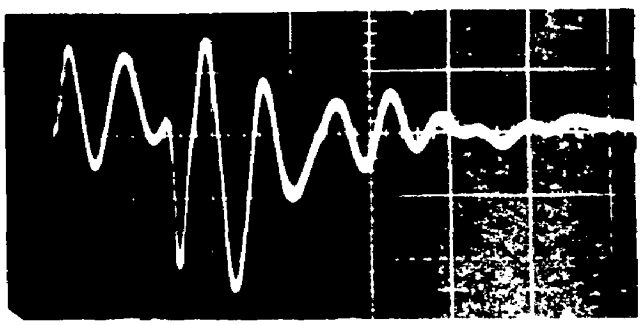
(15) Applied impulse voltage on HV terminal 'A'
Magnitude: 20 V /unit
Time base: 1 μs/unit

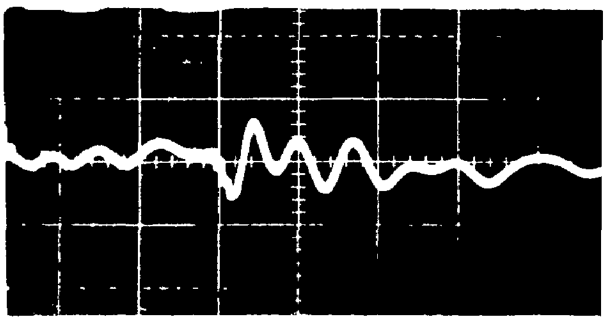
(16) Transferred surge at LV terminal 'a'
Magnitude: 5V/unit
Time base: 1 μs/unit

Oscillograms of transferred surges on tertiary

Tertiary kept unloaded

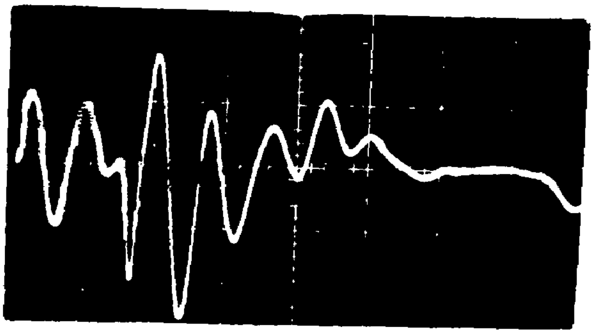
Tertiary with C= 0.1





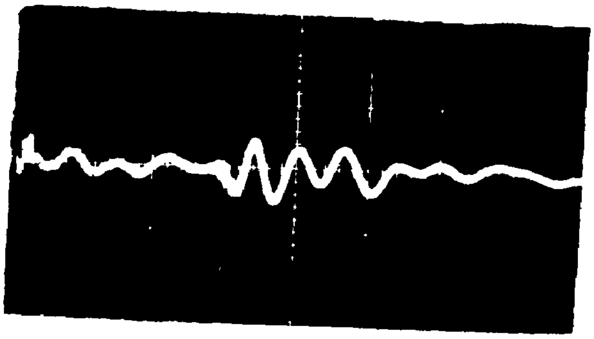
(17) Surge at terminal $3A_2$
Magnitude: 5V/unit
Time base: 2 μs/unit

(18) Surge at terminal $3A_2$
Magnitude: 1 V /unit
Time base: 1 μs/unit



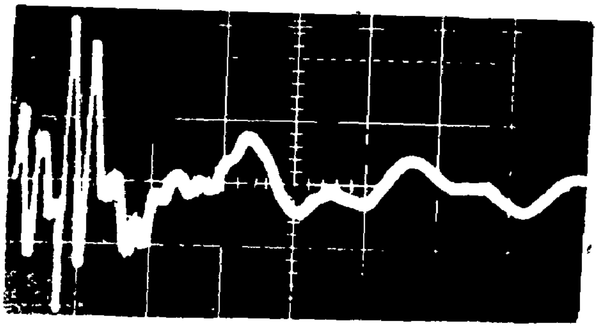
(19) Surge at terminal $3C_2$

Magnitude: 5 V/unit
Time base: 2 μs/unit



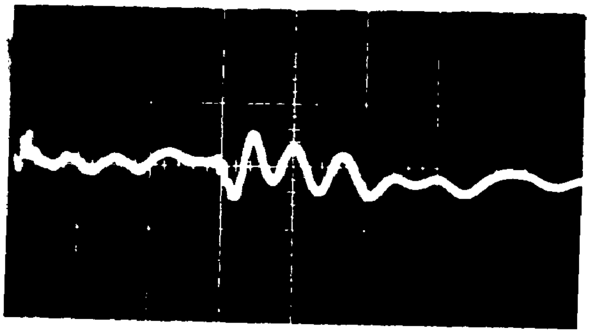
(20) Surge at terminal $3C_2$

Magnitude: 1 V/unit
Time base: 1 μs/unit



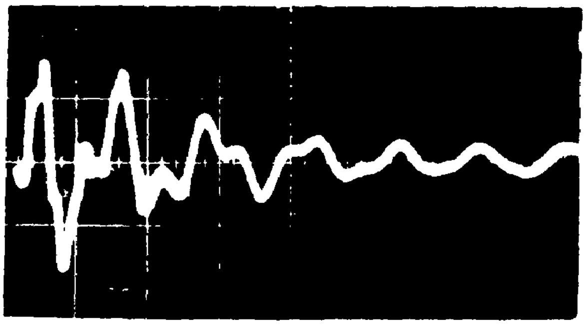
(21) Surge at terminal $3B_2$

Magnitude: 5V /unit
Time base: 5 μs /unit



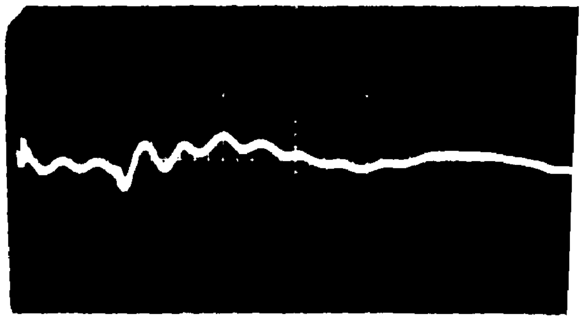
(22) Surge at terminal $3B_2$

Magnitude: 1 V/unit
Time base: 1 μs/unit



(23) Surge across terminals $3B_2$ - $3C_2$

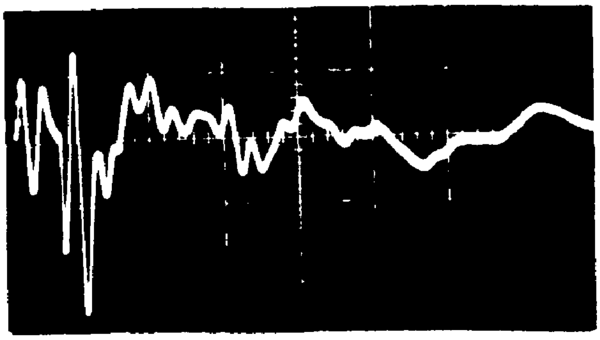
Magnitude: 5 V /unit
Time base: 10 μs/unit



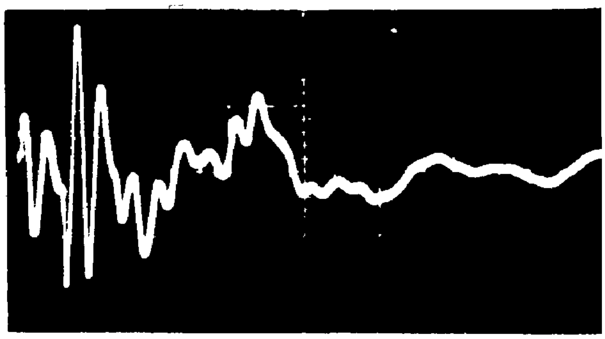
(24) Surge across terminals $3B_2$ - $3C_2$

Magnitude: 1 V /unit
Time base: 1 μs/unit

Terminal $3A_2$ earthed, remaining isolated.

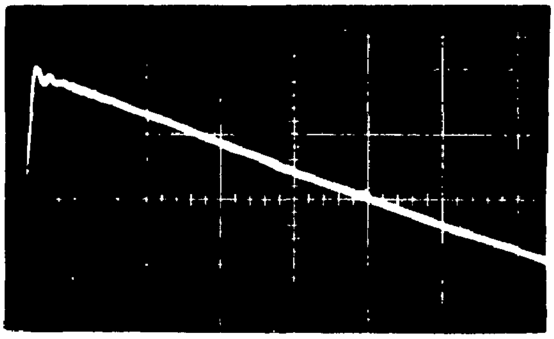


(25) Surge at terminal $3C_2$
Magnitude: 5V /unit
Time base: 5μs/unit

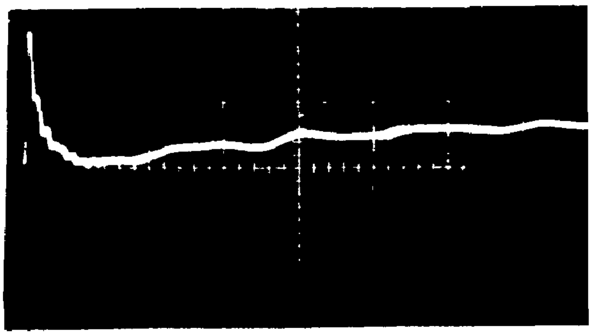


(26) Surge at terminal $3B_2$
Magnitude: 5 V/unit
Time base: 5μs/unit

II. Oscillograms of Surges when LV terminal 'a' impulsed



(27) Applied impulse voltage on LV terminal 'a'
Magnitude: 20V/unit
Time base: 10μs/unit

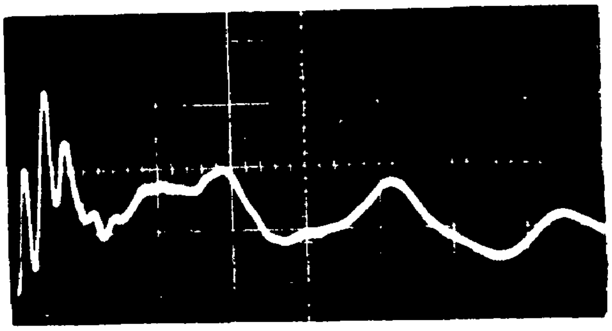


(28) Transferred surge at HV terminal 'A'
Magnitude: 20V /unit
Time base: 10μs/unit

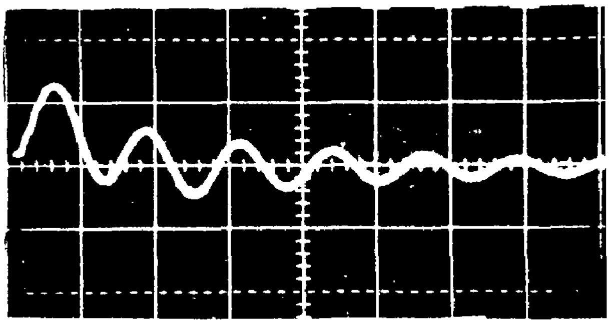
Transferred surges at tertiary terminals.

Tertiary kept unloaded

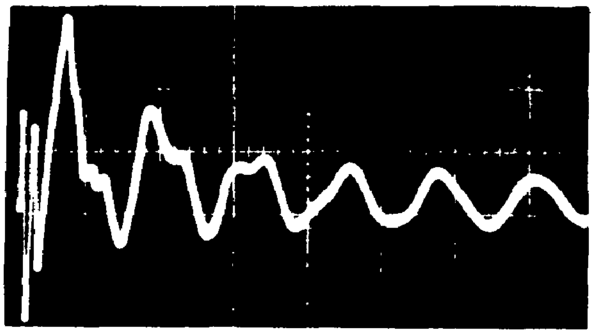
Tertiary earthed through C= 0.1 μF



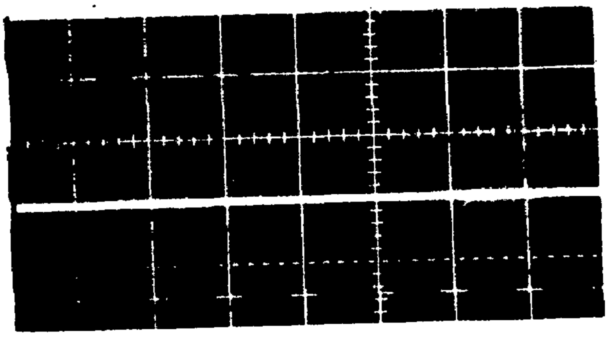
(29) Surge at terminal $3A_2$
Magnitude: 5V /unit
Time base: 5 μs/unit



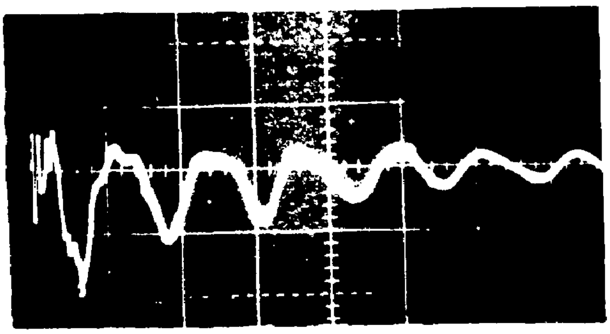
(30) Surge at terminal $3A_2$
Magnitude: 5 V/unit
Time base: 50 μs/unit



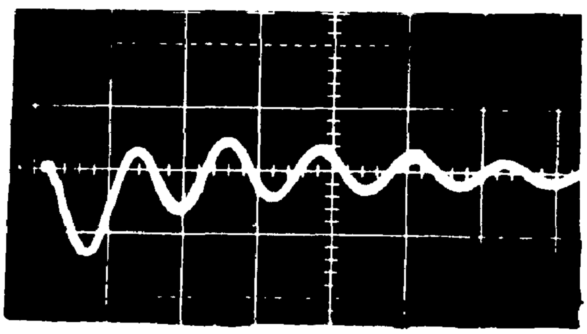
(31) Surge at terminal $3B_2$
Magnitude: 5V /unit
Time base: 10 μs/unit



