Impulse Breakdown Characteristics of Aged Oil Impregnated Paper

Bavisha Thomas and **Usa Savadamuthu**
Division of High Voltage Engineering
College of Engineering, Guindy
Anna University, Chennai, India

ABSTRACT

Voltage-time (v-t) characteristic plays an important role during the insulation coordination of a power system. Power transformer is the crucial equipment in the design of a reliable power system. During the operation of a transformer, Oil Impregnated Paper (OIP), the widely used winding insulation of transformer, undergoes significant irreversible aging. Aging alters the dielectric properties of the OIP reducing it's withstand capability. Hence in this work, the impulse v-t characteristic of fresh OIP and 8 years service aged OIP of the same manufacturer are compared. Moreover, when the transformers are directly connected to Gas Insulated Substations (GIS) and during the switching operation of vacuum circuit breakers, OIP is stressed by Very Fast Transient Overvoltage (VFTO). In addition, transformers are subjected to repeated impulses generated during multiple lightning strokes, switching operations of circuit breakers and HVDC converters. Various studies have pointed out the adverse effect of VFTO and repeated impulses on transformer insulation. Therefore, the effects of VFTO and repeated impulses (both LI and VFTO) on the v-t characteristics of fresh and service aged OIP are quantitatively assessed and discussed with reference to the Basic Impulse Insulation Level (BIL) and protection level of the transformer insulation.

Index Terms — **Aging, v-t characteristic, VFTO, Repeated impulses, insulation Coordination.**

1 INTRODUCTION

WITH recent advancements in EHV and UHV transmission systems, Gas Insulated Substations (GIS), Distributed Generation etc, there is an increasing concern towards a reliable power system. Good insulation coordination is essential for the reliable operation of power system. Voltage-time (v-t) characteristic forms the basis of insulation coordination. During insulation coordination, a sufficient safety margin is established between the design level of the equipment to be protected and the protective level of the protective device. Protection of power transformer is more important as it is the most crucial and highly expensive equipment in the power system. Even after proper insulation coordination, a significant number of transformers fail [1]. More than 19% of transformer failures are in winding insulation [2, 3] and the most commonly used winding insulation of transformer is Oil Impregnated Paper (OIP). Moreover, bushing failures contribute to 13% of the total transformer failures [3] and in general 80% of the transformer bushings are OIP bushings [4].

As the transformers age, OIP is subjected to various stresses like electrical, thermal, mechanical, environmental stresses etc. These stresses degrade the insulation reducing it's withstand capability [5]. Degradation during aging will affect the impulse v-t characteristic of OIP virtually reducing the safety margin considered during insulation coordination. Hence, for reliable insulation coordination, v-t characteristic of the aged OIP needs to be analyzed.

Nowadays transformers are directly connected to GIS and Very Fast Transient Overvoltages (VFTO) are likely to stress these transformers. VFTO also occur due to the switching operation of vacuum circuit breakers and at certain conditions due to lightning. Many transformer failures due to VFTO have been reported in the literature threatening the stability and reliability of powers system [6, 7]. Vandermaar et al have reported that even fresh OIP fails when subjected to VFTO of magnitude comparatively lower than the lightning impulse magnitude [8].

On the other hand, there has been growing interest in investigating the status of electrical insulations after repeated impulses. Transformers are subjected to repeated impulses generated during multiple lightning strokes, switching operations of circuit breakers and HVDC converters**.** Okabe et al [9] have observed that, after repeated impulses, OIP undergoes

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degradation leading to transformer insulation failure. He has also emphasized that, the decision of impulse test voltage level must be based on the effect of repeated impulses using V-N characteristic [10] which deals with the number of repeated impulses the insulation can withstand at different voltages.

Thus in addition to aging, factors like VFTO and repeated impulses influence the v-t characteristics of OIP and hence the insulation coordination. Therefore, in this work, the effects of VFTO and repeated impulses on the v-t characteristic of the fresh and aged OIP have been quantitatively analyzed. The results will provide guidance for deciding on the effective safety margin during insulation coordination and for selecting an appropriate design voltage level of transformers to prevent premature failure of power transformers.

2 PRINCIPLES OF INSULATION COORDINATION

Insulation coordination is the correlation of the characteristics of the power equipment to be protected and the characteristics of protective device such that the insulation of the power equipment is protected from excessive overvoltages. In the present study, the equipment to be protected and the protective device are power transformer and surge arrester respectively. As per IEC 60076-3, 2013, for Class I equipment (1-170 kV), the insulation withstand level is given by standard lightning impulse (BIL-Basic Impulse Insulation Level) and for Class II equipment (>170 kV), the withstand level is given by switching impulse (BSL-Basic Switching Impulse Level) in addition to BIL [11]. Figure 1 shows the classical approach of insulation coordination for a non-self restoring insulation like OIP.

