Modeling Faults During Impulse Testing of Transformers

V.Jayashankar, C.Kumaravelu, A.Palani, S.Usa, K.Udayakumar

Abstract— A major difficulty in devising and assessing methods of impulse analyzing systems for transformers is the lack of an adequate fault model. Experimental results on breakdown with lightning impulse (LI) voltages involving solid, liquid, and gaseous media are shown. The LI is applied across a string of discrete elements, and a uniform layer winding. Failures involving the chopped lightning impulse (CLI) test are studied. A simplified circuit model is proposed to account for the faults. This would have direct utility in assessing analysis methods of LI tests. The utility of the model reference approach as an analysis method is illustrated.

Keywords: Transformer, breakdown, partial discharge, impulse

I. NOMENCLATURE

FW, RFW : Full-wave, Reduced full-wave voltage
FWC, RFWC : Full-wave, Reduced full-wave current
CW, RCW : Chopped-wave, Reduced chopped-wave voltage
CWC,RCWC: Chopped-wave, Reduced chopped-wave current
t_1, t_2 : Time at which the fault initiation, excitation occurs respectively

II. INTRODUCTION

THE impulse test on a power transformer is a dielectric test intended to confirm its integrity at the basic insulation level (BIL). The method of performance of the test is specified in standards such as IEEE Std C57.98-1993 or the IEC-60076 also. The detection of failure during an impulse test is not trivial and a separate standard IEC-60722 caters to this need. One difficulty with the interpretation of test results is that adequate experimental data on faults during impulse tests do not exist. IEC 60722 provides several examples of such failures but it can be appreciated that identical results would not be obtained on other types of transformers and other ratings of transformers. On the other hand it would be equally unacceptable to treat each fault in each winding on a case-by-case basis with no generalized results. In this work we work from first principles and provide experimental results on various types of faults that can occur during impulse tests. This paves way for a generalized fault model. In the generic case, failures can involve a spark over across gaseous, liquid or solid media. Of these, breakdown in solid insulation is non-self restoring and is permanent. A recourse to literature reveals that a variety of techniques have been employed for conducting fault simulations within transformers. For example, Heller and Veverka [1], state that a physical short between sections of the winding frequently results in waveforms that are similar to a fault across them. Malewski and Poulin [2] connected a semiconductor device (a diac) between sections of a disc winding for the purpose of fault simulation. Other results on faults have been reported in [3], [4]. We were particular about the following aspects in conducting staged tests:

- There was a progression in the nature of the study from the recognition of gross faults to those based on subtle distinctions;
- Studies were performed on failure modes involving self-restoring and non self-restoring insulation;
- The influence of changing input waveforms such as the standard lightning impulse (LI), chopped wave (CLI) and the switching surge were addressed;
- Partial discharges within windings were analyzed.

We begin with a study of breakdown across discrete elements.

III. BREAKDOWN ACROSS DISCRETE ELEMENTS

A lumped parameter model involving R, L and C elements has often been invoked to explain the behavior of a winding when exposed to a step voltage. Indeed, the estimation of stresses due to impulse is often studied with about 10 elements [5]. Prior to the study of breakdown within windings we first consider a string of elements, which are connected in series. A sphere-gap is connected across a portion of the string to provide visual indication of spark over. The arrangement is shown in Fig. 1.

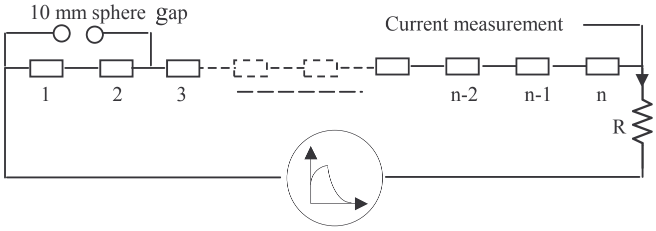

Fig. 1 Fault simulation across string of discrete elements

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In the subsequent figures normalized values for (voltage and current) rather than absolute values are shown. This is the practice adopted in IEEE Std C57.98-1993 from which also follows the terminology of RFW, FWC etc. The time axis of each figure is chosen so as to elucidate the essential features of the experiment.

