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Evaluation of Natural de-Magnetization of Power Transformer Due to Capacitor Interaction with Area Under the Curve Method

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Abstract: Transformer energization at random point presents inrush phenomena and is unfavorable for equipment due to high magnitude asymmetric current flow. These asymmetric currents are largely affected by level and polarity of residual flux presents in transformer core post its de-energization. Controlled switching technology is widely used to limit inrush current. Moreover, ignorance of residual flux would yield only moderate level of inrush current. Also, inaccurate estimation of de-magnetization status leads to improper estimation of energization instants during independent pole switching and the resulting inrush currents could not be reduced below desired level. Therefore it is quite important to know the exact level of residual flux post every de-energization operation of power transformer. Presence of capacitor bank, filter banks and connected XLPE cables offer natural de-magnetization of power transformers. The de-magnetization is categorized in no, partial and full de-magnetization. This paper presents novel approach for detection of natural de-magnetization of Power Transformer using load side measurements. Numerical integration has been used for the evaluation. Suggested method has been verified from field data collected from power transformers of different design and connection configuration across globe used for various grid voltage levels. Lastly, the effect of variation in sampling rate and level of residual fluxes is analyzed and the suggested method is found to be equally effective for said variations. The categorization of natural de-magnetization play important role in deciding energization instant for next switching of transformer

Keywords: Controlled Switching, Natural de-magnetization, Partial de-magnetization, Residual flux, Inrush Current

1. INTRODUCTION

In the de-regulated environment of power utilities across world, outage time of major equipments like transformer has been greatly reduced. This requires frequent switching of transformer and poses stress on power system and equipment itself. Energization of power transformer leads to magnetization of its core for requisite flux creation used for energy conversion from primary winding to secondary winding. Relationship of flux is governed by core material and the hysteresis curve. The residual flux in the core is set after every de-energization of the transformer and depends upon the current chopped at the time of de-energization. Moreover, routine tests including winding resistance measurement would alter residual flux in core because of the application of DC voltage. The winding resistance test is conducted by forcing the core into saturation and thereby alters the residual flux in core due to high amount of DC component injected in the winding [1]. Furthermore, the transformer core may be virtually de-magnetized with natural processes like thermal treatment and resting of core. However, thermal processes and resting take longer time [2]. The presence of capacitive elements with transformer can also naturally de-magnetize the core. Natural de-magnetization needs specific network configuration in which one or more windings of transformer are directly connected to capacitive element like long cable, capacitor bank, grading capacitor of CB etc. [3].

Residual flux can be reduced by artificial methods like Variable Voltage Constant Frequency (VVCFS), Constant Voltage Variable Frequency (CVVF), Constant Current Variable Frequency and Variable Current Constant Frequency (VCCF) methods[4][5]. Artificial De-magnetization methods use either application of alternative polarity current or voltage. In VCCF method,

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known value of DC Current is injected with alternate changing polarity through core. The steps are repeated with progressively reducing the magnitude or time period of applying DC voltage [6]. VVCFS method is best method among all but needs large energy source to meet requirements of power transformers. For all above mentioned methods, accessibility of transformer terminals to apply the DC current or voltage is quite challenging. It has also been reported that while de-magnetizing one core leg, other core legs get magnetized due to improper procedure applied [7]. On the other hand, natural de-magnetization of transformer core depends on the magnitude of capacitance connected to it. Consequently, long cables offering large shunt capacitance or directly connected large capacitor banks can fully de-magnetize the core leaving residual flux to negligible level. Whereas, the lower level of capacitive elements (short HV cable connected to transformer) can lead to partial de-magnetization. In this context, de-magnetization can be categorized into no, partial and full de-magnetization. Furthermore, it can be well appreciated that, the level of residual flux plays an important role in reducing inrush currents in next energization when applied with control switching methods. In this regard, if the level of residual flux is brought down to negligible level due to natural de-magnetization, default control switching strategies based on design and connection configuration of transformer can be directly applied without need for correcting targets to cater residual fluxes[8].

The resultant flux linking with individual phase of transformer comprises of transient component superimposed with level of residual flux. Furthermore, residual flux is a function of chopping current & capacitive component in the vicinity of transformer windings. Chopping current at the moment of de-energization can be evaluated using Rizk's Theory [3]. Normally, residual flux is evaluated by integrating voltages of all three phases across any one winding of the transformer [9][10]. In this paper, a novel approach has been proposed to detect the type of core de-magnetization. The results are found to be quite reliable for various types & connection configurations of transformers connected at various grid voltage levels in presence of aforesaid different type of capacitive elements. Also, being simple and reliable, this method can be easily implemented in latest generation of numerical relays.