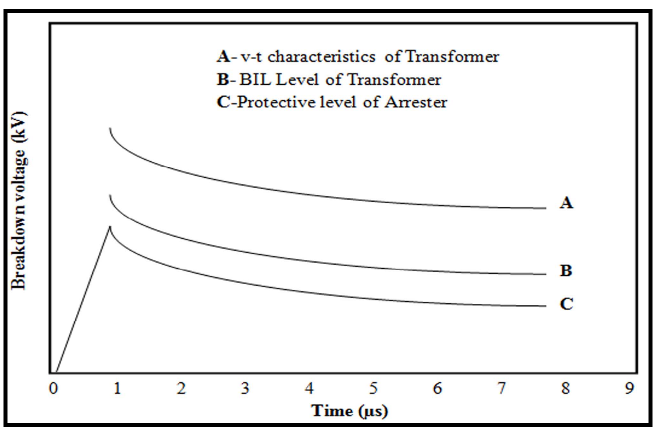


Figure 1. Insulation Coordination for a non self restoring insulation.

v-t characteristic is defined as the characterizing curve drawn with the maximum voltage withstood by the insulation and the corresponding time to breakdown. Time to breakdown (t_b) is defined as the time interval from the virtual zero to the time when breakdown occurs. Curve A in Figure 1 is the Lightning Impulse (LI) v-t characteristics of the transformer insulation. Curve B is the BIL level of the transformer insulation. Upto an insulation thickness of 1.2 mm, inception voltage of partial discharges is 85%-90% of breakdown voltage and extinction voltage is 75%-80% of the breakdown voltage [12]. Therefore it is recommended that, curve B is at least 30% below curve A (70% of curve A) to prevent any partial discharges. The protective level of the protective device, Curve C must lie below Curve B with a safety margin as shown in Figure 1. IEC 60071-2 recommends a minimum safety margin of 15% between the BIL Level and protection level [13].

But aging of insulation virtually reduces the above safety margin. Moreover, many transformer failures are reported due to VFTO and repeated impulses questioning the safety margin and insulation coordination.

3 EXPERIMENTAL METHODOLOGY

3.1. TEST SAMPLES

Winding insulation of power transformer comprises of inter-turn and inter-disc insulation. Due to the excellent dielectric characteristics and lower cost, OIP is still widely used as the transformer winding insulation. Hence in this work, experiments are carried out on OIP with test cell designed as per ASTM D149-97a to model the inter-turn winding insulation [14]. Figure 2 shows the electrode configuration and test cell used in the study.

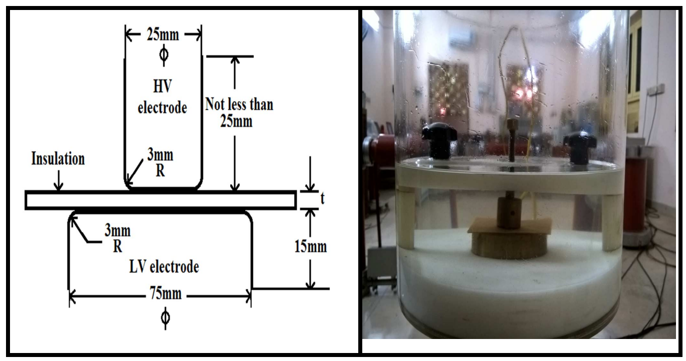


Figure 2. Electrode configuration and test cell.

OIP of 0.25mm thickness is considered for the analysis as the inter-turn insulation thickness of transformer is usually from 0.2 mm to 1.5 mm [12]. Five layers of OIP each of thickness 0.05 mm (5 × 0.05 mm = 0.25 mm) and dimension 80 mm × 80 mm are used. The kraft paper used has an apparent density of 0.795 g/cm^3, tensile strength of 96 N.m/g and relative permittivity 2. Moisture content in the kraft paper is reduced by heating at 75˚C for 72 hours as in [8]. The moisture content can be calculated from the dissipation factor of the OIP using the non linear function provided in [15]. The dissipation factor of the paper before and after heating are measured using the impedance analyzer (Wayne Kerr 6500b) and the corresponding moisture contents are calculated as 5.5% and 1.4% respectively. The paper samples are then impregnated in mineral oil for a minimum of 3 days.

To study the effect of aging, tests are also conducted on service aged OIP samples taken from an eight years old 16 MVA, 33/11 kV transformer, whose age is neither in infant mortality period (upto 5 years) nor in the highly aged period (more than 35 years) [2]. Since the transformer is exposed to air after dismantling, the samples are heated and impregnated similar to fresh OIP as described above. Thus, the effect of oil aging is not taken into account for the analysis. It is noted that the fresh and aged OIP samples are from a single manufacturer with same physical properties and dimensions.

3.2. TEST WAVESHAPES

The winding insulation design of transformer is generally based on the v-t characteristics of standard Lightning Impulse (LI) and switching impulse voltages. Hence standard LI of waveshape 1.2/50 µs is considered as one of test waveforms. In case of VFTO, it has smaller rise time, in the range of 4 to 100 ns and is normally followed by oscillations having frequencies in the range of 1 to 50 MHz. As per IEC 60071-1, front time of VFTO from 3ns to 100 ns and the tail time is less than 3 ms [16]. Using a 140 kV, 250 J single stage modified Marx circuit of MWB (Mess Wandler-Bau, Germany) make in the High Voltage Laboratory of Anna University, Chennai, both the test waveforms, LI (1.2/50 µs) and VFTO (90 ns/50 µs) are generated. The schematic diagram used for generating and measuring impulse voltage is shown in Figure 3.

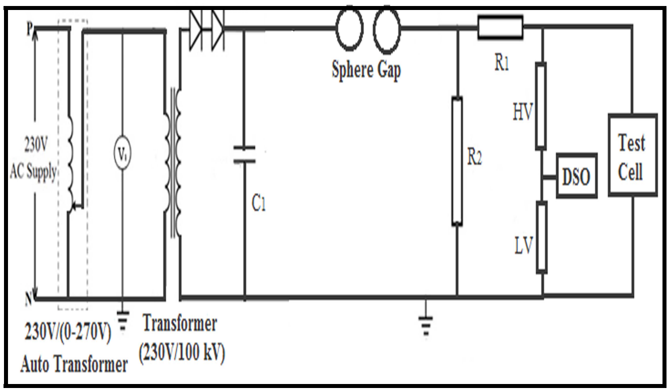


Figure 3. Schematic Diagram of Impulse generator.