A. Breakdown across inductors

We first consider a string of three inductors connected in series. Their values are 375 mH, 25 mH and 1 mH. It is energized by a PU12 Hafely Impulse Generator. The applied voltage and the current are monitored with a Tektronix TDS 420 oscilloscope. An initial reduced voltage (RFW) is applied and the current (RFWC) observed. The voltage is increased to FW when a flash over of the sphere-gap occurs and the current FWC noted. It is seen from Fig. 2 that substantial changes are seen in both the applied voltage and current.

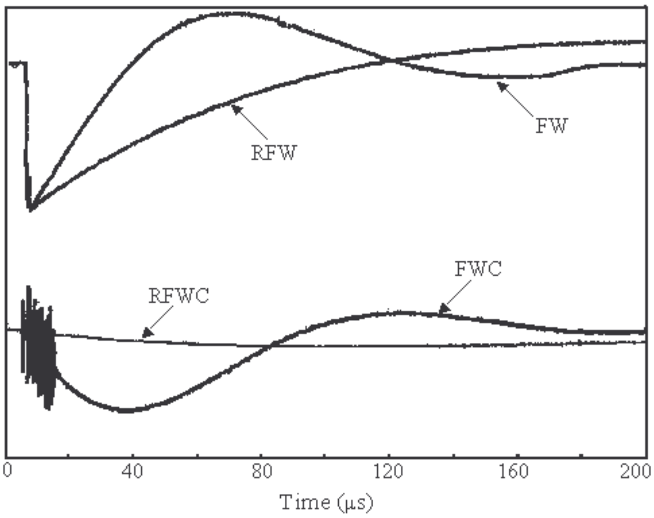


Fig. 2 Spark over during LI across 375 mH of string of inductors

If a fault is created across the intermediate value of 25 mH, the resulting waveforms are as in Fig. 3. Here, lesser deviation is seen in the voltage waveform but a change in current shape is evident.

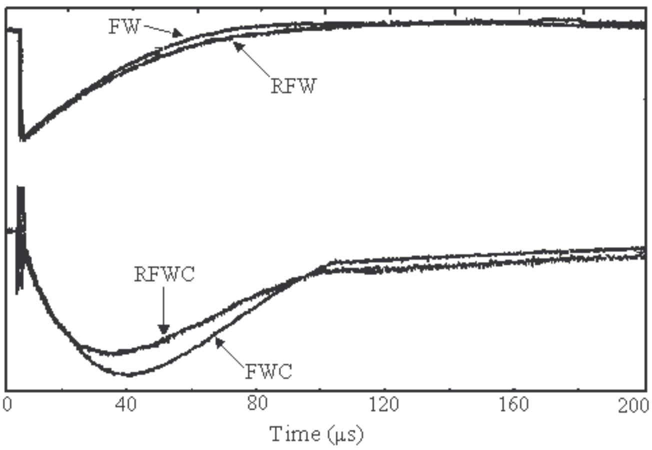


Fig. 3 Spark over during LI across 25 mH of string of inductors

B. Breakdown across string of resistors

A string of 10 resistors of 15 kΩ were connected in series. A sphere gap was placed across a portion of the string. It was energized with LI for increasing sphere gap lengths. Fig. 4 shows the effect of changing the gap length on the current response. The time of initiation of fault 't_1', keeps increasing with increased gap length. The influence of the volt-time curve of the gap is evident. With the sphere-gap immersed in oil, the current waveform is as shown in Fig. 5. One also notes a finite fault extinction time 't_2' here. If a switching surge (50/1600 µs) is applied to the resistor string, with the sphere gap in air, a fault appears as shown in Fig. 6.