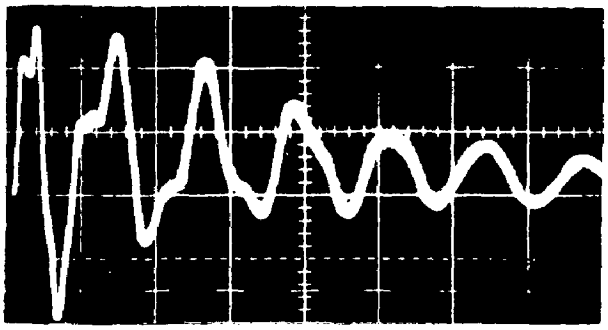
(32) Surge at terminal $3B_2$
Magnitude: 5V /unit
Time base: 50 μs/unit



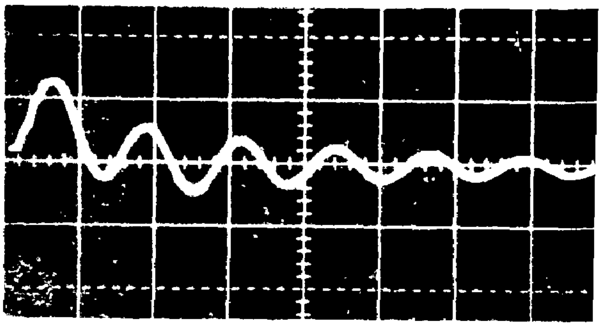
(33) Surge at terminal $3C_2$
Magnitude: 5 V/unit
Time base: 10 μs/unit



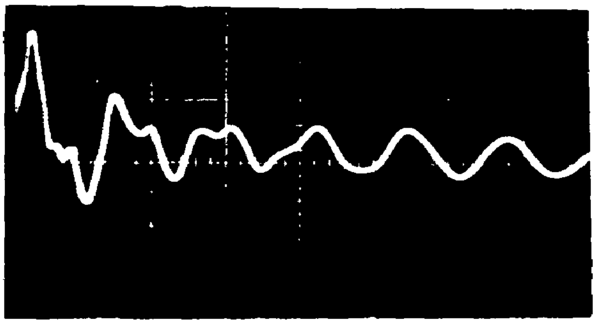
(34) Surge at terminal $3C_2$
Magnitude: 5V /unit
Time base: 50 μs/unit



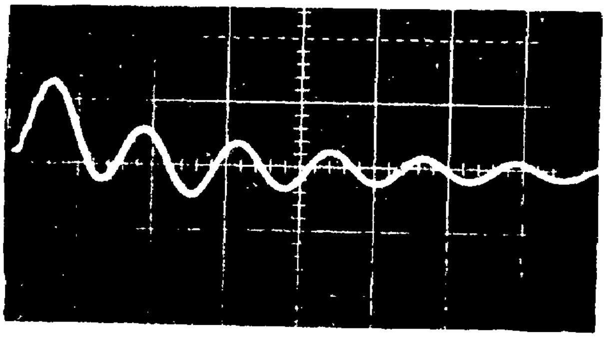
(35) Surge across terminals $3A_2 - 3B_2$
Magnitude: 5 V/unit
Time base: 10 μs/unit



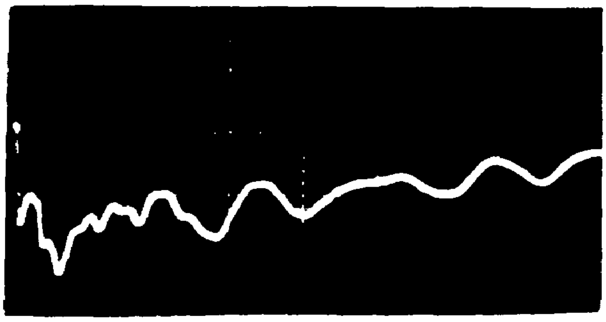
(36) Surge across terminals $3A_2 - 3B_2$
Magnitude: 5 V/unit
Time base: 50 μs/unit



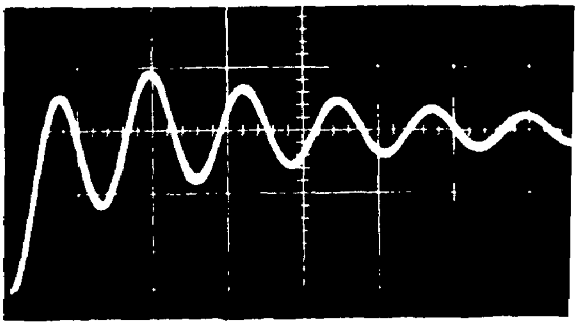
(37) Surge across terminals $3B_2 - 3C_2$
Magnitude: 10V /unit
Time base: 10 μs /unit



(38) Surge across terminals $3B_2 - 3C_2$
Magnitude: 5 V/unit
time base: 50 μs/unit

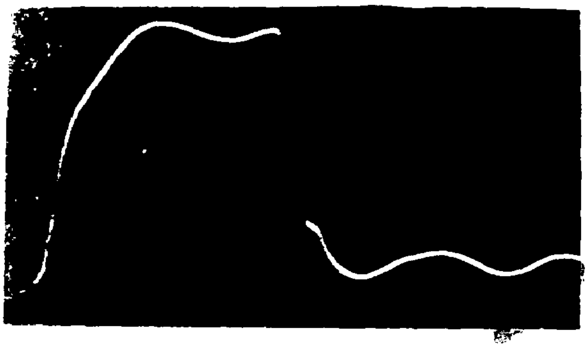


(39) Surge across terminals $3C_2 - 3A_2$
Magnitude: 5V /unit
Time base: 10 μs/unit



(40) Surge across terminals $3C_2 - 3A_2$
Magnitude: 5 V /unit
Time base: 50 μs/unit

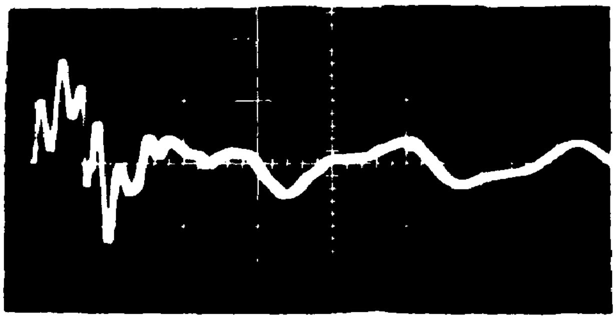
Chopped impulse voltage application.



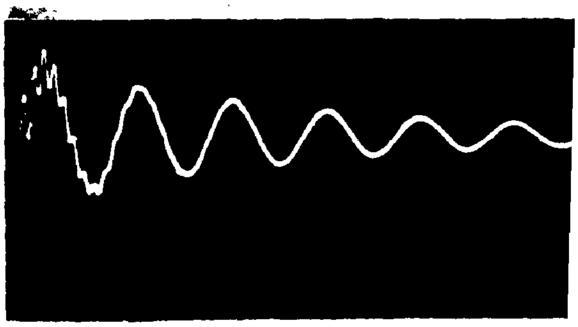
(41) Applied chopped impulse wave at LV terminal 'a'

Magnitude: 20V /unit
Time base: 1 μs /unit

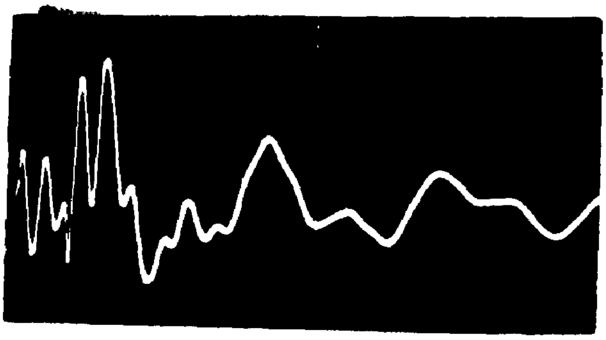
Tertiary kept unloaded   Tertiary with C= 0.1 μF



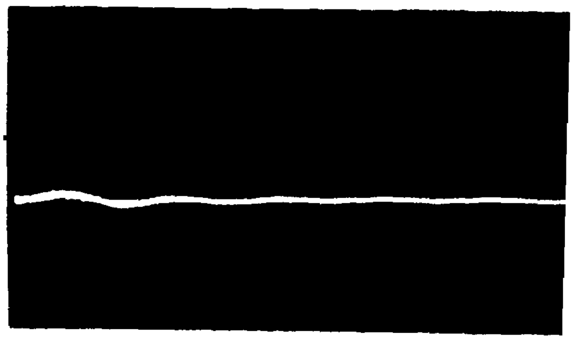
(42) Surge at terminal $3A_2$
Magnitude: 10 V/unit
Time base: 5 μs/unit



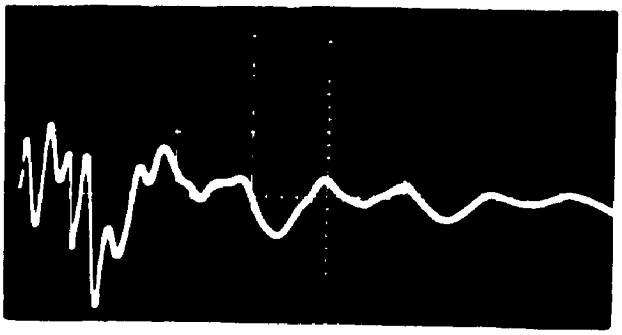
(43) Surge at terminal $3A_2$
Magnitude: 1 V/unit
Time base: 50 μs/unit



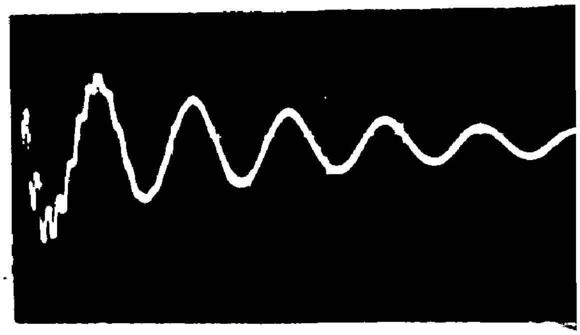
(44) Surge at terminal $3B_2$
Magnitude: 10 V /unit
Time base: 5 μs /unit



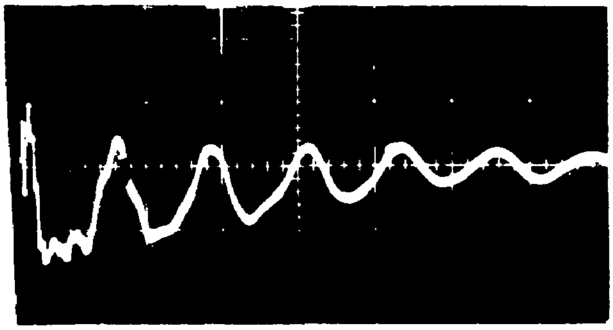
(45) Surge at terminal $3B_2$
Magnitude: 1 V/unit
Time base: 50 μs/unit



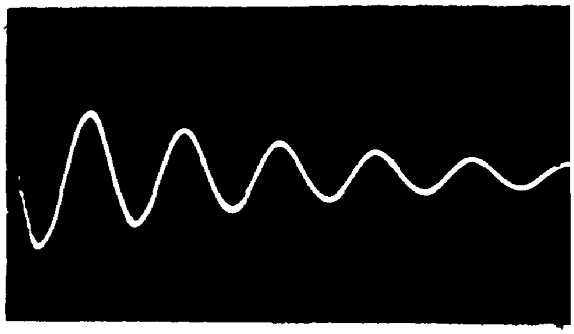
(46) Surge at terminal $3C_2$
Magnitude: 10V /unit
Time base: 5 μs/unit



(47) Surge at terminal $3C_2$
Magnitude: 1 V/unit
Time base: 50 μs/unit



(48) Surge across terminals $3C_2 - 3A_2$
Magnitude : 5V /unit
Time base : 10 μs/unit



(49) Surge across terminal $3C_2 - 3A_2$
Magnitude: 2 V/Unit
Time base: 50 μs/unit

4.3 TRANSFORMER SERIAL NUMBER -3

3 Phase, 100 MVA, 220/132/11 kV Auto Transformer

GENERAL PARTICULARS

HV	-	900 kVp
LV	-	550 kVp

Percentage impedance at rated MVA

% Z H-L	10.5
% Z H-S	36
% Z L-S	24.2

Core details :

Dia	550mm
Length	2350mm

Electrical clearances :

Core - SV	14mm
SV - LV	63mm
LV - TAPS	63 mm
TAPS - HV	54mm

Coil thickness :

SV	17mm
LV	122mm
TAP	24 mm
HV	60 mm (excluding 88 mm inter layer clearances)

I. 1.1/47 microsecond impulse voltage applied on <u>LV terminal 'a'</u>

Magnitude of applied impulse voltage considered : 550 KVp

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals		
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminal earthed by $C = 0.1 \mu F$
$3A_2$ - Earth	77 at 1.8 μs	Zero	43.3 (7.87%)
$3B_2$ - Earth	81.5 (14.8%) at 6.4 μs	-111 (20%)	Nil
$3C_2$ - Earth	49.5 at 5.5 μs	-103	-43.3
$3A_2$ - $3B_2$	79 at 2.5 μs	111	43.3
$3B_2$ - $3C_2$	126.5 (23%) at 5.8 μs	127 (23.1%)	43.3
$3C_2$ - $3A_2$	- 73 at 5.5 μs	-103	-86.6