The test waveforms are generated by suitably choosing the charging capacitor C_1 and waveshaping resistors R_1 and R_2. The generated waveforms are measured using capacitive and resistive voltage dividers for LI and VFTO respectively and shown in Figures 4a and 4b.

3.3. TESTS PERFORMED

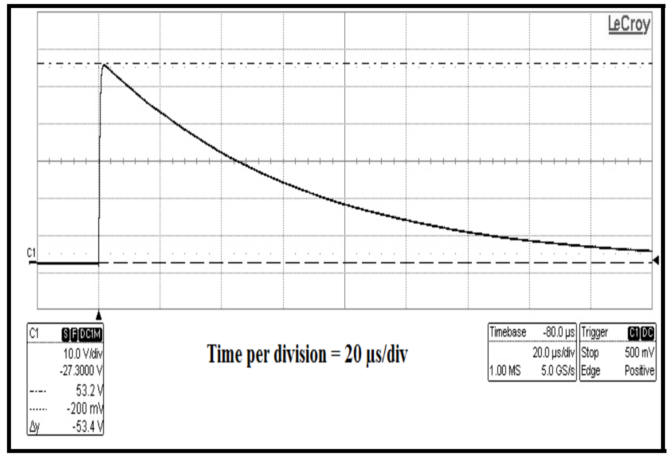
Considering all the factors discussed in Section 1, the following characteristics are experimentally obtained for both fresh and service aged OIP:

- v-t characteristics under LI and VFTO
- V-N characteristics under LI and VFTO
- v-t characteristics after repeated LI and VFTO

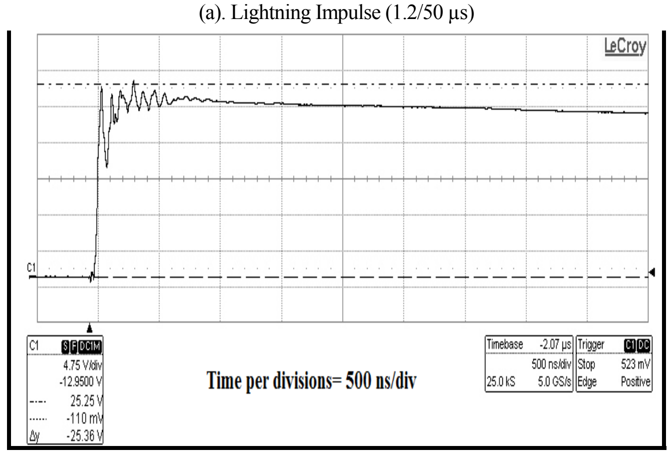
In general, the insulation coordination is based on the v-t characteristics of fresh insulation under LI. Hence, in the present study, all the characteristics viz. after service aged, under VFTO and after repeated impulses are compared with that of the LI characteristics of fresh OIP.

4 *v-t* CHARACTERISTICS OF FRESH AND AGED OIP

Lightning Impulse v-t characteristic of fresh insulation is usually considered during the design of transformer winding insulation. To study the effect of service aging, v-t characteristics is obtained for fresh and 8 years service aged OIP under LI. Reports [7,17] on the definite decrease in the impulse withstand capability of insulation under VFTO necessitates a study on the effect of VFTO on both fresh and service aged insulation. Hence in this section, the v-t characteristics of fresh and aged OIP under both LI and VFTO are analyzed.



(a). Lightning Impulse (1.2/50 µs)



(b).Very Fast Transient (90 ns/50 µs).

Figure 4. Generated waveforms

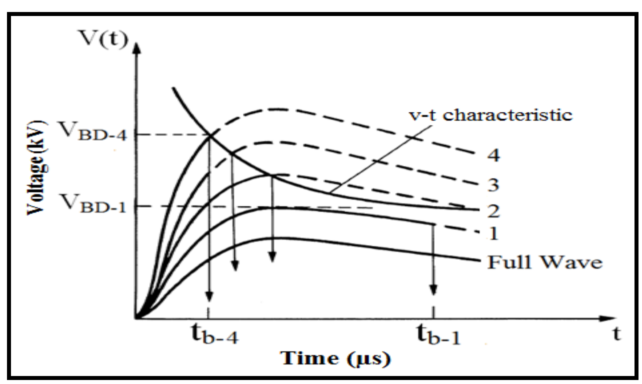


Figure 5. Typical v-t characteristic [18]

v-t characteristic of OIP is obtained by applying impulses of constant waveshape and different peak values as per IEC 60060 part-1 and 2 [19]. The applied voltage is increased/decreased in steps of 3% till the breakdown occurs in the wavefront/wavetail. A typical v-t characteristic is shown in the Figure 5.

For each voltage application, the peak value of the voltage withstood by the OIP and the corresponding time to breakdown (t_b) are noted from the waveform acquired by the oscilloscope. Since breakdown phenomenon is highly statistical in nature under impulse excitation, minimum of 5 samples are tested at each voltage level. The OIP sample is replaced after each breakdown and it is ensured that there is no air gap between the layers.