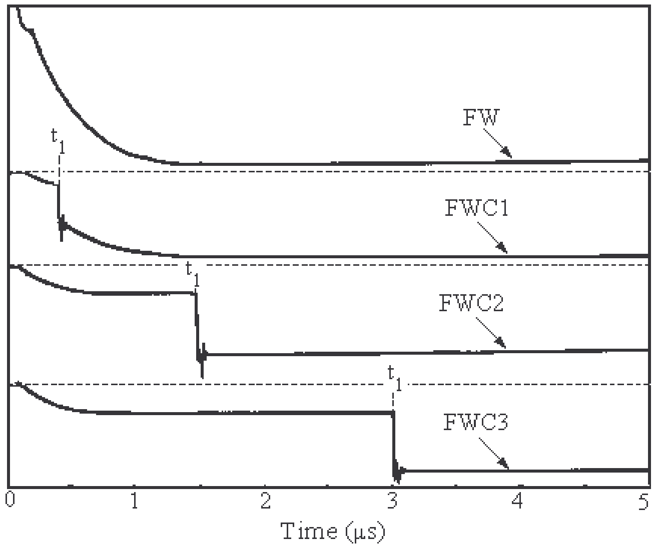


Fig. 4 Breakdown across string of resistors with increasing gap lengths

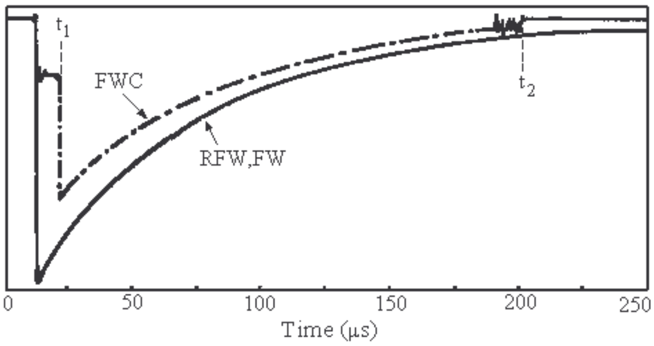


Fig. 5 Spark over in oil immersed sphere gap across resistor string

C. Breakdown across string of capacitors

Ten identical polyester capacitors (Philips, PET, 0.003 nF) are connected in series with a 30 kΩ resistor. In this case the sphere-gap has to be placed across 35% of the total capacitance value in order for breakdown to occur. The wave-forms observed with gap is shown in Fig. 7. One notes multiple extinctions in the current waveform FWC.

IV. Breakdown across uniform layer winding

Having studied the behavior of discrete elements we now consider breakdown across a uniform layer winding. It has

4000 turns of round wire wound on a former of 90 mm diameter with tapings brought out every 10%. An inner round