II. Impulse voltage chopped at 3 µs applied on <u>LV terminal 'a'</u>

Magnitude considered : 550 KVp

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals		
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by $C = 0.1 \mu F$
$3A_2$ - Earth	77 at 1.8 µs	Zero	6.8
$3B_2$ - Earth	107 (19.6%) at 6 µs	- 105.6	1.4
$3C_2$ - Earth	- 86 at 5 µs	- 136	-7
$3A_2$ - $3B_2$	-122	- 105.6	6.8
$3B_2$ - $3C_2$	157 (285%) at 6 µs	164	7.2
$3C_2$ - $3A_2$	57.8	-136	-138

III. Two-pole surges : 1.1/47 micro second full wave and chopped wave (3 μs)

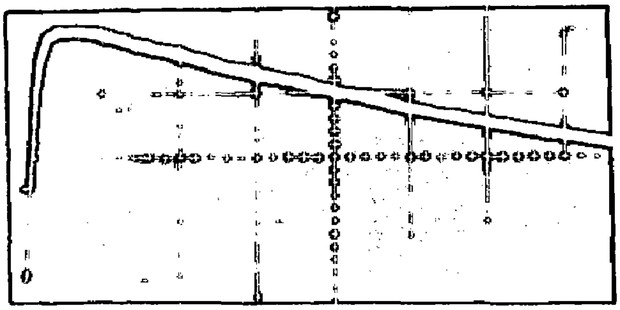
(Impulse voltage simultaneously applied on LV 'a' and 'b' phases)

Tertiary terminals	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Full wave application		Chopped wave application	
	Case 1 Unloaded tertiary	Case 2 Terminals earthed by C= 0.1 μF	Case 1 Unloaded tertiary	Case 2 terminals earthedby C= 0.1 μF
$3A_2$ - Earth	92.5 (16.8%)	-15.4	92.5	All the values less than 10 KVp
$3B_2$ - Earth	85	46.4	85	
$3C_2$ - Earth	75.6	-41.2	75.6	
$3A_2$ - $3B_2$	-120 (21.88%)	-44.7	-151	
$3B_2$ - $3C_2$	82.5	87.6	58.4	
$3C_2$ - $3A_2$	-72	-41.2	110	

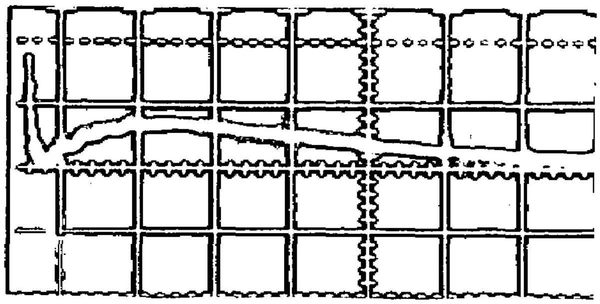
IV. [illegible]
(Impulse voltage simultaneously applied on LV phases)

Tertiary terminal	Transferred surge peak magnitude (KVp) at tertiary terminals: Full wave application, Case 1 Unloaded tertiary	Full wave application, Case 2 terminal earthed by C=0.1μF	Chopped wave application, Case 1 Unloaded tertiary	Chopped wave application, Case 2 Terminals earthed by C=0.1μF
$3A_2$ - Earth	107.5(19.6%)	8.5	107.5	8.4
$3B_2$ - Earth	107.5	8.5	107.5	8.4
$3C_2$ - Earth	107.5	8.5	107.5	8.4
$3A_2$ - $3B_2$	Nil	Nil	Nil	Nil
$3B_2$ - $3C_2$	Nil	Nil	Nil	Nil
$3C_2$ - $3A_2$	Nil	Nil	Nil	Nil

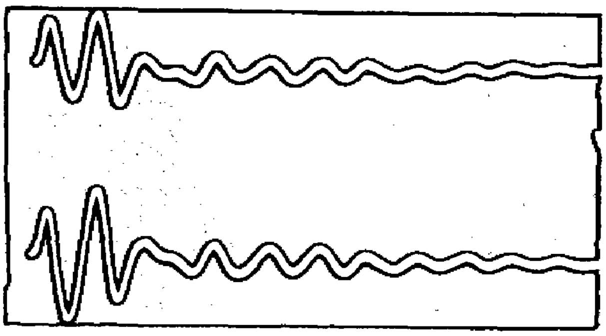
Oscillograms of transferred surges when impulse voltage applied on 132 kV terminal.



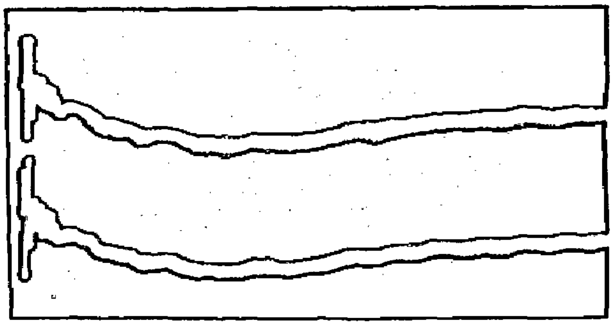
(1) Applied impulse voltage at LV terminal 'a'
Magnitude: 20V /unit
Time base: 5 μs /unit



(2) Transferred surge at HV terminal 'A'
Magnitude: 20 V/unit
Time base: 50 μs/unit

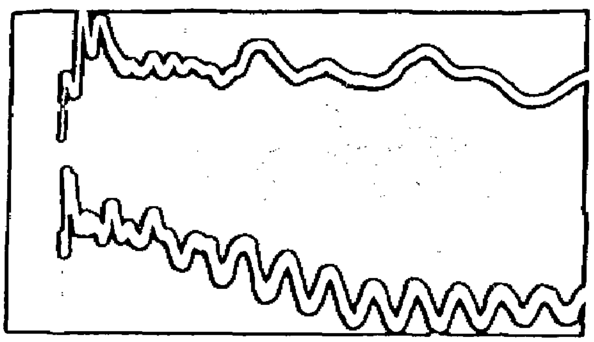


(3) Surges at HV terminals B & C
Magnitude: 5 V/unit
Time base: 2 μs /unit

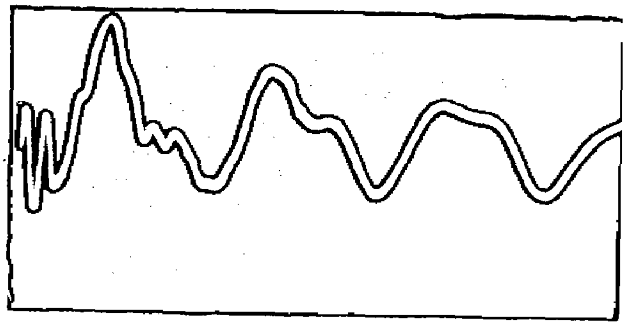


(4) Surgest at LV terminals b & c
Magnitude: 5 V/unit
Time base: 20 μs /unit

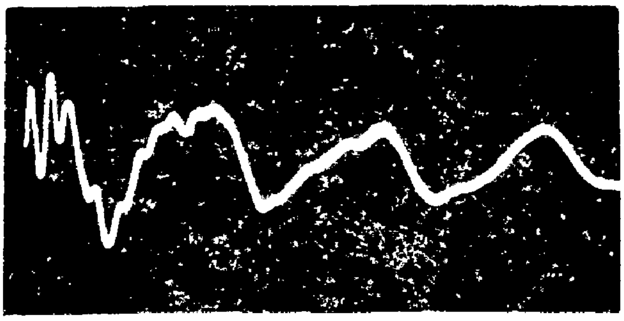
Transferred surges on unloaded tertiary.



(5) Surge at terminal $3A_2$
Magnitude: 5 V/unit
Time base: 5 μs and 20 μs /unit

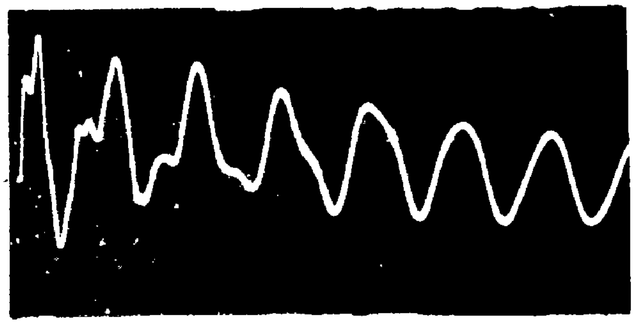


(6) Surge at terminal $3B_2$
Magnitude: 5 V/unit
Time base: 5 μs/unit



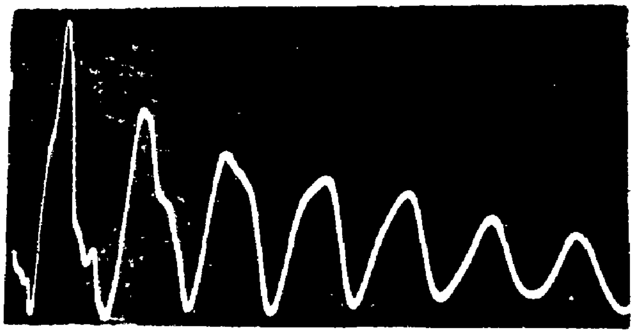
(7) Surge across terminal $3C_2$

Magnitude: 5 V/unit
Time base: 5 μs/unit



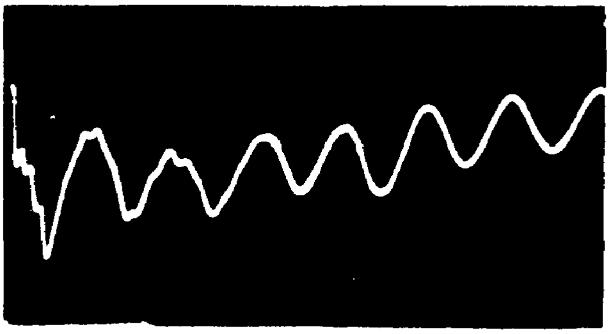
(8) Surge across terminals $3A_2$ - $3B_2$

Magnitude: 5V/ unit
Time base: 10 μs/unit



(9) Surge across terminals $3B_2$ - $3C_2$

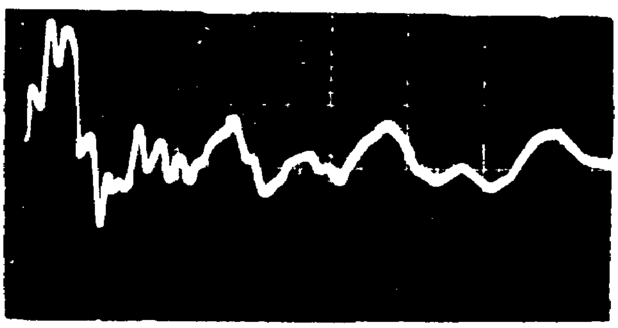
Magnitude: 5V /unit
Time base: 10 μs/unit



(10) Surge across terminals $3C_2$ - $3A_2$

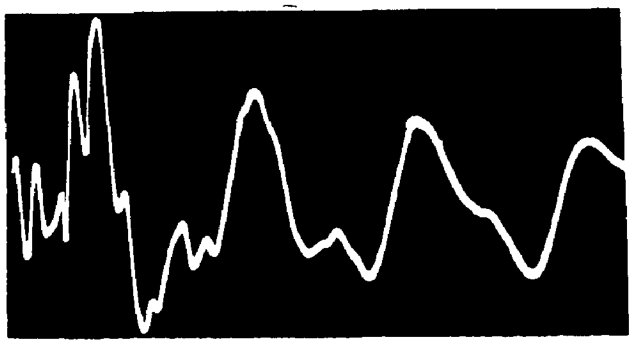
Magnitude: 5 V/unit
Time base: 10 μs/unit

Transferred Surges with chopped impulse voltage.



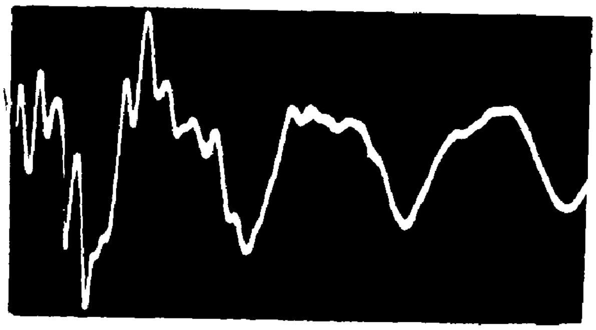
(11) Surge at terminal $3A_2$

Magnitude: 5 V/unit
Time base: 5 μs/unit

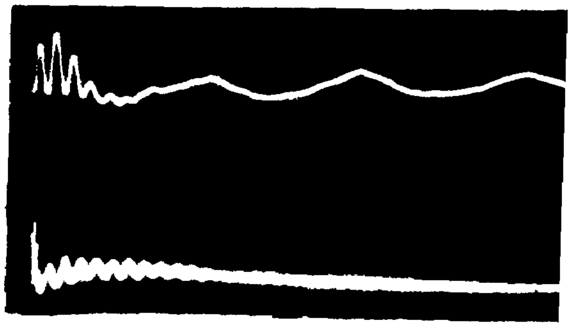


(12) Surge at terminal $3B_2$

Magnitude: 5 V/unit
Time base: 5 μs/unit

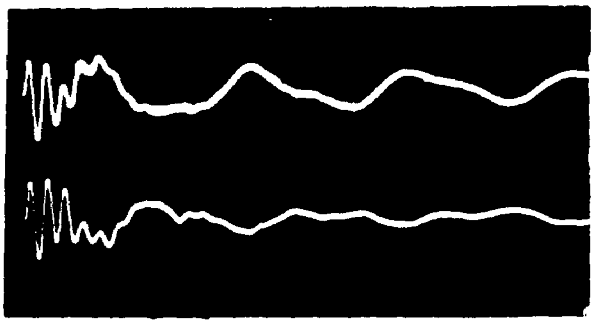


(13) Surge at terminal $3C_2$
Magnitude : 5 V/unit
Time base: 5 μs/unit



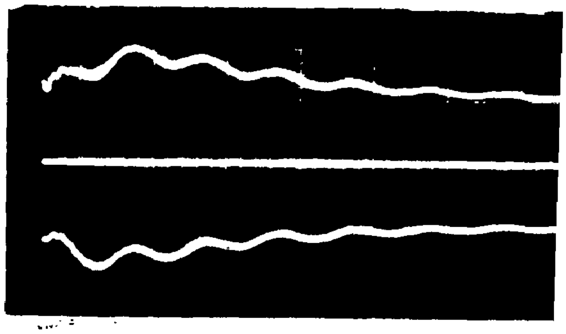
(14) Surge at terminal $3A_2$
Magnitude: 5 V/unit
Time base: 5 μs and 50 μs/unit