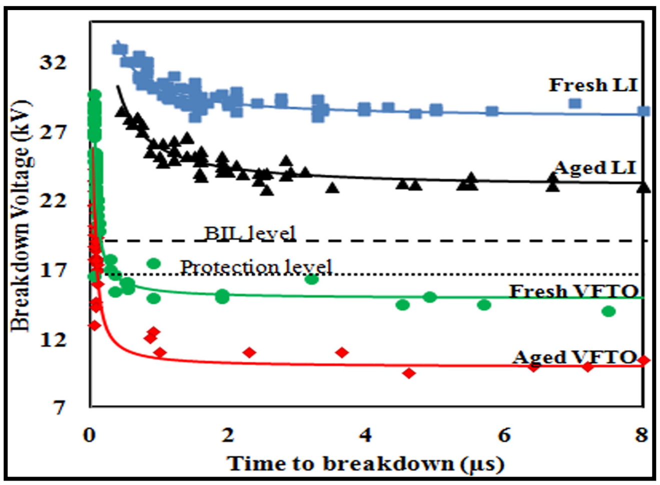


Figure 6. v-t characteristic of fresh and aged OIP

Initially the v-t characteristic of fresh OIP under LI is obtained and is shown in Figure 6. It is evident that, with increase in impulse voltage magnitude, t_b is smaller. The v-t characteristic is found to vary hyperbolically. The experimental data are fitted with hyperbolic model using regression analysis as in [17] and the reliability of the data is checked using 95% confidence interval. The v-t characteristic is very steep for t_b less than 2 μs and may be due to the minimum time lag required to initiate the breakdown.

Similarly, the v-t characteristic is obtained experimentally under VFTO. It is evident that, the v-t characteristic under VFTO shifts down indicating the reduced withstand capability. The v-t characteristic under VFTO is found to be around 46%-51% lower than corresponding LI after 0.4 μs which is in accordance with [17]. The shift in v-t characteristic is more for t_b between 0.4 μs to 2 μs and almost the same for t_b greater than 2 μs. In addition, the initial part of the v-t characteristic from 0.04 μs to 0.4 μs is steeper for VFTO. It is also observed, that the number of breakdowns are more near the peak of both LI and VFTO.

The minimum breakdown voltage in the v-t characteristic is defined as breakdown voltage (V_{BD}). In case of LI, the minimum breakdown voltage ($V_{BD[LI]}$) from the v-t characteristic is found to be 28.5 kV. During insulation coordination, as the BIL level is usually 70% of $V_{BD\ [LI]}$ to prevent partial discharges, 19.95 kV ($0.7V_{BD\ [LI]}$) is the BIL level. The protection level is 16.9 kV which is 15% below BIL level ($0.85\times0.7V_{BD\ [LI]}=0.6V_{BD\ [LI]}$). The BIL level and protection level are represented in Figure 6. It is observed that the v-t characteristic under VFTO lies below the protection level for t_b >0.4 μs. This implies that fresh OIP designed based on LI BIL may fail under VFTO of magnitude lower than the protection voltage level.

To study the influence of aging, v-t characteristics of the 8 years service aged OIP under LI and VFTO are experimentally determined and shown in Figure 6 along with the characteristics of fresh OIP. It is found that v-t characteristic of aged OIP follows the same pattern as fresh OIP. The following are observed:

- *Fresh and aged LI Characteristics*: The characteristics of aged OIP lies below that of the fresh OIP. The percentage reduction is around 10% near the wavefront and 17.5% in the wavetail.
- *Fresh and aged VFTO Characteristics:* The characteristics of aged OIP lies below that of the fresh OIP by around 13% near the wavefront and 33% in the wavetail.
- *Fresh LI and aged VFTO characteristics:* Comparing both the characteristics after 0.4 μs, the percentage reduction is around 66% at 0.4 μs and 64.5% at 8 μs.

From the above study, it is observed that, the 8 years service aged paper under LI can withstand the BIL whereas both the fresh and aged OIP under VFTO are well below the BIL and protection level. However, the magnitude of the VFTO arising in the system has to be considered for confirming the severity of VFTO.

To study the effect of oil aging, the v-t characteristics of the aged OIP impregnated in aged oil from the same transformer is determined. Under both LI and VFTO, v-t characteristics of aged OIP with aged oil are found to be almost same as those of the respective aged OIP impregnated in fresh oil. As aged oil in transformers are usually replaced or treated during maintenance and many researchers have carried out experiments on aged OIP impregnated in fresh oil [20-22], further experiments are carried out only on aged OIP impregnated in fresh oil. In the next section, the effect of repeated impulses is studied using V-N characteristic.

5 *V-N* CHARACTERISTICS OF FRESH AND AGED OIP

Researchers [9, 10, 23 and 25] have analyzed the deteriorating effect of repeated impulses on insulation using V-N characteristic. CIGRE working group C4.302 has emphasized the need for V-N characteristic to study the long term performance of insulation system [1]. V-N characteristic relates the voltage levels below the breakdown voltage ($V_{BD'}$) and at each voltage level, the number of impulses (N) withstood by the insulation.

V-N characteristic of the test samples are obtained as follows: $V_{BD'}$ is defined as the voltage at which the insulation fails in a single impulse (N=1) and is measured using the standard up and down method. Different percentages of $V_{BD'}$ in steps of 5% are calculated (i.e. 95%, 90% up to 70% of $V_{BD'}$). For each percentage of $V_{BD'}$, the impulses are repeatedly applied till breakdown occurs and the corresponding number of impulses is noted down for a minimum of 5 samples. Auto-reclosing of circuit breaker operates between 0.5 s and 3 minutes [24]. The coauthor Usa S and Balaji et al have studied the effect of time duration (Δt) between consecutive impulses for 1, 3 and 5 s on the V-N characteristic and found that 1s time duration between impulses is severe [25]. Hence, Δt =1 s is considered between the successive impulses.