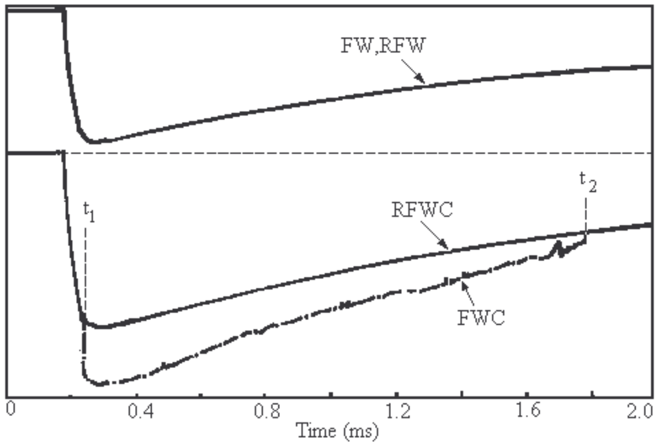


Fig. 6 Spark over in resistor string with switching impulse

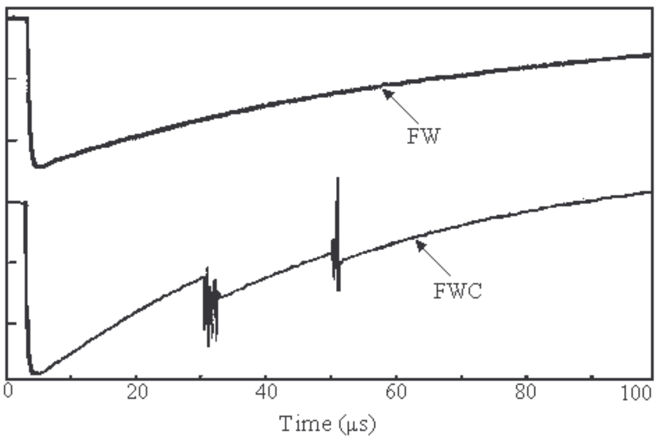


Fig. 7 Spark over across capacitor string with sphere gap of 0.025 mm

aluminum tube formed the secondary. For the simulation of non-self restoring insulation, paper insulation was placed across the sphere gap. The voltage was increased until the paper punctured. This is shown in Fig. 8. Similar results for breakdown across polyester film were reported in [6].

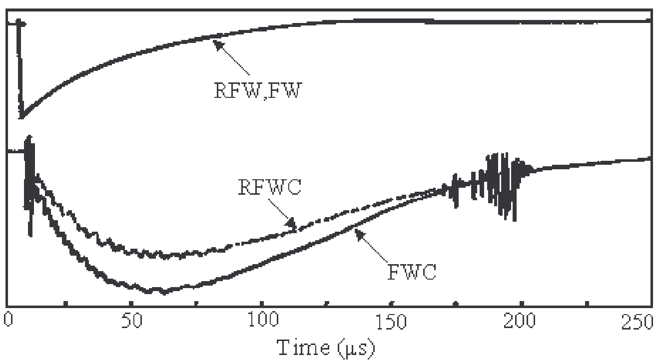


Fig. 8 Breakdown of non-self restoring medium

We now consider breakdown during chopped waves. A clear recognition of failure during a chopped test is shown in Fig. 9. Here a sealed gas tube was used as the breakdown medium. In this case a fault occurs for the CLI of 11 μs (FCWC) whereas the response for CLI of 14 μs (RCWC) refers to a withstand. An expanded portion of Fig. 9 is shown in Fig. 10, which also shows the voltage across the sphere gap.

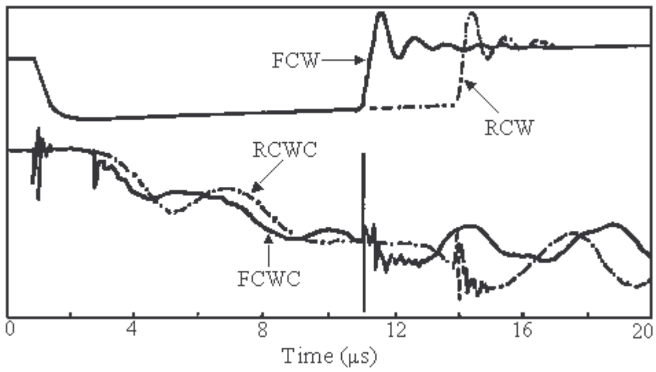


Fig. 9 CLI failure using sealed gas tube

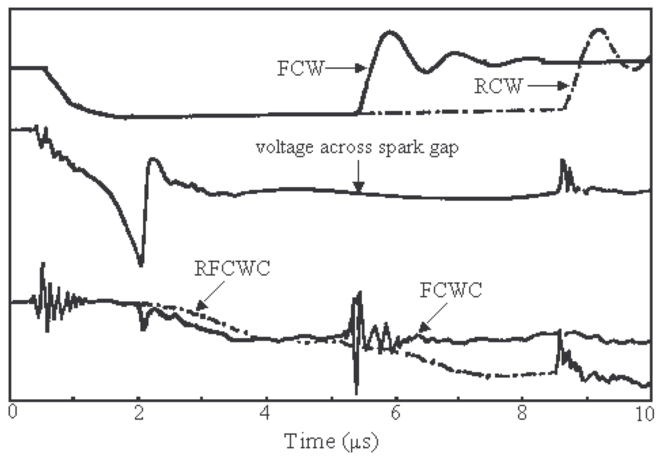


Fig. 10 CLI wave failure using sealed gas tube (enlarged version of Fig. 9)

V. SIMPLIFIED FAULT MODEL

A two-dimensional circuit representation of any insulation structure can be conceived to be of the form as shown in Fig. 11. Only two rows are shown but a larger number is possible. It is not essential that all the sectional resistances or capacitances be equal. For complete breakdown of a non-self restoring insulation, a conducting part between the two electrodes is needed. Once such a path is created, the overall resistance becomes zero. With intermittent failures, a switch in one row conducts but does not bridge the electrodes. On the other hand a PD can be represented by the switching 'ON' of any one switch for a duration and subsequent switch 'OFF'.