Transferred surges at tertiary when HV terminal 'A' impulsed (Oscillogram Nos. 14 to 18)

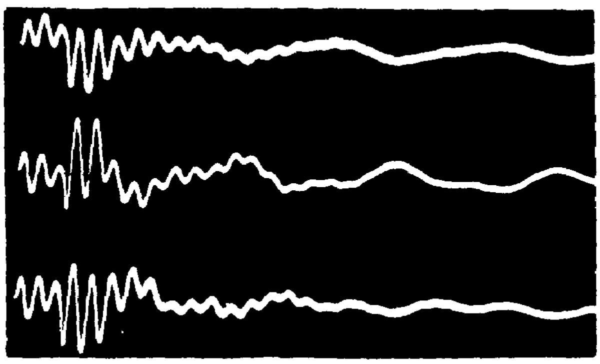


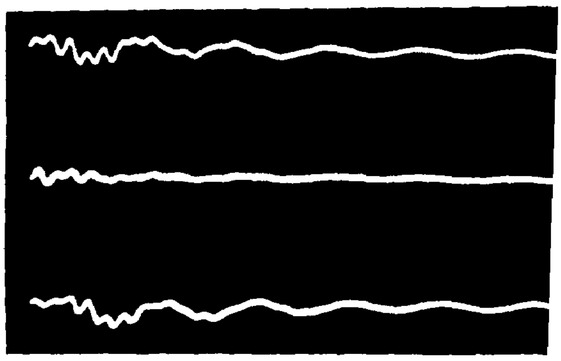
(15) Surges at terminals $3B_2$ & $3C_2$

Magnitude: 5 V/Unit
Time base: 5 μs /unit



(16) Surges at terminals $3A_2$, $3B_2$ & $3C_2$
with C= 0.25 μF
Magnitude: 1 V/Unit
Time base: 50 μs/unit



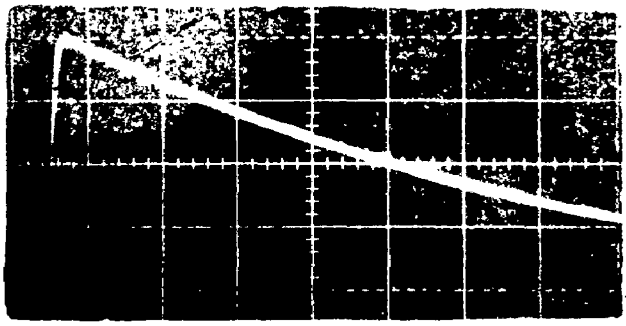


Surges at terminals $3A_2$, $3B_2$ & $3C_2$ under chopped wa

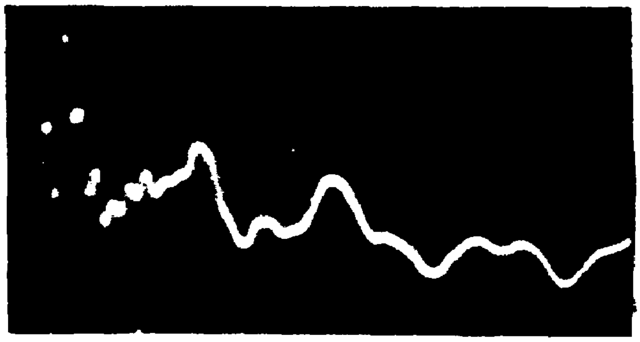
(17) Unloaded tertiary
Magnitude: 10 V/unit
Time base: 5 μS /unit

(18) Tertiary with C=0.25 μ
Magnitude: 1V /unit
Time base: 5 μS/unit

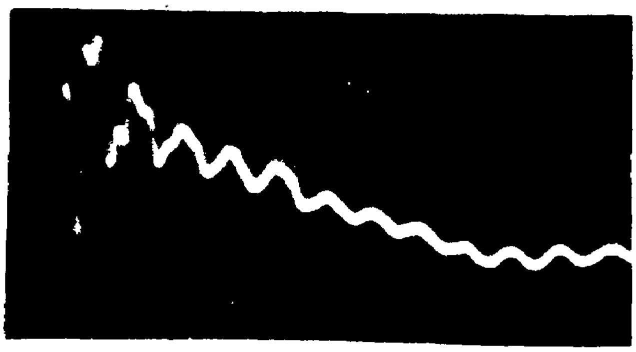
Transferred surge oscillograms for single poleand 3 pole surge application on 132 kV terminals of 220/132/11 kV, 8% impedance Auto Transformer.



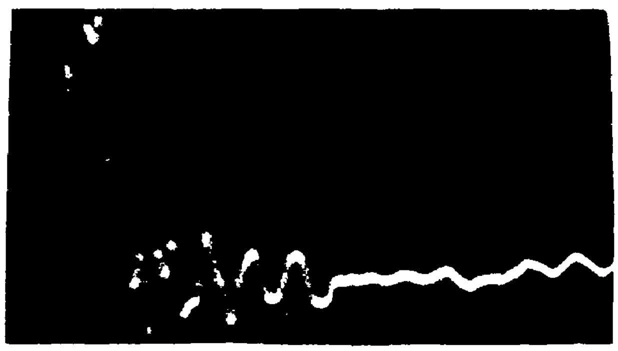
(1) Applied surge on LV terminal 'a'
Magnitude: 20V/unit
Time base: 10 μs/unit



(2) Surge at tertiary terminal $3A_2$
Magnitude: 4V/unit
Time base : 5 μs/unit



(3) Surge at terminal $3A_2$ for 3 pole surge on LV terminals
Magnitude: 4V/unit
Time base: 5 μs/unit



(4) Surge at terminal $3A_2$ for 3 pole chopped surge on LV
Magnitude: 4 V/Unit
Time base: 5 μs/unit

4.4 TRANSFORMER SERIAL NO.4

3 Phase, 100 MVA, 220/110/11 kV Auto Transformer

GENERAL PARTICULARS

Impulse voltage level:

HV - 900 KVp

LV - 450 KVp

Percentage impedance at rated MVA

% Z H-L - 15

% Z H-T - 41.3

% Z L-T - 23

Core details

Dia - 610mm

Length - 2230mm

Electrical clearance

Core - TV 20mm

TV - LV - 55mm

LV - Tap - 54mm

Tap - LV - 50.5mm

Coil thickness

TV - 45mm

LV - 104mm

TAPS - 16.5mm

HV - 61mm

(excluding 88 mm inter layer clearances)

I. 1.1/48 impulse voltage applied on HV terminal 'A'

Magnitude of applied impulse voltage considered : 900 KVp

Transferred surge peak magnitude at LV terminal 'a' : 280 KVp (31.1%)

TERMINALS	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3C_2$ earthed, others unloaded	Case 3 terminals earthed by C= 0.25 μF	Case 4 terminals earthed by R= 500 Ohms
$3A_2$ - Earth	82 (19.1%) at 0.5 μs	76	9 (60th μs)	55.5
$3B_2$ - Earth	73	50.6	negligible	41
$3C_2$ - Earth	73	Nil	-8.6	48.5
$3A_2$ - $3B_2$	-50.6	-56	9	31
$3B_2$ - $3C_2$	67.5	50.6	8.6	40.6
$3C_2$ - $3A_2$	-36.6	-76	-17.6	-22

II. Chopped impulse voltage applied on HV terminal 'A' (chopped at 4 μS)

Magnitude considered : 900 KVp

Transferred surge peak magnitude at LV terminal 'a' : 346 KVp (38.4%)

TERMINALS	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminals 3C2 earthed, others unloaded	Case 3 terminals earthed by C= 0.25 μF	Case 4 terminals earthed by R= 500 Ohms
3A2 - Earth	-140	-123	4	-110
$3B_2$ - Earth	164 (18.2%)	-140	1.5	130
$3C_2$ - Earth	-130	Nil	-4.5	-103
$3A_2$ - $3B_2$	-112	110	4	-67.5
$3B_2$ - $3C_2$	-100 (11.1%)	-140 (15.5%)	2.5	60
$3C_2$ - $3A_2$	40.5	123	-5	-27

III. 1.1/48 μs impulse voltage applied on LV terminal 'a'

Magnitude of applied impulse voltage considered : 450 KVp

Transferred surge peak magnitude at HV terminal 'A' : 193.5 KVp (43%)

TERMINALS	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by C=0.25 μF	Case 4 terminals earthed by R= 500 Ohm
$3A_2$ - Earth	83.3(18.5%) at 1.8 μs	Nil	43 at 20	58
$3B_2$ - Earth	92.7(20.7%)	-112(25%)	negligible	40
$3C_2$ - Earth	58	-104	-42	35
$3A_2$-$3B_2$	82	112	43(9.55%)	57
$3B_2$-$3C_2$	124 (27.6%) at 2 μs	128(28.5%)	42	82
$3C_2$-$3A_2$	-76	-104	-85(18.9%)	-52.5

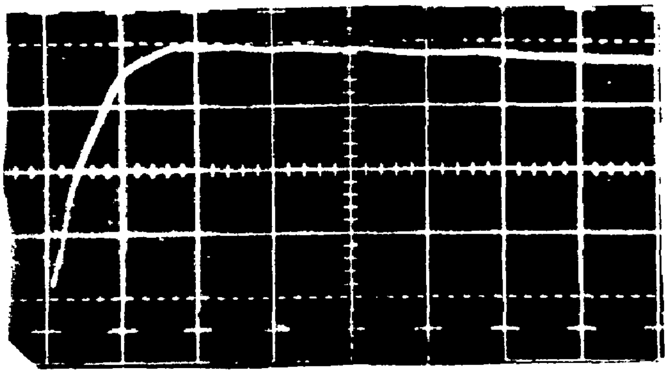
IV. Chopped impulse voltage applied on LV terminal 'a' (chopped at 4 μs)

Magnitude considered : : 450 KVp

Transferred surge peak magnitude at HV terminal 'A' : 247.5 KVp (55%)

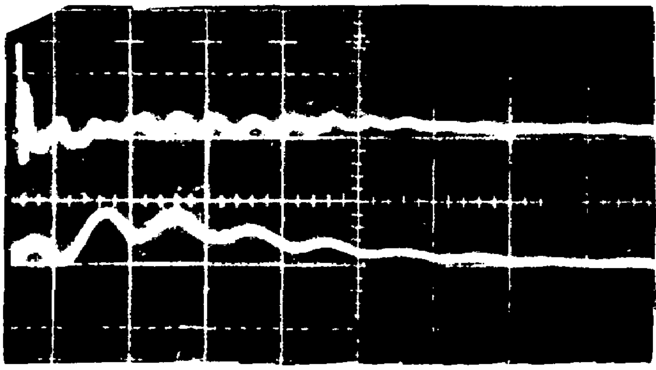
TERMINALS	Transferred surge peak magnitude (KVp) at tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed	Case 3 terminals earthed by C=0.25 μF	Case 4 terminals earthed by R= 500 Ohm
$3A_2$ - Earth	83	Nil	8.4	57.5
$3B_2$ - Earth	150(33.3%)	-126	Negligible	110
$3C_2$ - Earth	-90	-157.5(35%)	-8.4	-79
$3A_2$-$3B_2$	-135	-126	-8.4	-84
$3B_2$-$3C_2$	148	152	8.4	98
$3C_2$-$3A_2$	-61	-157.5	-16.8	-45

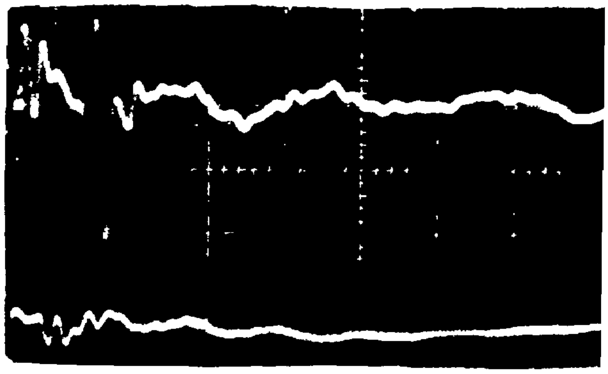
Applied impulse wave shape at HV/LV 'A' phase
Magnitude: 20V/unit, Time base: 1 µs /unit



Transferred surges at tertiary terminal $3A_2$ shown in middle and bottom rows when impulse voltage applied at HV terminal 'A' and LV terminal 'a' respectively.