So far, the effect of repeated impulses using V-N characteristic on the fresh transformer insulation under impulses of different wavefronts have been reported [10, 23 and 25]. As the V-N characteristic of the aged insulation is also important, the effect of repeated LI and VFTO on fresh and aged OIP using V-N characteristic is analyzed in this section.

The V-N characteristic of fresh OIP under LI is experimentally determined and is shown in Figure 7. The $V_{BD'}$ of fresh OIP under LI is determined using standard up and down method and for each percentage of $V_{BD'}$ (i.e. 95%, 90%... 70% of $V_{BD'}$), number of impulses withstood by fresh OIP is plotted. It is observed that, the number of impulses withstood by OIP increases exponentially as the voltage level decreases. The experimental data are fitted with exponential model using regression analysis as in [25] and the reliability of the data used is checked using 95% confidence interval.

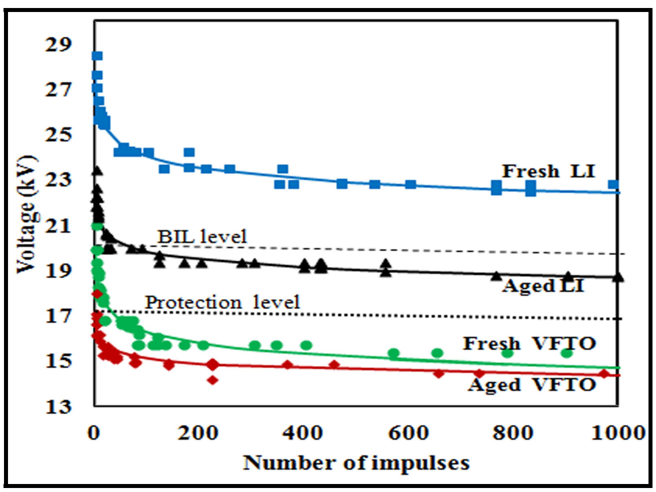


Figure 7. V-N characteristic of fresh and aged OIP upto 1000 impulses

The V-N characteristic under VFTO is also determined as described above and is found to follow the same pattern as LI. The percentage reduction under VFTO is around 30% compared to the LI characteristics of fresh OIP. In the case of LI, both $V_{BD\,[LI]}$ and $V_{BD'}$ happens to be same (as 28.5 kV) and whereas in case of VFTO, as most of breakdowns occur near the wavefront, $V_{BD'}$ is 21 kV and $V_{BD\,[VFTO]}$ is 15 kV.

V-N characteristic of aged OIP under LI and VFTO are experimentally determined upto 10,000 impulses. Figure 7 shows the V-N upto 1000 impulses as the characteristic becomes almost flat after 1000 impulses. Figure 8 shows the V-N upto 50 impulses. The following observations are made:

- *Fresh LI V-N characteristics*: OIP withstands more than 10,000 impulses at the BIL level indicating the withstand capability of fresh OIP for any number of repeated LI.

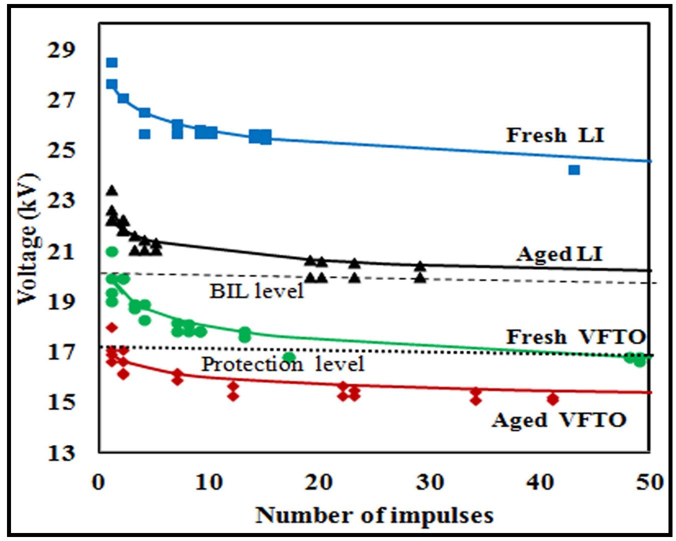


Figure 8. V-N characteristic of fresh and aged OIP upto 50 impulses

- *Aged LI V-N characteristics*: The characteristics of aged OIP lies below that of the fresh OIP. The percentage difference is around 18% at N=1 and 16.5% at N=1000. Though at the BIL, the service aged OIP withstands around 75-90 LI, it can withstand the protection level for any number of LI.

- *Fresh VFTO V-N characteristics*: The VFTO characteristics of fresh OIP drops by around 26% at N=1 and 33% at N=1000 from the LI characteristic of fresh OIP. At the BIL level, the fresh OIP withstands 2 VFTO and at the protection level fresh OIP withstands around 55-60 VFTO.

- *Aged VFTO V-N characteristics:* The percentage drop of aged VFTO from the fresh VFTO is around 15% at N=1 and 17.5% at N=1000. The percentage difference between fresh LI and aged VFTO is around 40% at N=1 and 37% at N=1000. At the BIL level, the aged OIP breaks down under VFTO and at the protection level fresh OIP withstands only around 1-2 VFTO.

From the above study, it is found that aged transformer insulation may fail if they encounter few VFTO at the protection level itself. Even new transformer insulation may fail if they encounter few tens of VFTO at the protection level. In the following section, the influence of repeated impulses on the v-t characteristics is analyzed.