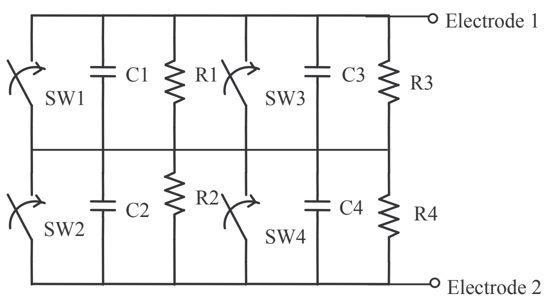
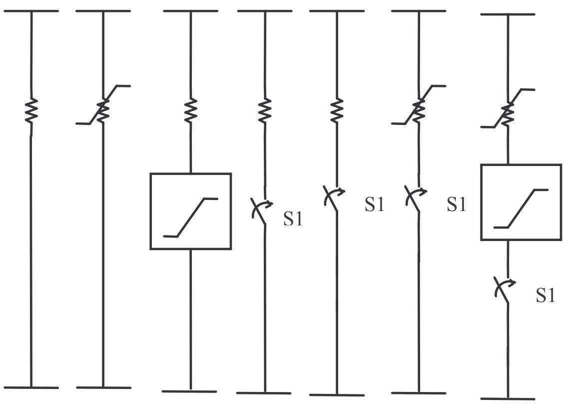


Fig. 11 Insulation structure equivalent circuit

It would be more convenient to have a one-dimensional representation of the model. Based on a study of the experimental data shown in the earlier sections and from a study of literature [6] we propose a simplified fault model as shown in Fig. 12. The formal definition of each of the faults is given in Table 1.



A B C D E F G

Fig. 12 Schematic representation of faults

TABLE I
CLASSIFICATION OF FAULTS

Type	Description	Mathematical definition
A	Constant resistance	$R = R_m \forall T$, $R_m \in [0, R_{max}]$
B	Non-linear element	$R = f(V)$, $R \rightarrow$ deterministic and no hysterisis
C	Hard limit with resistance	$R = R_m \forall T$, $V = V_{m,}$, $V_m \in [V_{min}, V_{max}]$
D	Random switching constant resistance	$R = R_m \forall T$, $R_m \in [0, R_{max}]$, $t_1 < T$, t_1 is random
E	Random intermittent switching	$T > t_2 - t_1 > 0$, $R = R_m \forall T$, $R_m \in [0, R_{max}]$
F	Progressive breakdown	R_i, R_m, and R_f are initial, minimum and final resistance, t_1, t_2 random, $t_2 - t_1 > 0$, $R_f < R_i$, $R_i, R_m, R_f \in [0, R_{max}]$.
G	Partial discharge	Similar to Type F except that $R_f = R_i$, $R_m \neq 0$

The correspondence between the proposed model and the experimental data is as follows:

In the simplest representation when a wire is placed across electrodes for the duration of the impulse, a resistor R is sufficient (Type A). 'B' caters to the presence of non-linear element such as a lightning arrester within the winding. Type 'C' caters for the spark gap model of Fig. 10. To account for the finite switching time t_1, along with a finite resistance model of spark over model D is required. E and F represent progressive breakdown where a switch closes for a finite time t_1 opens after time t_2 before the end of the impulse response. A partial discharge (G) is represented by the absence of a continuous short between electrodes at any time during the response.