Full wave application   Chopped wave application



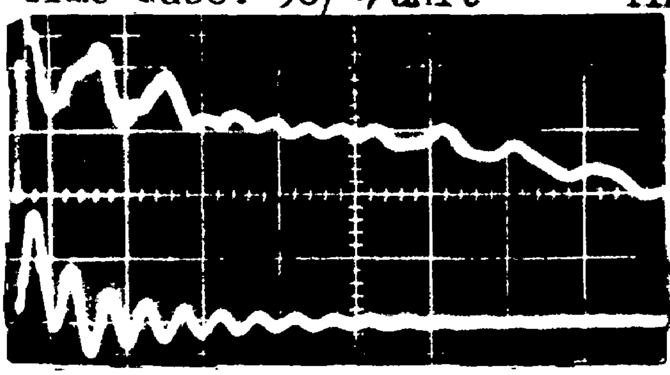


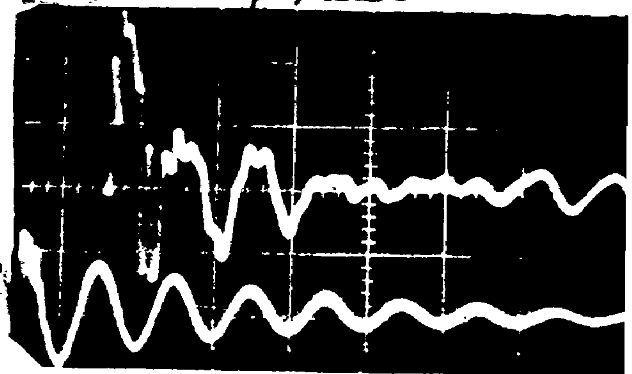
Upper surges with tertiary unloaded

Magnitude: 5V /unit   Magnitude: 5V /unit
Time base: 10µs/unit   Time base: 5µs/unit

Lower surges with C = 0.1µF connected

Magnitude: 1V/unit   Magnitude: 1 V/unit
Time base: 50µs/unit   Time base: 10µs/unit





Upper curve: Magnitude 5V/unit, Time base: 10 µs /cm
Lower curve: Magnitude 5V/unit, Magnitude: 5V /unit
Time base: 100µs/unit (LHS) 50µs /unit (RHS)

4.5 TRANSFORMER SERIAL NUMBER -5

Transferred Surge study on 3 Phase bank consisting of 3 Nos., Single Phase, 33.33 MVA, 220 /110/11 kV Auto Transformer.

GENERAL PARTICULARS

Percentage impedance at rated MVA

% Z H-T - 10
% Z H-T - 30
% Z L-T - 18

Impulse Voltage level

HV - 1050 KVp
LV - 550 KVp

Core details

Dia : 690 mm
Length: 2150mm

Coil thickness

TV - 21 mm
LV - 89 mm
TAP - 10 mm
HV - 68 (exluding 106mm inter layer clearances)

Electrical clearances

Core - Tertiary : 14 mm
Ter - LV : 79 mm
LV - TAP : 67 mm
TAP - HV : 55 mm

Impulse voltage applied on HV terminal 'A'

Magnitude considered : 1050 KVp

(Tertiary kept unloaded)

TERMINALS	Transferred surge peak magnitude (KVp) on tertiary Case 1 1.1/50 μs Impulse voltage applied on HV	Case 2 Impulse voltage chopped at 4 μs applied on HV
$3A_2$ - Earth	103	-180
$3B_2$ - Earth	69	147
$3C_2$ - Earth	101	-177
$3A_2$-$3B_2$	-82.1	146.8
$3B_2$-$3C_2$	93.2	158
$3C_2$-$3A_2$	-36.2	62.5

Impulse voltage applied on LV terminal 'a'

Magnitude considered : 550 KVp
(tertiary kept unloaded)

TERMINALS	Transferred surge peak magnitude (KVp) on tertiary		
	Case 1 1.1/50 μs Impulse voltage applied on LV	Case 2 Impulse voltage chopped at 3 μs applied on LV	Case 3 Impulse voltage chopped at 4 μs applied on LV
$3A_2$ - Earth	108.6	108.6	108.6
$3B_2$ - Earth	84	123.7	143
$3C_2$ - Earth	62	-116.8	-130.3
$3A_2$-$3B_2$	90.8	110	124
$3B_2$-$3C_2$	137.5	152.6	146.8
$3C_2$-$3A_2$	-103	-84	-100

Switching impulse voltage applied on LV

Magnitude considered : 460 KVp

(Tertiary kept unloaded)

TERMINALS	Transferred surge peak magnitude (KVp) on tertiary	
	For single pole surge on terminal 'a'	For 3 pole surges on LV terminals
$3A_2$ - Earth	46	59.8
$3B_2$ - Earth	20	59.8
$3C_2$ - Earth	-20	59.8
$3C_2$-$3A_2$	48	Negligible

4.6 TRANSFORMER SERIAL NUMBER -6

50 MVA

3 Phase 220/66/11 kV step down system transformer

GENERAL PARTICULARS

Impulse voltage level

HV	-	900 KVp
LV	-	325 KVp

Percentage impedance at rated MVA

% Z H-L	15.07
% Z H-S	22.6
% Z L-S	4.9

Core details

Diameter	740 mm
Length	1950 mm

Electrical clearances

Core - SV	18mm
SV- LV	40mm
LV - TAP 1	41mm
TAP 1 - TAP 2	25.5mm
TAP 2 - HV	22mm

Coil thickness

SV	17mm
LV	76mm
TAP 1	10.5mm
TAP 2	9mm
HV	60mm (excluding 88 mm interlayer clearances)

I. 1.1/48 Micro sec. Impulse voltage applied on HV terminal 'A'

Magnitude of applied impulse voltage considered : 900 KVp

Transferred surge voltages at LV terminals 'a','b' & 'c' : 94.5 KVp (10.5%), -4.4% and -4.2%

Transferred surge voltage at HV terminals 'B' & 'C' : 5.4% and 5.2%

TERMINALS	Transferred surge voltage in (KVp) on tertiary terminals			
	Case 1 unloaded tertiary	Case 2 Terminal $3C_2$ earthed	Case 3 terminals earthed by R=500 Ohm	Case 4 Terminals earthed by C=0.25 μF
$3A_2$ - Earth	58.1 at 0.5 μs	-54	50	10
$3B_2$ - Earth	-52.5	-51	-44	Nil
$3C_2$ - Earth	-51	Zero	-44	-10
$3A_2$ - $3B_2$	-27	-27.5	-17.2	10
$3B_2$ - $3C_2$	-15.8	-51	-9.8	10
$3C_2$ - $3A_2$	28.5	54	21.6	-20

II. Chopped impulse voltage applied on HV terminal 'A' (Chopped at 3μs)

Magnitude considered : 900 KVp

Transferred surge voltage at LV terminals 'a', 'b' and 'c' : -90 KVp (10%)

Transferred surge voltage at HV terminals 'B' and 'C' : -10%

TERMINALS	Transferred surge voltage (in KVp) on tertiary terminals			
	Case 1 unloaded tertiary	Case 2 Terminal 3C2 earthed	Case 3 Terminals earthed by R=500 Ohm	Case 4 Terminals earthed by C=0.25 μF
$3A_2$ - Earth	90	85.5	72	4.2
$3B_2$ - Earth	85.6	-70	66	2.8
$3C_2$ - Earth	103.5	Zero	45	4.6
$3A_2$ - $3B_2$	-45	-45	-23	3.6
$3B_2$ - $3C_2$	40	-70	21	4
$3C_2$ - $3A_2$	34	-85.5	14	6.6

III. 1.1/47 μsec. Impulse voltage applied on <u>LV terminal 'a'</u>

Magnitude of applied impulse voltage considered : 325 KVp

Transferred surge peak magnitude at HV terminals 'A','B'&'C' : 60 KVp (18.4%), -5.5%, -5.5%

Transferred surge peak magnitude at LV terminals 'b' & 'c' : 35.8 KVp (11%), 10.5%

TERMINALS	Transferred surge peak magnitude (KVp) on tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal $3A_2$ earthed, others unloaded	Case 3 terminals earthed by 500 Ohm resistors	Case 4 terminal earthed by C=0.25 μF Capacitors
$3A_2$ - Earth	-62.8 (20%) at 4 μs	Zero	45.2	48 (at 40 μs)
$3B_2$ - Earth	48	104.0 (32%)	27.5	Nil
$3C_2$ - Earth	-44	-100	-40.5	-46
$3A_2$ - $3B_2$	56.3	104	37.8	48
$3B_2$ - $3C_2$	89.5	95	65	46
$3C_2$ - $3A_2$	-104 (32%)	-100	-81	-94 (at 40 μs)

IV. Chopped impulse voltage applied on LV terminal 'a' (Chopped at 3 μs)

Magnitude considered : 325 KVp

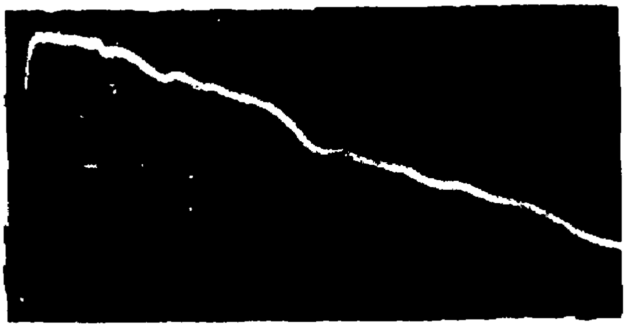
Transferred surge voltage at : HV terminals 'A','B' &'C' : -40 KVp (12.3%), -9%, -9%

Transferred surge voltage at : LV terminals 'b' & 'c' : -11% and -10%

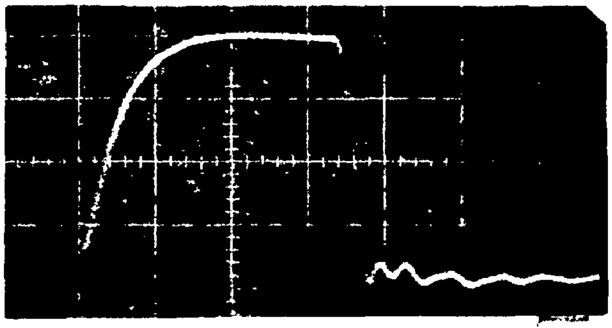
TERMINALS	Transferred surge voltage in (KVp) on tertiary terminals			
	Case 1 Unloaded tertiary	Case 2 terminal 3A2 earthed, others unloaded	Case 3 terminals earthed by 500 Ohm resistors	Case 4 Terminal earthed by C=0.25 μF capacitors
$3A_2$ - Earth	- 63	Zero	40.5	10.8
$3B_2$ - Earth	70.2	-100.7	27.5	Nil
$3C_2$ - Earth	-67.5	-116	-43.2	-10.8
$3A_2$ - $3B_2$	54	100.7	37.5	10.8
$3B_2$ - $3C_2$	91.8	91.8	64	10.8
$3C_2$ - $3A_2$	-92	-116	-80	-21.6

Oscillogram of surges when 66 kV terminal 'a' impulsed (220/66/11kV transformer)

Oscillogram of surges on tertiary coil (with and without earthed shield) of experimental set up.

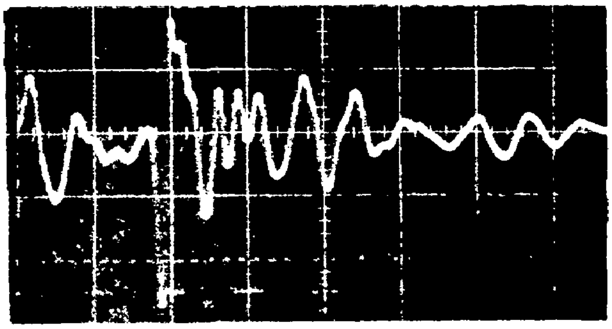


(1) Applied impulse at LV terminal 'a'
Magnitude: 20 V/unit
Time base: 10 μs/unit



(I) Applied chopped wave at LV terminal
Magnitude: 20 V/unit
Time base: 1 μs/unit

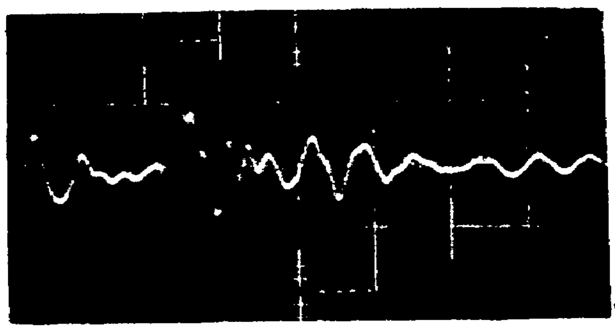
(2) Surges at terminal $3A_2$ without and with $C = 0.25\ \mu F$
Magnitude: 5V and 20V/unit
Time base: 10 and 10 μs/unit



(II) Surge at tertiary coil terminal without shield

Magnitude: 10 V/unit
Time base: 2 μs/unit

(3) Surges at terminal $3A_2$ without and with $C = 0.25\ \mu F$
(Chopped wave application)
Magnitude: 10V and 1V/unit
Time base: 10 μs /unit



(III) Surge at tertiary termin with earthed shield

Magnitude: 10V/unit
Time base: 2 μs/unit

CHAPTER - 5.

DISCUSSIONS ON THE TEST RESULTS

5.1 GENERAL REMARKS

The tests conducted on 3 phase 220 kV class Auto Transformers, 3 Phase bank of single phase auto transformer units and 3 phase 220 kV system transformers are analysed in this chapter.

It is observed that the magnitude of transferred surge on tertiary winding is generally more when the impulse voltage is applied on the adjacent LV winding (e.g. 132 kV winding in the case of 220/132/11 kV auto transformer) as compared to the condition when HV winding is impulsed. This is because of the close capacitive coupling between the tertiary and LV windings as these are placed adjacent to each other. The magnitude of transferred surges on tertiary tend to increase when the electrical clearances between different windings (particularly between LV and tertiary) are kept as minimum as permissible and tertiary to core clearance is kept large. The clearances between the coils primarily depend upon the is about 400 to 500μs (refer Oscillogram No. 2 on page 67). The magnitude of electrostatic and electromagnetic components of transferred surge depends upon the value of impedance connected at HV terminals, capacitance distributio between HV and LV windings etc. The magnitude of transferred surges at other two HV terminals are about 6 to 10% of LV BIL and the surges consis only two high frequency (about 1 MHz) oscillations and collapse quickly. In the above cases, all the non-impulsed HV and LV terminals of transforme were earthed through 400 and 450 Ohm resistors. In case HV terminals are kept floated which is ofcourse an unpractical condition, the magnitude of transferred surge at HV 'A' phase terminal shoots upto about 825 kVp (150% of LV BIL) and at HV 'B' and 'C' phase terminals it is about 40% of LV BIL.