6 *v-t* CHARACTERISTICS AFTER REPEATED IMPULSES

The coauthor Usa S and Balaji et al [25] have reported that, as the number of repeated impulses at each voltage level increases, the life time of OIP decreases. The dielectric parameters of OIP like relative permittivity, volume conductivity and dielectric loss angle increases significantly, after repeated lightning impulses [26]. Thus it is clear that repeated impulses electrically stress the OIP and can accelerate the aging phenomena. Hence, it is necessary to study the effect of repeated impulses on the v-t characteristic of OIP which is essential for proper insulation coordination

Transformer insulations are designed to withstand impulses of BIL level. But usually arresters are installed near the transformers preventing overvoltages of magnitudes greater than its protection level. Even with arresters, transformers are exposed to repeated impulses of magnitude less than or equal to the protection voltage level.

6.1 EFFECT OF REPEATED IMPULSES AT THE BIL LEVEL

To check the withstand capability of insulation at BIL after repeated impulses, the v-t characteristics are obtained after a definite number of impulses. The BIL level is 19.95 kV which is 70% of $V_{BD\,[LI]}$ of fresh OIP. Table 1 shows the number of impulses withstood at the BIL level for four different cases. Case 1 and Case 2 denote the number of repeated LI and repeated VFTO withstood respectively by the fresh OIP. Case 3 and Case 4 denote the number of repeated LI and repeated VFTO withstood respectively by the 8 years service aged OIP.

Table 1. Number of impulses withstood at the BIL level.

At 19.95 kV	Fresh OIP		Aged OIP	
	Under LI	Under VFTO	Under LI	Under VFTO
Number of impulses withstood	>10,000	1-2	*20-29*	0
	Case 1	Case 2	*Case 3*	Case 4

For case 1, the number of repeated impulses withstood by the OIP is >10,000. This case need not be analyzed as possibility of practical occurrence of 10,000 repeated impulses is less. The effect of repeated impulses need not be analyzed for case 2 and 4 as the insulation could not withstand repeated impulses. In Case 3, the minimum number of repeated impulses withstood is 20 and to study the effect of repeated impulses before breakdown 10 impulses are repeatedly applied at BIL level on aged OIP. Let (BIL, 10, LI, Aged) represents that at BIL, 10 repeated LI are applied on aged OIP samples.

The v-t characteristic of aged OIP after repeated LI (BIL,10,LI,Aged) is determined and is shown in Figure 9 along with the v-t characteristics of fresh OIP and aged OIP before repeated LI. After 10 impulses at BIL level on aged OIP, v-t characteristic shifts down by a maximum of around 20% with reference to aged OIP and 37% with reference to fresh OIP. It is also evident that, the v-t characteristic has shifted below the BIL level but still lies above the protection level.

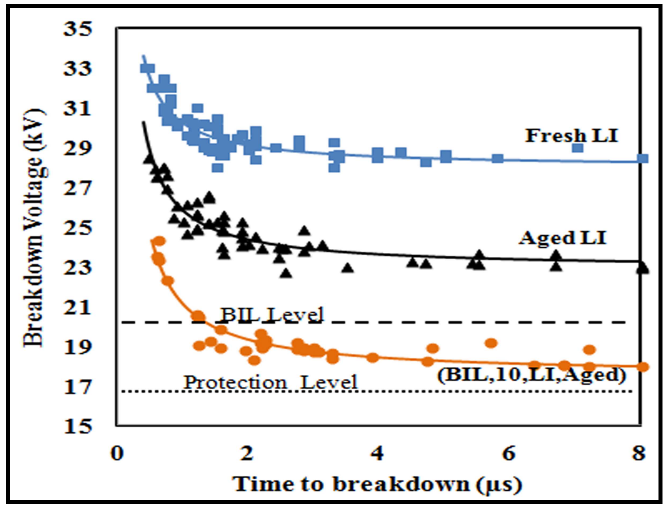


Figure 9. v-t characteristic of aged OIP before and after repeated LI

6.2 EFFECT OF REPEATED IMPULSES AT THE PROTECTION LEVEL (PL)

The protection level is 16.9 kV which is 15% below the BIL level and also corresponds to 60% of $V_{BD\,[LI]}$. Table 2 shows the number of impulses withstood at the protection level. In case of repeated LI, i.e. for case 5 and 7, the number of repeated impulses withstood by the OIP is >5,000. These cases need not be analyzed as possibility of practical occurrence of 5,000 repeated impulses is less. The effect of repeated impulses need not be analyzed for case 8 as the insulation could not withstand repeated impulses. In Case 6, fresh OIP withstands a minimum of 50 VFTO, OIP samples are stressed with 25 VFTO at the protection level (PL). Let (PL, 25, VFTO, Fresh) represents that at PL, 25 VFTO are applied on Fresh OIP samples.

Table 2. Number of impulses withstood at the protection level.

At 16.9 kV	Fresh OIP		Aged OIP	
	Under LI	Under VFTO	Under LI	Under VFTO
Number of impulses withstood	>10,000	*50-65*	>5000	1-2
	Case 5	*Case 6*	Case 7	Case 8

The v-t characteristic of fresh OIP after repeated VFTO (Case 6) is determined and is shown in Figure 10 along with the v-t characteristics of fresh and aged OIP before repeated VFTO. After 25 VFTO on fresh OIP, the v-t characteristic lies between fresh OIP and 8 years service aged OIP characteristic and shifts down by around 10% and around 58% with reference to fresh VFTO and fresh LI respectively.