VI. Model reference based analysis of impulse tests

In order to draw useful results from the fault model of Fig. 12, it is necessary to design a method for precisely creating the faults. Further impulse analysis methods also need to address each of these faults. One method that has been proposed for this purpose is the model reference approach [7] shown in Fig. 13. Here a difference current $i_\Delta(t)$ between the winding under test and a model of the winding $I_m(t)$ forms the basis of failure identification. With no fault $i_\Delta = 0$. With any fault $i_\Delta(t) > 0$. To elaborate on this notion a lumped parameter model of a winding with 10 discrete elements is constructed. The parameters of the model Cs, Cg and Ls are so chosen that they yield a frequency response similar to that of a uniform layer winding. Here Ls represent the air core inductance of the coil, Cg, Cs are the capacitance to ground and across sections and Rs represents resistance of coil. The network parameters are given in Appendix I.

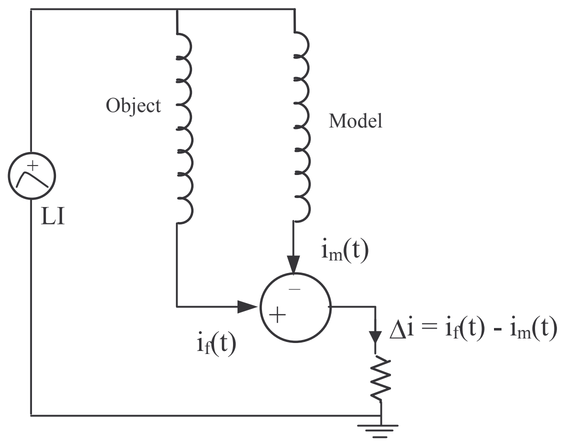


Fig. 13 Schematic representation of model reference approach

B. Partial discharge simulation

The simulation of PD within a winding is difficult. Experiments involving PD in idealized dielectric medium with impulse excitation have shown that PD pulses are of very short duration. For eg. Yamashita [7] shows PD durations of the order of 200 ns. Similar results have been [8],[9], [10]. Other results show the duration to be as high as 5 μs. Thus one has to cater to a wide requirement of rise and fall times of the PD pulse. One method of simulation would be to use a suitable non-linear element with switches (Type G) to obtain current shapes of PD. A traditional way of analyzing PD behavior is the use of the 'abc' model. Here a switch is assumed to discharge across 'a' for a short duration and regain its non-conducting state after finite time. It has been shown that a sphere-gap does not have the desirable property of regaining its non-conducting state under all circumstances [4]. We used an analog switch, which can be independently controlled. An arbitrary function generator is used to create a waveform similar to a lightning impulse waveform. A second arbitrary function generator connected to an analog switch, which is placed across nodes. It is programmed to independently control the switching 'ON' and 'OFF' of the switch. Results of PD detection are shown in [4].

C. Tests involving chopped wave

With existing methods it is difficult to identify failure when the times to chopping between the reduced full wave voltage and the full wave chopped voltage are not identical. We hence performed a set of experiments on the model involving such situations. Two conditions of fault are simulated. In one the fault occurs before the instant of chopping and the second case the fault occurs after the instant of chopping.