The magnitudes of transferred surges on tertiary terminals $3A_2$, $3B_2$ and $3C_2$ are however not found in the above pattern. As both the ends of each phase tertiary coil are connected to the terminal of other two phase coils, the magnitude of transferred surges on tertiary terminals $3B_2$ and $3C_2$ are comparable with that of $3A_2$ even when surge is applied to LV 'a' phase only. The magnitude of electrostatic component of transferred surge at terminal $3A_2$ in case of transformer serial test voltage requirements. However, as these clearances also govern the values of percentage impedance voltage between the coils, these are adjusted to arrive at the specified values. It is also checked that the clearances between the coils or core to inner most coil are kept sufficient from cooling considerations. For example, the clearance between 33.33 MVA rated 11 kV tertiary winding and core is kept more than the 11 kV stabilising winding to core clearance in a 100 MVA 3 winding transformer.

Thus the magnitude of transferred surges on tertiary windings differ to certain extent from transformer to transformer depending upon their voltage ratios, percentage impedance, MVA rating BIL requirements etc. The transferred surge study carried on transformers having different characteristics is discussed in the following clauses :

5.2 STUDY ON 3 PHASE 220/132/11 KV AUTO TRANSFORMERS

The behaviour of transferred surges on tertiary under different tertiary terminal conditions when impulse voltage is applied either on a 132 kV terminal or 220 kV terminal is explained.

5.2.1 TRANSFERRED SURGES ON TERTIARY WHEN 132 kV LV TERMINAL IS IMPULSED

The transfer of surges on non-impulsed terminals when 'a' phase of 132 kV LV winding is impulsed is considered first. Circuit connections are made as shown in Fig.2(b). BIL of LV winding is considered 550 kVp. Following cases are considered for the study of transferred surge phenomena.

5.2.1.1 TERTIARY TERMINALS KEPT UNLOADED

This is the most common case as terminals of delta connected stabilising winding are kept floating. Even the terminals of tertiary windings are kept unloaded for considerably long periods in service as equipments for tertiary loading are generally connected only when required.

When 1.1/50 micro second impulse voltage is applied on 'a' phase of LV winding, the peak values of transferred surge voltage on its 'b' and 'c' phase terminals are quite low (about 6 to 10% of LV BIL). The transferred surge wave lasts for 250μs and consists of electro-static component and electromagnetic component over which oscillations are superimposed. The peak values of electromagnetic components of transferred surge at 220 kV HV terminal 'A' are about 40% and 20% of LV BIL respectively. The rise time for electromagnetic component is about 80μs and total duration of the wave is about 400 to 500 μs (refer Oscillogram No. 2 on page 67). The magnitude of electrostatic and electromagnetic components of transferred surge depends upon the value of impedance connected at HV terminals, capacitance distributio between HV and LV windings etc. The magnitude of transferred surges at other two HV terminals are about 6 to 10% of LV BIL and the surges consis only two high frequency (about 1 MHz) oscillations and collapse quickly. In the above cases, all the non-impulsed HV and LV terminals of transforme were earthed through 400 and 450 Ohm resistors. In case HV terminals are kept floated which is ofcourse an unpractical condition, the magnitude of transferred surge at HV 'A' phase terminal shoots upto about 825 kVp (150% of LV BIL) and at HV 'B' and 'C' phase terminals it is about 40% of LV BIL.

The magnitudes of transferred surges on tertiary terminals $3A_2$, $3B_2$ and $3C_2$ are however not found in the above pattern. As both the ends of each phase tertiary coil are connected to the terminal of other two phase coils, the magnitude of transferred surges on tertiary terminals $3B_2$ and $3C_2$ are comparable with that of $3A_2$ even when surge is applied to LV 'a' phase only. The magnitude of electrostatic component of transferred surge at terminal $3A_2$ in case of transformer serial numbers 1,2 and 3 as noted in chapter 4 are 103.5, 110 and 77 kVp respectively (refer oscillogram Nos.2, 29 and 5 on pages 39, 58 and 67). As seen from these oscillograms the values of electromagnetic components can be considered 55, 60 and 52.4 kVp respectively. The magnitude of electromagnetic components including superimposed, oscillary components (f= 84 KHz) at terminal $3A_2$ are 67.5, 70 and 60 kVp respectively. Thus it appears that magnitude of transferred electrostatic component is higher when clearances between the coils are kept as minimum as permissible whereas electromagnetic component is higher when percentage impedance voltage between the coils are high in a transformer. The peak value of transferred surge voltage at terminal $3A_2$ occurs at about 1.8 to 2.3μs and the surge lasts for about 125 to 150 duration.

The surge induced at tertiary terminals $3B_2$ and $3C_2$ are oscillatory in nature (refer oscillogram Nos.31 and 33 on page 58). Leaving apart initial two high frequency oscillation (f = 640 KHz), the principle frequency oscillation is about 84 KHz). The peak values of transferred surges at terminal $3B_2$ for transformer serial No.1 and 2 are around 100 kVp whereas for terminal $3C_2$ these values are around 75 kVp. The damped oscillatory wave at terminal $3B_2$ reaches to zero value at 150-200μs and at terminal $3C_2$ this value is about 150μs.

The transient voltage across tertiary coils of B and C phase are also oscillatory in nature, whereas 'A' phase tertiary coil contain electrostatic, electromagnetic and oscillatory components. It is seen that the peak magnitude of transient voltage across coil C is highest and in case of transformer serial numbers 1 and 2 it has reached the value 132 and 140 kVp respectively (refer table IV at page 34 and table III at page 51).

The transferred surge study on 3 phase bank of single phase 40 MVA, 220/132/33 kV auto transformers having off-circuit tappings at centre of the tertiary windings for ± 5% voltage variation in steps of 2½% indicated that the mid point transient potential of tertiary coils may exceed their respective terminal potentials when one terminal of LV is impulsed (refer oscillograms on page 47). However, the magnitude of transient potential at the mid points of tertiary coils of each unit were found less than the magnitude of transient voltage across tertiary coil of 'C' phase unit which was found maximum when LV terminal of 'a' phase unit was impulsed. The transient voltage across 10%

tapping turns (i.e. 30 turns) was measured 58 kVp. Thus the transient voltage across a tapping turn is approximately 2 kVp.

On the basis of above results, it is assumed that the transient potential at central portion of any phase tertiary coil will not exceed 130 kVp in the case of transformer serial No.1 or 140 kVp in the transformer serial No.2. With 0.33 mm thick radial paper insulation on tertiary conductors the impulse withstand strength between any two tertiary turns is obtained about 20 kVp and the tertiary winding as a whole can easily withstand 200 kVp impulse voltage. For loaded tertiary coils, horizontal cooling ducts (generally 3 to 4 mm wide) between the turns are provided, which further increase the impulse withstand value between the turns. Thus the transient voltages produced across the turns of the tertiary coils pose no problem whether impulse voltage is applied either across LV or HV winding.

When applied impulse wave at LV terminal 'a' is chopped, the wave reaches to zero value at about 0.5 to 0.6 μs after the instant of chopping and soon afterwards oscillatory voltage builds up due to inter action between effective capacitance and inductance of the circuit. These oscillations damp out in 6-8μs. The transferred surge voltage at other two LV terminal reach the value about 15 to 17.5% of LV BIL, when applied impulse voltage is chopped at about 3μs. The magnitude of transferred surge voltage at HV terminal 'A' reaches about 50 to 55% of LV BIL while that on other two HV terminals it reaches to 14-17%. The transferred surge at HV terminal 'A' reaches to negligible value in about 10 to 15μs.

The transferred surge wave shape at tertiary terminals $3A_2$, $3B_2$ and $3C_2$ remain same till the instant of chopping and soon after this one or two significant high frequency oscillations or spikes build up. These voltage spikes are clearly distinguished in transferred surge wave shape at tertiary terminals when chopped impulse voltage is applied on 220 kV HV terminal, refer oscillogram No. 17 on page 69. The magnitude of these oscillations depend upon the rate of fall of voltage during chopping and at the instant of chopping. The rate of fall of voltage cannot be controlled, but the instant of chopping can be varied. It is generally observed in the transformers selected for study that when applied impulse voltage at LV terminal 'a' is chopped at about 3μs the transferred surge voltage across 'c' phase coil is obtained highest as compared to chopping at other instants. As observed in the case of full wave application, here also the magnitude of transferred surge voltage across coil 'c' is more than the values either across coils A and B or at any tertiary terminals. When applied impulse voltage at LV terminal is chopped at about 4μs, the transferred surge voltage at terminal $3B_2$ is obtained highest, but this value as well as surge magnitude across coil c are lower than the surge magnitude obtained across coil 'C' when applied impulse is chopped at 3μs. The magnitude of transferred surge at terminal $3A_2$ remains same when applied impulse voltage is chopped at any instant as the peak value of the oscillations (produced by chopping action) is less than the magnitude of initial electrostatic component. This is due to the fact that polarity of transferred surges at terminal $3A_2$ through out remains positive as that of applied wave at LV terminal 'a'. (refer oscillogram Nos.29 and 42 at pages 58 and 60). When these two oscillograms are compared, it is found that electromagnetic component in the later oscillogram is negligible. This is due to chopping of applied voltage. Similar phenomenon happens in transient voltage across A phase tertiary coil. Thus the transient voltages at terminal $3A_2$ and across 'A' phase tertiary coil produce less severe stresses in the case of chopped wave application. The crest magnitude of transferred surges at terminals $3B_2$ and $3C_2$ and across coils of B and C phases increase due to super imposition of a few voltage spikes after the instant of chopping. For instance in transformer serial number 2 the crest magnitude of these spikes at tertiary terminal $3B_2$ and across coil C now become 154 and 180 kVp respectively (refer oscillogram No.44 on page 60 and table IV, page 52). However, the transformer insulation can withstand the stresses produced due to comparatively high magnitude voltage spikes as their duration are very short (about 0.8μs). It is practically observed that the transformer winding insulation which is designed to withstand 900 kVp full impulse voltage can easily withstand 1035 kVp (i.e. 115%) chopped impulse voltage. Thus the higher magnitude voltage spikes present in the transferred surge does not create a problem.

5.2.1.2 ONE TERMINAL EARTHING OF TERTIARY

When one tertiary terminal is earthed its potential becomes zero and the transferred surge voltag wave shape at the remaining two tertiary terminals are modified. However, the transient surge voltag across these two unearthed terminals remains nearly same (refer oscillogram Nos.3 and 9 at pages 39 and 40).

It is observed that when impulse voltage is applied on 'a' phase of LV terminals the earthing of tertiary terminal $3A_2$ produces higher magnitude of transferred surges on remaining two tertiary terminals as compared to earthing of the terminals $3B_2$ or $3C_2$. It is also observed that when terminal $3A_2$ is earthed the magnitude of transferred surges on terminals $3B_2$ and $3C_2$ are increased as compared to the case of unloaded tertiary terminals.

The earthing of one terminal of tertiary should not be preferred due to following reasons :

i) Probability of higher magnitude of transferred surges on remaining two unearthed terminals.

ii) Continuous higher power frequency voltage at these two floating terminals during normal service operation and during line to ground faults etc.

iii) When arresters installed on these two terminals get damaged, 3 phase dead short circuit to earth takes place causing excessive short circuit current in tertiary.

5.2.1.3 TERTIARY TERMINALS EARTHED THROUGH RESISTORS

When tertiary terminals are earthed through resistors, it is observed that the transferred surge voltage at tertiary terminals are suppressed. At terminal $3B_2$ the suppression is prominent (refer oscillogram Nos.2 and 14 on pages 39 and 41). The magnitude of transferred surge reduces if the values of resistors are brought down. It is seen that when resistor values are kept about 250 to 300 Ohm, the magnitude of transferred surges on tertiary is limited below 95 kVp under full and chopped wave application.

5.2.1.4 TERTIARY TERMINALS EARTHED THROUGH CAPACITORS

The capacitors offer very low impedance path for transient or very high frequency currents. Thus when tertiary terminals are earthed through capacitors the magnitude of transferred surge voltage at tertiary terminals are ~~xxxkhxd~~ suppressed considerably. These capacitors interact with inductance of transformer windings and form damped oscillatory wave form at tertiary terminals (refer oscillogram No.5 at page 39). The frequency of oscillations is about 16 to 20 KHZ and the rise time to reach the first peak value is about 20 to 25 μs. Thus when applied impulse at LV or HV phase terminal is chopped at about 3 to 8 μs (i.e. before the transferred surge wave at tertiary could reach its peak value) the magnitude of transferred surge voltage at tertiary terminals further reduces considerably. Also as the rate of fall of voltage during chopping is quite high (about 0.5μs), these capacitors vertually short circuit the tertiary terminals to earth. The capacitors (usually called "surge absorption capacitors") are very useful in suppressing the magnitude of transferred surge voltage at and across tertiary terminals. These capacitors are also useful in suppressing the transferred surges at tertiary terminals when reactive load is connected. The magnitude of transferred surges at tertiary terminals under three different terminal conditions i.e. unloaded, loaded by 3 phase 3.33 MVAr shunt reactor and loaded by 0.1μF capacitors along with 3.33 MVAr shunt reactors are given in table Nos.III and IV at pages 51 and 52 can be compared in this regard.

These capacitors reduce the magnitude of transferred surge voltages at end turns of tertiary coils, tertiary line terminal gear and tertiary bushings and on reactive load if connected on tertiary but do not have significant effect on potential at mid point or major portion of the tertiary coil. The surge voltage between tertiary turns are rather slightly increased. These findings are based on experimental results obtained on 33 kV tertiary coils having tappings at central portion of the coil. Similarly the lightning arresters installed near the tertiary terminals can reduce the magnitude of transferred surges at tertiary terminals only.