The degradation under repeated impulses is being associated with partial discharges and enhanced field-induced processes. For an insulation not containing any voids, charges can be injected into the insulation from the metal electrode under high electric fields that may in turn break chemical bonds, gradually degrading the solid insulation. If sufficient gas evolution occurs due to bond scission, a void is created which may be large enough to support partial discharges degrading the insulation[27, 28].

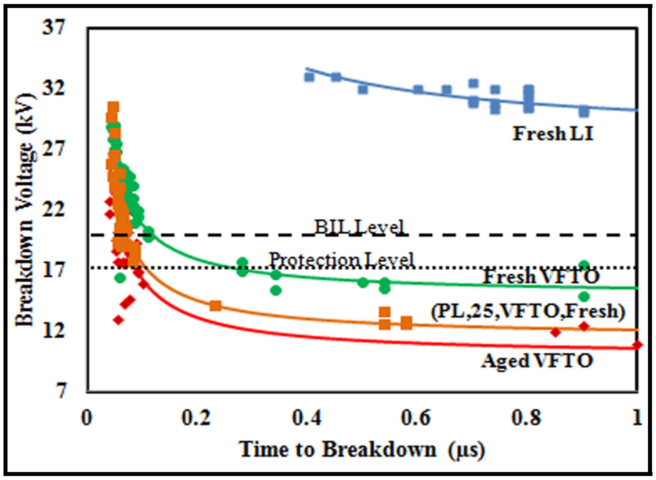


Figure 10. v-t characteristic of Fresh OIP before and after repeated VFTO

In addition to (PL,25,VFTO,Fresh), the v-t characteristics of fresh OIP after 15 and 45 repeated VFTO are determined to study the effect of number of repeated impulses (N)at PL. It is observed that 15, 25 and 45 repeated VFTO have shifted down the v-t characteristic of fresh OIP by around 5%, 10% and 20% respectively. Moreover, the v-t characteristic after 45 repeated VFTO is found to be below the characteristic of aged OIP. Thus, repeated impulses can simulate accelerated aging. As accelerated aging test under AC is time consuming, by appropriately choosing the voltage level, type of impulse and number of impulses, accelerated aging test can be formulated.

7 CONCLUSIONS

As the insulation design of transformer is based on the characteristics of fresh OIP under LI, the effects of 8 years service aging, VFTO and repeated impulses are compared quantitatively with the characteristics of fresh OIP under LI and the following observations are made:

7.1 *v-t* CHARACTERISTICS:

It is observed that, the 8 years service aged paper under LI can withstand the BIL whereas both the fresh and aged OIP under VFTO are well below the BIL and protection level.

7.2 *V-N* CHARACTERISTICS:

Fresh OIP under LI withstands more than 10,000 impulses at the BIL level indicating the withstand capability of fresh OIP for any number of repeated LI. Aged OIP under LI, withstands around 75-90 LI at the BIL and can withstand any number of LI at the protection level.

Fresh OIP under VFTO, withstands 2 VFTO at the BIL level and at the protection level fresh OIP withstands around 55-60 VFTO. Aged OIP under VFTO breaks down under VFTO at the BIL level and withstands around 1-2 VFTO, at the protection level.

It is found that aged transformer insulation may fail if they encounter one or two VFTO at the protection level. Even new transformers may fail if they encounter few tens of VFTO at the protection level.

7.3 *v-t* CHARACTERISTICS AFTER REPEATED IMPULSES

After 10 LI impulses at BIL level on aged OIP, v-t characteristic has shifted by 37% but still lies above the protection level. After 25 VFTO on fresh OIP at protection level, the v-t characteristic lies between fresh OIP and 8 years service aged OIP. As the number of repeated VFTO increases, the v-t characteristic shifts downwards.

This work highlights the necessity for incorporating the effect of aging, VFTO and repeated impulses during insulation coordination. The results will provide guidance at the design stage of transformer to ensure reliable insulation coordination. The load history of the aged transformer is not considered in the study and shall be accounted in the future studies. In addition, the analysis can be extended to few more transformers aged between 8-35 years to predict the v-t characteristics of OIP at any age. Moreover, accelerated aging test method using repeated impulses can be formulated to predict the degradation as it consumes lesser time than accelerated aging under AC.

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REFERENCES

[1] CIGRE WG A2/C4.39, "Electrical transient interaction between transformer and power system," CIGRE, 2013.

[2] S. Chakravorti, D. Dey and B. Chatterjee, "*Recent Trends in the Condition Monitoring of Transformers - Theory, Implementation and Analysis*", Springer-Verlag, London, 2013, Chapter 1.

[3] R. Murugan and R. Ramasamy, "Failure Analysis of Power Transformer for Effective Maintenance and Planning in Electric Utilities", Engineering Failure Analysis, Elsevier Ltd,Vol.55,pp. 182-192, 2015

[4] L.Jonsson and M.Lundborg, "Dry Transformer bushing with composite insulators –the obvious combination for increases reliability", IEEE Central America and Panama Convention, CONCAPAN XXXIV, pp. 1- 6, 2014.

[5] J. P. van Bolhuis, E. Gulski, and J. J. Smit, " Monitoring and Diagnostic of Transformer Solid Insulation", IEEE Trans. Power Delivery, Vol. 17, No. 2, pp. 528–536, 2002.

[6] D. D Shipp, T. J. Dionise, V. Lorch and B. G. MacFarlane, "Transformer Failure Due to Circuit-Breaker-Induced Switching Transients", IEEE Trans. Industry Appl., Vol. 47, No. 2, pp. 707-718, 2011.