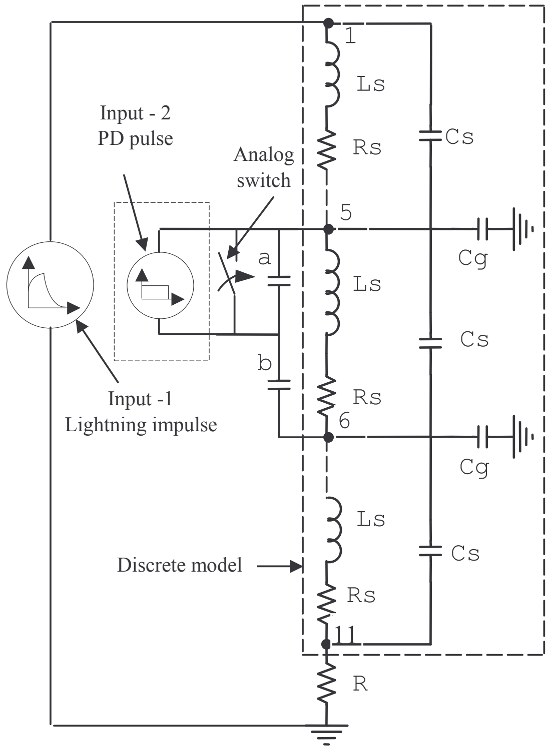


Fig. 14 Scheme for controlled switching / PD creation

A CLI test with a time to chopping of 6µs and a fault at 3µs for an excitation with CLI of 10 V is shown in Fig. 15(a). The difference current is shown in Fig. 15(b). Similar results for a fault created after the instant of chopping (at 10 µs) are shown in Fig. 16(a) and Fig. 16(b) respectively. Thus differences due to faults are visible in the time domain. The model reference approach can cater to changes in chopping times as it uses the difference in waveforms between the object and the model. A major result is that there does not appear to be any need to distinguish a failure before chopping from that after chopping. This was one of the features of IEC 60722 method of failure identification.

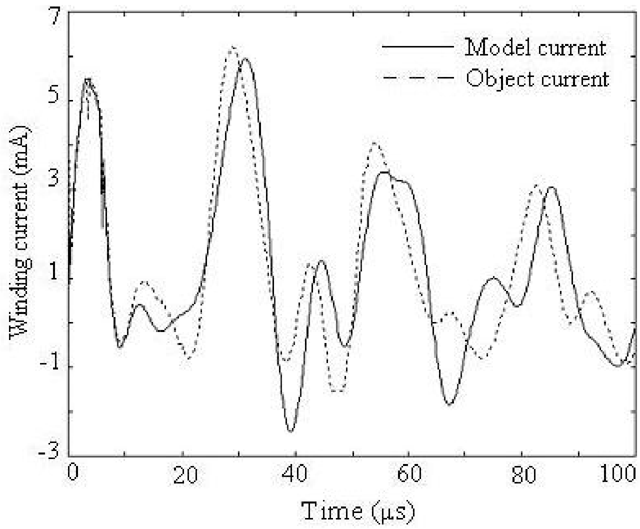


Fig.15(a) Measured Model and Object currents for the CLI of 6 µs (with a fault at 3 µs before instant of chopping)

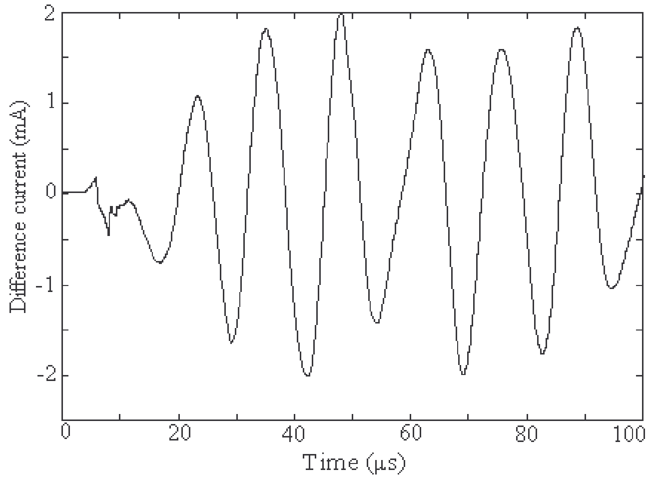


Fig.15(b) Difference currents for the CLI of 6 µs (with a fault at 3 µs before instant of chopping)

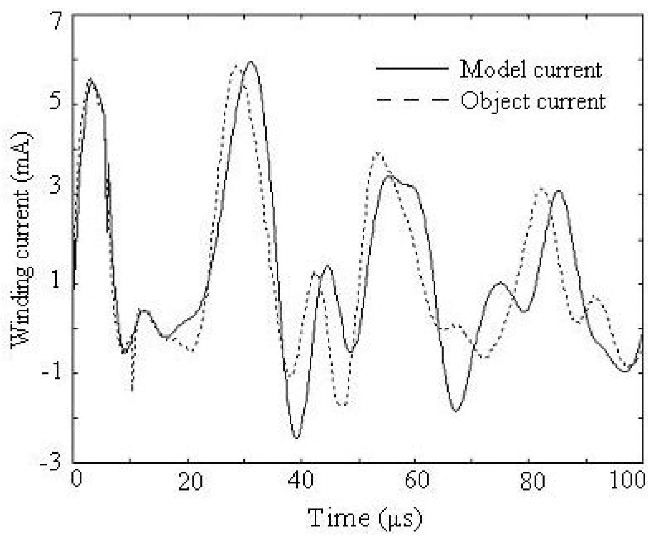


Fig.16(a) Measured Model and Object currents for the CLI of 6 µs (with a fault at 10 µs)