The study indicates that when 0.25μF capacitors are connected on tertiary, the magnitude of transferred surges at tertiary terminals $3A_2$ and $3C_2$ are limited between the values 40-45 kVp. It is interesting to note that these capacitors eliminate the transferred surge voltage at tertiary terminal $3B_2$ and create the polarity of transferred surge voltage at terminal $3C_2$ exactly opposite to that of $3A_2$ (refer oscillogram Nos. 30 and 34 at page 58). Thus the crest magnitude of surge across tertiary coil A (i.e. across terminals $3A_2$ and $3C_2$) is found between 80-90 kVp which is twice the value of surge voltage appearing either across coil B or coil C. Further increase in the value of capacitance cause little reduction in the magnitude of transferred surges. As explained earlier the magnitude of transferred surges at tertiary terminals are negligible under chopped wave application (refer oscillogram 43 at page 60).

5.2.1.5 <u>TERTIARY TERMINALS EARTHED THROUGH REACTORS</u>

It is known that the inductor offers high impedance path for high frequency transient currents. Thus when tertiary terminals are earthed through reactors, the magnitudes of transferred surges at tertiary terminals are not effectively suppressed. However, as noticed in clause 5.2.1.3 when surge capacitors of the order of 0.1μF are connected alongwith 3.33 MVA shunt reactor on tertiary the magnitude of transferred surges are suppressed considerably.

5.2.1.6 0.7/100 MICRO SECOND IMPULSE VOLTAGE APPLICATION

Consider the case when 0.7/100μs impulse voltage is applied on LV terminal instead of standard 1.2/50μs impulse voltage. It is observed that the increase in electrostatic and electromagnetic components due to steeper front and longer tail respectively is about 6 to 10%.

In the case of chopped wave application the reduction in the wave front duration has no effect on the magnitude of transferred surges at tertiary terminals. The magnitude of high frequency oscillations generated due to chopping action depends basically upon the rate of collapse of voltage and the instant of chopping as indicated earlier.

5.2.1.7 THREE POLE SURGES

When standard impulse voltage is applied at all the three LV terminals simultaneously the magnitude of transferred surges at tertiary terminals are increased as compared to the condition when single pole surge is applied on a LV terminal. It is the electromagnetic component of transferred surge which increases considerably (about 80 to 100 percent) and not the electrostatic component which is slightly increased (refer oscillograms at page 70). The crest value of transferred surge at tertiary terminal $3A_2$ under 3 pole surge application is about 1.1 to 1.4 times the value obtained when LV terminal 'a' is impulsed alone. The forty percent increase is found when the magnitude of electrostatic component of the transferred surge at terminal $3A_2$ is low as noticed in the case of transformer serial number 3 (compare readings of table I and IV at page 63 and 66). The increase around ten percent is found when the magnitude of electrostatic component of the surge is high compared to electromagnetic component as noticed in oscillogram on page 70. In the case of transformer serial number 2, this rise was found about fifteen percent. The magnitude of transferred surge voltage at tertiary terminals remain same when applied impulse voltage is chopped between 2 to 8μs as the oscillations generated due to chopping action have lesser magnitude than the initial electrostatic component of the transferred surge.

Since the waveshape of transferred surges at all the three terminals are identical, the magnitude of transient voltage across the tertiary coils is zero. The surge capacitors limit the magnitude of transferred surges at tertiary terminals effectively in this case also (refer table IV on page 66).

5.2.1.8 TWO POLE SURGES

When impulse voltage is simultaneously applied on two terminals 'a' and 'b' of LV winding the magnitude of transferred surges at tertiary terminals lie in between the values obtained in the cases of single pole and three pole surges. The increase in the magnitude of transferred surge voltage at terminal $3A_2$ is about 20% as compared to the condition of single pole surge in transformer serial No.3. The effect of surge capacitors is shown in table III at Page 65.

5.2.1.9 SWITCHING SURGE VOLTAGE

The switching surge voltage transferred from LV terminal 'a' to tertiary terminal $3A_2$ and across tertiary coil 'A' are about 10% and 11%

of LV switching impulse level (460 kVp), when tertiary terminals are kept unloaded. These values are not considered high (refer oscillogram No.38 at page 45). Here also the surge capacitors or resistors make the magnitude and polarity of transferred switching surges at terminals $3A_2$ and $3C_2$, equal and opposite, whereas the magnitude of transferred surge at $3B_2$ is negligible. These also increase the total duration of the transferred surges at tertiary terminals $3A_2$ and $3C_2$.

For simultaneous 3 pole surge application on LV terminals the magnitude of transferred surge at tertiary terminals becomes 13% (i.e. 60 kVp).

.2.1.10 EFFECT OF EARTHED SHIELD

The electrostatic component of transferred surge voltage at 11 kV tertiary terminal is usually greater than the corresponding electromagnetic component. Thus if the magnitude of electrostatic component alone can be suppressed the magnitude of transferred surge will autbmatically be suppressed by that amount. The electrostatic component of transferred surge voltage at tertiary can be suppressed either by increasing the gap between LV and tertiary coils or by putting an earthed shield outside the tertiary coil which also increases the over-all gap between the LV and tertiary coil. An experimental set up was made by keeping tertiary coil, intermediate earthed shield and outer LV coil over iron core. It was observed that the earthed shield suppressed the electrostatic and high frequency oscillatory components of transferred surge at tertiary coil to an extent of about 50% for full and chopped wave application on outer LV coil (refer RHS oscillograms at Page 86). This shield suppresses the electrostatic component of transferred surge along the complete coil as it surrounds the whole length of coil.

3 Phase, 100 MVA,220/132/11 kV Auto Transformer (ZH-L = 7.5%, HV and LV BILS 1050 and 650 kVp) was manufactured with earth shield outside the tertiary coil. Surge study indicated that with rated impulse voltage at LV terminal 'a'the magnitude of transferred surges at tertiary terminals $3A_2$, $3B_2$ $3C_2$ and across tertiary coils A, B, C are 45, 20, -45, 90, 56, 50 kVp respectively. The surge wave shapes at terminals $3A_2$ and $3C_2$ are similar and opposite in polarity. The BIL of 11 kV tertiary for 220 kV auto transformer provided with earthed shield can be safely kept 125 kVp.

2.2 TRANSFERRED SURGES ON TERTIARY WHEN IMPULSE VOLTAGE IS APPLIED AT 220 KV HV TERMINAL.

The presence of intermediate LV and tapping coils affect the magnitude of transferred surges on tertiary. It is observed that the magnitude of transferred surges at tertiary terminals and across tertiary coils are comparatively less when impulse voltage is applied at 220 kV terminal instead of 132 kV LV terminal. (The crest values of transferred surges stated in tables III may be compared with the values stated in tables I at pages 51 and 49). Under chopped wave application, the magnitude of transferred surges on tertiary are however comparable with the values obtained when LV terminal is impulsed. Also it is noted that one terminal earthing of tertiary does not increase the magnitude of transferred surges on remaining two terminals.

It can thus be concluded that for 220/132/11kV auto transformer the BIL of the tertiary winding can be decided based on the magnitude of transferred surges on tertiary from 132kV LV side.

It is observed that the transferred surge voltage at LV terminal 'a' is about 25 to 33% of HV BIL, when HV terminal 'A' is impulsed. Thus about 67-75% of applied impulse voltage is dropped across the series coil itself, although the number of turns in it are about 40% of the total turns. Thus in the case of 220/132/11 kV auto transformer, it is the normal practice that 220 kV series winding is designed for 900 kVp impulse voltage although 132 kV common winding is in series with it to share the impulse voltage distribution. The magnitude of transferred surges at LV 'b' and 'c' phase terminals are about 6% of HV BIL.

5.2.3 FIXATION OF BIL FOR TERTIARY WINDINGS

First the case of tertiary windings without any earthed shield is considered and afterwards the case of tertiary coil having earthed shield outside it will be considered.

5.2.3.1 TERTIARY WINDING WITHOUT EARTHED SHIELD

Consider the case of auto transformer in which the magnitude of transferred surge is maximum. It is noted that the crest values of transferred surge voltage at tertiary terminal and across the coil can reach upto 110 and 140 kVp respectively for a single pole surge application on LV terminal. For chopped wave application these values can reach upto 155 and 180 kVp respectively. As IS 2026 does not call for 3 pole impulse voltage application during the test, this condition is not considered for deciding the tertiary BIL. The lightning surge may appear at transformer terminals at any instant when the instantaneous value of service voltage may be at zero or peak or at any intermediate value. Taking this into account, the BIL of the 11 kV delta connected tertiary/stabilising windings can be kept 200 kVp.

5.2.3.2 TERTIARY WINDINGS PROVIDED WITH EARTHED SHIELD

As seen earlier with the provision of earthed shield over the tertiary coil, its BIL canbe kept 125 kVp. However, the provision of shield increases the cost of the transformer as the diameter of LV, tapping and HV coils increase and affects the core and tank size. The saving in the cost of transformer due to reduction of BIL of tertiary say from 220 to 125 kVp is negligible as the cost difference for 3 Nos. porcelain bushings with 200 kVp and 125 kVp BIL is hardly about thousand rupees and if 0.25 mm radial paper is used instead of 0.33 mm radia paper over conductors of tertiary coils saving of paper per transformer is hardly 5 kg. costing only about Rs.200/-. Moreover this is not the net saving as the space created by reducing the paper thickness has to be filled by press board packing in the tertiary coil. Also sufficient space is already available below the transformer cover for tertiary terminal gear formation and about 100 mm clearances in oil is easily obtained between the line

contd. ... 10

leads of tertiary coils or line lead to earth parts. Spiral coils are used for 11 kV stabilising windings. For mechanical reasons minimum 13 to 14 mm clearances between core to spiral coils are needed. For loaded tertiary, helical coils are used for which minimum 20 to 24mm clearance betwenn core to the coil is required (for cooling considerations). For mixed insulation i.e. oil duct and pressboard/bakelite cylinder, average withstand strength per mm can be taken 5 kV for power frequency and 15 kVp for impulse. Thus the above mentioned core to coil clearances are sufficient for 200 kVp impulse voltage. Normally earthed shield is provided over the tertiary coils when customer insists for it otherwise it is not preferred. Now consider when an equipment having 75 kVp BIL is connected to the tertiary provided with earthed shield. To protect this equipment properly the magnitude of transferred surge at its terminals should not be allowed to exceed 80% of its BIL. As the earthed shield itself cannot restrict the magnitude of transferred surges to this amount (0.8X75=60 kVp), the use of lightning arresters has to be made. Thus this earthed shield alone cannot protect the tertiary load nor its provision in transformer is economical.

5.3 STUDY ON 3 PHASE 220/110/11 KV AUTO TRANSFORMER

The 110 kV common winding can be kept comparatively closer to 11 kV tertiary coil because of its lower BIL (i.e. 450 kVp). Thus the percentage value of transferred surge may slightly increase due to increase in capacitance between LV and tertiary coils. However, the actual magnitude of transferred surges on tertiary are reduced because of the lower BIL of 110 kV common winding. The magnitude of surges at tertiary when HV winding is impulsed are slightly more than the values obtained in the cases of transformer serial Nos.1,2 and 3 due to comparatively tight clearances and as the HV BIL remains same.

The study of test results indicate that the BIL of tertiary winding in this case also canbe fixed at 200 kVp.

5.4 STUDY ON 3 PHASE BANK OF 220/110/11 KV AUTO TRANSFORMERS

The magnitude of the transferred surges on stabilising winding in the case of 3 phase bank formed by single phase 220/110/11 kV auto transformer units are somewhat higher than the values found in 3 phase 220/110/11 kV auto transformer.

Although the BIL of HV and LV windings are 1050 and 550 kVp as against the values of 900 and 450 kVp for 3 phase unit, the magnitude of transferred surges on tertiary are not increased in the same proportion because the electrical clearances between the coils are kept high due to higher test voltage levels.

The only difference noticed is that the magnitude of transferred surge on terminal $3A_2$ is more than on $3B_2$ when LV terminal 'a' is impulsed.

In this case also the BIL of the 11 kV stabilising winding can be kept 200 kVp.

5.5 STUDY ON 3 PHASE 220/66/11 KV SYSTEM TRANSFORMER

When impulse voltage is applied on HV terminal, the transferred surge voltage on corresponding LV terminal is only about 10% of HV BIL. It is also seen that when impulse voltage is applied on LV terminal, the transferred surge voltage on corresponding HV terminal which is terminated by 400 Ohm res
or is also very less (i.e. about 16 to 20% of LV BIL).

The magnitude of transferred surges at tertiary terminals of system transeformer are also lower than the magnitudes obtained in auto transformers.

The tapping coil which is situated between neutral side of HV coil and LV, acts as low potential shield and thus the magnitude of transferred surges at LV and tertiary terminals are found less when HV is impulsed. Also as the BIL of LV winding is only 325 kVp the magnitude of transferred surges at tertiary terminals are found low. It is observed that the magnitude of transferred surges either at tertiary terminals or across tertiary coils are less than 105 kVp. Thus the BIL of 11 kV tertiary winding for 220/66/11 kV system transformers can be safely kept 150 kVp.

CHAPTER - 6

PROTECTION OF TERTIARY WINDINGS AND THE CONNECTED LOAD

First the protection of 11 kV stabilising windings is considered and in next para the protection of tertiary winding and the connected load is considered.