[7] U. Massaro, "Electrical transient interaction between transformer", CIGRE JWG C4-104, Paris, France, 2009.

[8] A.J. Vandermaar, M. Wang, J.B. Neilson and K.D. Srivastava, "The electrical breakdown characteristics of oil-paper insulation under steep front impulse voltages," IEEE Trans. Power Delivery, Vol. 9, pp.1926-1935, 1994

[9] S. Okabe, T. Ohno, E. Zaima, A. Kishi, K. Aono and N. Hosokawa, "AC V-t and Impulse V-N Characteristics of Shell-Form Transformer Insulation Model," Electr. Eng. Japan, Vol. 116, No. 4, pp. 49-63, 1996.

[10] S. Okabe, "Voltage-time and voltage-number characteristics of insulation elements with oil-filled transformers in EHV and UHV classes," IEEE Trans. Dielectr. Electr. Insul., Vol. 13, No. 2, pp. 436-444, 2006

[11] IEC 60076-3, "Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air", 2013
[12] K. Karsa, D. Kerenyi and L. Kiss, "*Large Power Transformers*", Elsevier Science Ltd., New York, 1987, Chapter 5.
[13] IEC 60071-2, "Insulation Coordination-Part 2: Application Guide," 1996.
[14] ASTM standard D149-97a ,"Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies", 2004,
[15] W. S. Zaengl, "Applications of dielectric spectroscopy in time and frequency domain for HV Power Equipment", IEEE Electr. Insul. Mag., Vol. 19, No. 6, pp. 9–22, 2003.
[16] IEC-60071-1, "Insulation coordination (Part-1): Definitions, Principles and rules", Edition 8, 2006.
[17] Krithika and S. Usa, "v-t Characteristics using Extended Disruptive Effect Model for Impulses of Varying Front Times", IEEE Trans. Dielectr. Electr. Insul., Vol. 22, No. 4, pp. 2191–2195, 2015.
[18] E. Kuffel, W.S. Zaengl and J. Kuffel, "*High Voltage Engineering: Fundamentals"*, Second Edition, Butterworth-Heinemann, Elsevier Publications Oxford, UK, 2000.
[19] IEC 60060, "High voltage test techniques, Part I&II: Second edition 1994
[20] S.-Q. Wang, G.-J. Zhang, H.-B. Mu, D. Wang and M. Lei, "Effects of Paper-aged State on Space Charge Characteristics in Oil-impregnated Paper Insulation", IEEE Trans. Dielectr. Electr. Insul., Vol. 19, No. 6, pp. 1871 –1878, 2012.
[21] T.K. Saha, M. Darveniza, D.J.T. Hill and T.T. Le," Electrical and Chemical Diagnostics of Transformers Insulation-Part A: Aged Transformer Samples", IEEE Trans. Power Delivery, Vol. 12, No. 4, pp. 1547–1554, 1997.
[22] A. Badr, L. Nasrat and A. Ibrahim,"Examining dielectric properties of paper ageing in scrapped transformers", Int'l. J. Innovative Research Electr., Electronics, Instrumentation and Control Eng., Vol. 3, No. 1, pp. 69-71, 2015.
[23] P. Sun, W. Sima, M. Yang, X. Lan and J. Wu, "Study on Voltage-number Characteristics of Transformer Insulation under Transformer Invading Non-standard Lightning Impulses," IEEE Trans. Dielectr. Electr. Insul., Vol. 22, No. 6, pp. 3582–3591, 2015.
[24] IEC standard 62271,"High-voltage switchgear and control gear Part 100 High-voltage alternating-current circuit-breakers", Ed. 2.2, Switzerland.
[25] S.P. Balaji, I.P. Merin Sheema, G. Krithika and S. Usa, S, "Effect of Repeated Impulses on Transformer Insulation," IEEE Trans. Dielectr. Electr. Insul., Vol. 18, No. 6, pp. 2069-2073, 2011.
[26] W. Sima, P. Sun, Q. Yang, T. Yuan, C. Lu and M. Yang, "Study on the Accumulative Effect of Repeated Lightning Impulses on Insulation Characteristics of Transformer Oil Impregnated Paper", IEEE Trans. Dielectr. Electr. Insul., Vol. 21, No. 4, pp. 1933–1941, 2014.
[27] G. C. Stone, R. G. van Heeswijk and M. Kurtz, "The Statistical Analysis of a HV Endurance Test on an Epoxy Insulation", IEEE Trans. Electr. Insul., Vol. 14, pp. 315-326. 1979.
[28] R. Bartnikas, R. M. Eichhorn, Editors, *Engineering Dielectrics*, Vol. IIA, STP783, ASTM Philadelphia, USA, 1983.

Usa S (M'07) received the B.E., M.E., and Ph.D. degrees in electrical and electronics engineering from the College of Engineering, Guindy, Anna University, Chennai, India in 1986, 1989 and 1995, respectively. In 1992, she joined the Department of Electrical and Electronics Engineering at Anna University and at present she is a Professor in the Division of High voltage Engineering. She is a member of one of the working group members for CIGRE A2/C4.39 Electrical transient interaction between transformers and power systems. (IEEE Membership ID: 80633405)

Bavisha T received the B.E. degree from Government College of Engineering, Tirunelveli, Anna University in 2012. She received the M.E. degree from the College of Engineering, Guindy, Anna University, in 2014, and at present she is a Research student in the Division of High Voltage Engineering, Anna University, Chennai, India.