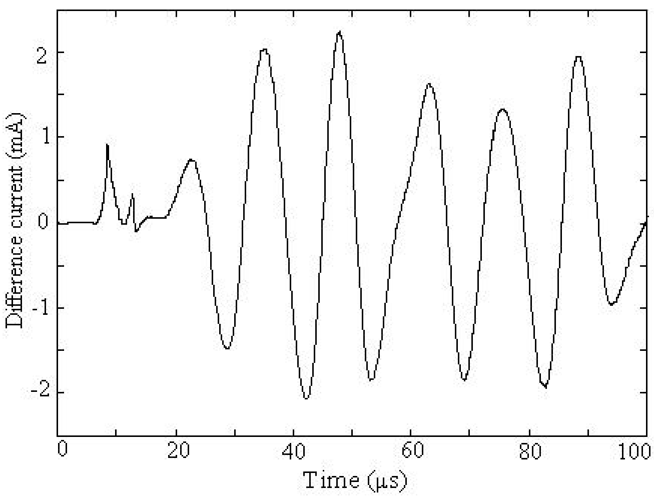


Fig. 16(b) Difference currents for the CLI of 6 µs (with a fault at 10 µs)

VII. SIGNIFICANCE OF FAULT MODEL

There are several aspects of the fault model that need some explanation. For example, the duration t_1 appears to be arbitrary. We show that an estimate on the upper bound on t_1 can be obtained from a consideration of the winding response to a standard LI. Fig. 17 shows the voltage across nodes 1-2 and 9-10 as a function of time on the application of a standard LI to the model. The voltage across the nodes is oscillatory. For such voltages, the modified disruptive effect can be used to compute the probable instant of breakdown as has been discussed in [11]. A very rough estimate of the probable time of switching can however be obtained from the time of occurrence of the peaks of the voltages. At node 1-2 this occurs at 5 µs whereas at nodes 9-10 it occurs at 15 µs.

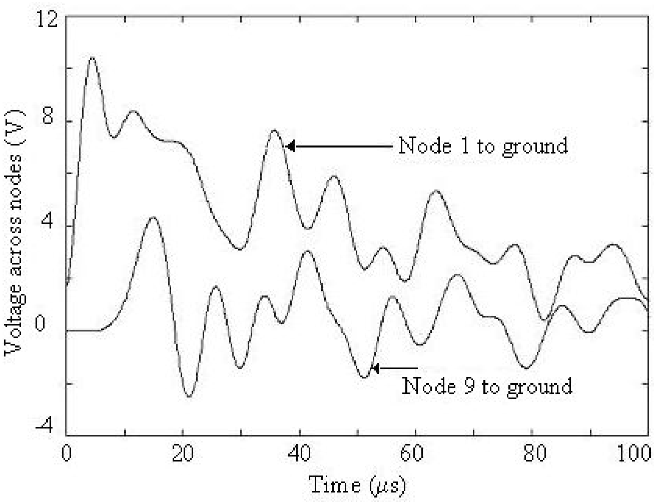


Fig. 17 Node to ground voltage distribution of model subjected LI

VIII. CONCLUSION

Experimental results involving breakdown across discrete elements and windings were shown. Methods were suggested to demonstrate controlled switching for partial discharge studies and studies involving chopped test. A simplified circuit model of faults was proposed. The model reference approach was shown to be ideal for analyzing such results. It does not appear necessary to distinguish a failure between the instant of chopping to one after.

APPENDIX-I

The parameters of the physical model with discrete element (shown in Fig. 14) are as follows:

Ls : 2.5 mH	Rs : 18 Ω
Cs : 150 pF	Cg : 850 pF

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