6.1 PROTECTION OF 11 KV STABILISING WINDINGS

It has already been seen in clause 5.2.1.4 that the surge capacitors when connected across tertiary terminals and earth, suppress the magnitude of transferre surges at tertiary terminals only. Thus these surge capacitors are useful in limiting the magnitude of transferred surges at tertiary line leads and bushings, across the tertiary coils and connected load. However, the transferred surge voltage distribution along the major portion of the tertiary coils with respect to earth are only marginally affected by these capacitors. Similarly when lightning arresters are installed at tertiary terminals, these limit the magnitude of transferred surges at tertiary terminals only. The voltage distribution along the tertiary coil is basically governed by the transient voltage distribution in the HV or LV windings whichever is impulsed, capacitance distribution among the windings and to earth, mutual impedance etc.

Thus the transferred surge voltage distribution along the tertiary or stabilising coil can be affected either by providing lightning arresters at HV and LV terminals of the transformer or by putting earthed shield outside the tertiary coil. The lightning arresters when installed at HV and LV terminals of the transformer will restrict the magnitude of lightning impulse voltage at these HV and LV terminals to their respective protective levels, which are generally kept at about 60% of the winding BILs. Thus the magnitude of transferred surges at tertiary terminals are automatically limited to about 60% of their original values.

Normally lightning arresters are installed as near as possible to the terminals of the transformer in the substation. In some cases due to the space limitations of other system considerations the arresters may not be installed near to the transformer terminals. However, for effective protection of the equipment the arresters are installed within 50 metres range. In such cases, the magnitude of lightning surge reaching the transformer terminal increases above the protective level of arresters due to the reflections of the travelling waves on the section of the line between the arrester and transformer. The rise in the voltage (ΔU) is determined very approximately by the following expression :

$$\Delta U = \frac{du}{dt} \cdot \frac{a}{150} \ \text{kV}$$

Where $\frac{du}{dt}$ = Steepness of the wave front (kV/μs) about 500 kV/μs for lines with earth wire or about 1000 kV/μs for lines without earth wire a = Length of line between the arrester and protected object in metres.

Thus it is the duty of manufacturer to design tho insulation of stabilising windings to withstand the stresses produced by transferred surge voltage assumin that lightning arresters are not installed either at HV or LV terminals.

When 11 kV stabilising winding and the connecte bushings are designed to withstand 200 kVp impulse voltage for 220/132/11 kV auto-transformer and 150 kVp BIL for 220/66/11kV system transformer, there is no need of any protection. The arresters installed at HV and LV terminals indirectly provide adequate safety margin for stabilising winding (In case earthed shield is provided on 11 kV stabilising windings, their BIL can be limited to 125 kVp and no protection is needed)

Either one or all the three stabilising termina can be brought out depending upon requirements of the user. One terminal earthing of stabilising windings is not recommended.

6.2 PROTECTION OF TERTIARY WINDING AND CONNECTED LOAD

As in the case of stabilising winding, here als the tertiary bushings and the windings should be desig for 200 kVp BIL in the case of auto transformer or fo 150 kVp in the case of system transformer.

The impulse withstand strength of synchronous condenser is lower than that of oil immersed transfor with the same rated voltage. The ageing of insulatio may further reduce the impulse withstand strength. The load connected to tertiary are usually synchronous condenser, reactors, capacitor bank or static compensator. For 100 MVA rating of 220 kV class transformer the tertiary loading is kept maximum about 33.3 MVAr. The BIL of these 11 kV rated apparatus can be taken as 75 kVp. The repeatative impulse withstand strength of these equipments may be considered approximately as 60 kVp (i.e. 0.8 X 75 = 60 kVp). Thus the impulse protective level of lightning arresters guarding these equipments should not be more than 60 kVp. These arresters should be installed at the input terminals of the load. The impulse protective levels of 18 kV and 20 kV rated indigenously available arresters are about 54 and 60 kVp respectively. Any of these two category of arresters can be chosen for the protection of tertiary load. These arresters should also be suitable for operating under long duration transferred switching surges or switching surges generated by operation of the tertiary load side breaker. Also taking into account the high energy stored by the load of the tertiary (i.e. reactors, capacitors etc.) the lightning arrester should be capable to discharge the high energy during its operation. To fulfil this condition the energy rating of the arrester itself should be high. The arrester manufacturer have achieved the energy rating of arresters upto 6 kilojou /kV which is quite sufficient for this application.

The normal light duty station class arrester is having the energy rating about 2 kilojoules/kV. Also these arresters should be capable to operate satisfactorily when a rectangular surge current having total duration not less than 2000 micro-seconds and magnitude about 1000 Amps discharges through it. This special test should be specified in the test schedule while ordering these heavy duty station class arresters. These arresters should also preferably be provided with current limiting feature.

If the protective levels of these arresters are kept low or its energy rating is low, then these arresters will operate frequently and during operati may fail due to excessive thermal loading. This lead to persistent short circuit at tertiary and connected load terminals and would lead to a disturbance in service.

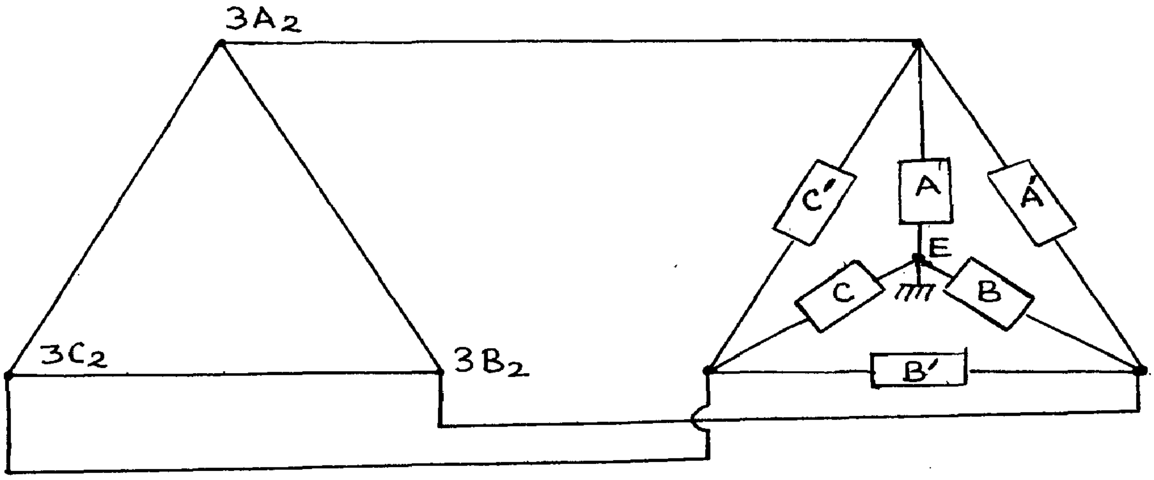
When lightning arresters are connected between terminals of tertiary load and earth, these will limit the magnitude of transferred surges at load terminals upto their impulse protective level. However, it is not necessary that these arresters will also limit the transferred phase to phase overvoltages to the same value. Thus it is safer to use lightning arresters between phases and earth as well as between phases. For the complete protection of the load connected to the tertiary against the transferred surges, it is recommended to use 18 kV arresters between phases and earth and 20 kV arresters between phases. As the magnitude of transferred surges across the terminals are more than those on terminals to earth, the voltage rating of arresters connected between phases is kept more to avoid their frequent operation. The protective scheme is shown in figure 7.

Alternative protection scheme is shown in fig. 8. For phase to phase transferred surges any two of the phase arresters (out of a, b and c) will provide the protection. The magnitude of phase to earth transferred surges are controlled by one of the phase arresters and the common arrester designated as 'n' in the figure.

Alternatively the protection scheme may consist of 0.25μF, 95 kVp BIL surge capacitors connected between phases to earth and 20 kV arresters between phases. This scheme can be used for inductive load. However, the first two schemes can be used whether the load on tertiary is capacitive or inductive.

In the case when load is connected to the tertiary provided with earthed shield, protection scheme should consists of 3 Nos., 20 kV rated arresters connected across tertiary phase terminals. As electrostatic component of transferred surges on tertiary are already suppressed by earthed shield, provision of 0.25μF surge capacitors between phases and earth will not serve any purpose.

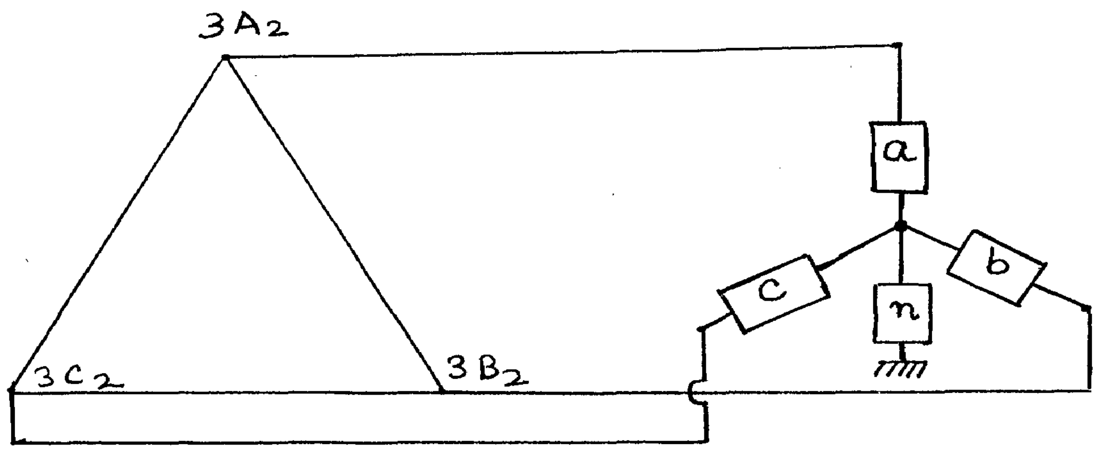
When tertiary windings are kept unloaded due to certain reasons no protection is required.



$3A_2$, $3B_2$ and $3C_2$ are	11 kV tertiary terminals
A B and C are	18 kV station class heavy duty lightning arresters
A' B' and C' are	20 kV station class heavy duty lightning arresters

Fig. 7

Protection scheme for 11 kV tertiary of 220 kV class transformers.



a,b,c and n are 9 kV station class heavy duty arresters.

Fig. 8

Alternative protection scheme for 11 kV tertiary of 220 kV transformers.

CHAPTER -7

CONCLUSIONS

The following conclusions can be drawn on the basis of transferred surge study on the transformers.

7.1 The transferred surge voltages in 3 winding transformers consist of four components: electrostatic, electromagnetic, free and forced oscillations. The electrostatic component of transferres surge voltage is high when electrical clearances between the windings are tight whereas the electromagnetic component is high when the mutual impedances between the windings are high. The magnitude of these components increase about 6 to 10% when wave front duration is reduced from 1.1 μs to 0.7 μs and wave tail duration is increased from 50 μs to 100 μs. The magnitude of these components also depend upon the surge impedance of transmission lines.

When chopped impulse voltage is applied on a transformer terminal, the magnitude of a few (normally two) high frequency oscillations at non-impulsed terminals generated due to chopping action are generally found quite high. However, as their duration is very short, they do not cause any damage to the insulation.

7.2 The magnitude of transferred surges at tertiary terminals depend upon the tertiary terminal conditions. The magnitude of transferred surges are found high

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when tertiary terminals are unloaded or connected to high impedance circuit or when one tertiary terminals is earthed and other two are kept floating. It also depends upon whether impulse voltage is applied on HV or LV windings of transformer. It is generally found that transferred surge voltages on tertiary are more when impulse voltage is applied on adjacent LV winding because close capacitive coupling exists between LV and tertiary windings.

It is found that the transferred surge voltage on 11 kV tertiary (or stabilising) terminals of 3 phase 220/132/11 kV or 220/110/11 kV Y-Yo,Δ connected auto transformers and of 220/66/11 kV Y/Y/Δ connected system transformers exceed considerably the specified BIL for 11 kV system voltage when tertiary terminals are unloaded. It is found that the magnitude of transferred surges at tertiary terminals are more in the case of auto-transformer.

7.3 When the load is connected to the tertiary of transformer, the magnitude of transferred surges at tertiary terminals are reduced. The reduction is not significant in the case of reactive loading as reactor offer high impedance for transient phenomenon, whereas it is significant for capacitive loading. Even when the tertiary terminals are earthed through the surge capacitors of the order of 0.05 to 0.1 μF, the magnitude of transferred surges at tertiary terminals and across tertiary coils are limited to about 45 kVp and 90 kVp respectively. However, these surge capacitors suppress the transient potentials at tertiary terminals only and not along the major portion of the tertiary as noted in chapter 6.

7.4 The BIL of tertiary (or stabilising) windings should be fixed on the basis of the magnitude of transferred surges on these windings when these are kept unloaded and assuming that no lightning arresters are installed either at 220 kV or LV terminals. The reduction in the magnitude of transferred surges due to the presence of arresters in service should be treated as the "safety margin".

On the basis of transferred surge study it is established that the BIL of 11 kV stabilising or tertiary windings should be kept 200 kVp in the case of 220 kV auto-transformers whereas it can be kept 150 kVp in the case of 220 kV system transformers.

7.5 When earthed shield is kept outside the tertiary winding, the BIL of the winding can be kept 125 kVp. However, this earthed shield may increase the cost of the transformer to about 1 or 1.5%.

7.6 The magnitude of transferred switching surges across tertiary coils for single pole and three pole surges (applied either at LV or HV terminals) are about 50 and 65 kVp respectively. These values are not considered high.

7.7 The equipment connected to the 11 kV tertiary is generally designed for 75 kVp impulse voltage level. The continuous impulse withstand strength of the equipment can be considered about 60 kVp (i.e. about 80% of the rated BIL). Thus the magnitude of transferred surges at and across the load terminals should be limited upto 60 kVp. The suitable protection scheme using the lightning arresters or the combination of surge capacitors and lightning arresters have been suggested. The impulse protective level of the arresters should not be above 60 kVp. It is shown in Chapter 6 that the thermal rating of these arresters is also very important as tertiary load (e.g. reactor or capacitor bank) can store high energy.

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