A. Transformer Energization and de-energization

Power Transformers are energized frequently or occasionally based on operating conditions like load shifting, maintenance, fault etc. Transformer energization at random instant creates unbalances in current and grid voltage due to inrush phenomena. Attaining steady state may take a number of seconds to some minutes based on X/R ratio of the system [11]. There are several factors affecting the magnitude of inrush current but level of residual flux and point of voltage wave at the time of energization are prominent one [12]. Due to doubling effect, the instanteous flux may attain two times of its rated value and may further change; if residual flux is also present. Flux created in one phase has no influence on other phases in case of non-coupled system and energization instant for individual phases can be evaluated independently. Three phase transformers with three limb design or the ones having one or more delta connected windings offer interphase coupling between induced fluxes. Consequently, dynamic behavior of fluxes due to aforesaid interphase coupling play a key role for evaluation of optimal instant for energization of individual phases. Furthermore, accurate evaluation of residual fluxes based on transformer side voltage measurement is quite a challenging task. The same demands for usage of electromagnetic potential transformer due to the fact that the capacitive voltage transformer will create resonance oscillations in voltage measurement due to its internal circuit behavior of CVT. This may further results into large errors in residual flux estimation which can be as low as 10% and may even go to values higher than 70% [13]. Consequently, the optimum target evaluation will have errors and can lead to considerably large level of inrush currents and hence, voltage dips on weak grids. These voltage dips beyond certain limit would cause commutation failure in HVDC systems. Hence, it's always desired that the inrush currents should be reduced to the acceptable limit.

Transformer –capacitor interaction plays an important role in natural de-magnetization of power transformer and same has been studied by Rui Zhang for a 132kV system [14]. During natural de-magnetization, the total energy stored in transformer is ($1/2LI^2$) gets transferred to capacitive components and create oscillations. During this transfer, some part is dissipated as losses due to resistance of the system. The energy moves to and fro in between capacitive and inductive elements for several cycles. In each cycle, the magnitude of voltage and energy goes on reducing and leads to natural de-magnetization of transformer core. Net residual flux remains after ringdown transient is logarithm proportional to the directly connected capacitance to the transformer [15]. On the other hand, winding capacitances, short cables and breaker grading capacitance can also contribute to moderate level of de-magnetization termed as partial de-magnetization. Therefore, full de-magnetization demands for significant level of capacitive element directly connected to one or more transformer windings post its de-energization.

Simulation studies have been carried out by various researchers with modeling non-linear core to accurately evaluate the level and polarity of residual flux [16]. Prototype voltage sensors have been developed to directly measure terminal voltage for evaluating residual flux by integrating voltage [17]. Frequency response analysis (FRA) technique has been explored by Y.Corrodi to study the magnetization pattern of transformer. Results from field tests using FRA scanner in complex form for 600kVA and 600MVA Power Transformer have been presented in this study [18]. Moreover, FRA is a diagnostic tool and requires outage of transformer are cannot be integrated in controller for further application of controlled switching. A laboratory prototype for detection of natural de-magnetization has been developed by Goran [19]. The voltage stored in capacitor is a function of voltage during de-energization of transformer. Principally, this method captures integral of secondary side voltage and stores in digital accumulators for further processing. In same line, another prototype has been developed to study the effect of transients on residual flux during line faults [20]. In this method, the terminal voltage in time domain has been converted into frequency domain using Fast Fourier Transformation technique and compensated terminal voltage is integrated to calculate residual flux [21].This conversion adequately separate fundamental component from higher order harmonics. However, it demands for a large computation effort with considerable time and hence, is not feasible for very short time span of 1-2 cycles, not sufficient for de-magnetization detection. Field tests have been carried out to estimate the residual flux and inrush currents on 170MVA Power Transformer of Super Bissorte Hydraulic Power Station [22]. Residual flux has been obtained from geometric determination method, which is not found to be accurate and therefore, may lead to non acceptable level of inrush currents [23]. Residual flux has been evaluated as a function of connected capacitance and chopping current as per Rizk's theory. Furthermore, integration of port-voltage method has also been used to calculate the residual flux in core [24][25].

In context to application of controlled switching on power transformers, CIGRE working group A3.07 emphasizes the presence, significance and effect of residual flux for successful application of controlled switching on power transformer. Effect of circuit breaker grading capacitance and network disturbances on residual flux has been analyzed in their study [26]. Evolution of micro hysteresis leading to micro oscillations during de-energization is also discussed. However, these studies do not include effects of presence of large capacitive elements with transformer [27]. The natural de-magnetization phenomenon has also been explained through simulations and laboratory prototypes. Moreover, it is not field tested on diverse power system scenarios and hence is not generalized [26]. This paper presents novel approach for detection of natural de-magnetization of power transformer using load side measurements. It also successfully categorizes the types of de-magnetization among partial, full and nil-de-magnetization. In existing methods, de-magnetization status is considered when transformer is de-energization but natural de-magnetization status may changes over lapse of time due to capacitor interaction.

2. MODES OF TRANSFORMER DE-MAGNETIZATION

Transformer with connected capacitor represents parallel L-C circuit with negligible resistance between them. In steady state conditions, energy balance holds good and net energy is nil. Moreover, de-energization operation of the transformer results into interaction between transformer inductance and connected capacitance. Consequently, the capacitance discharges its energy into transformer core and vice versa. This results into square shape pulses with opposite polarity and decreasing magnitude as shown in Figure 1. During this process, resistance of the circuit will result into energy loss and will progressively damp out the voltage magnitude. Oscillatory frequency of the voltage is governed by the inductance (Lm) and capacitance (Cm) of the circuit, and is given by equation (1):-

$$\omega_0 = \frac{1}{L_m C_m} \qquad (1)$$

This charging and discharging of capacitance virtually applies voltage of alternating polarity across the transformer core and naturally de-magnetize the core.

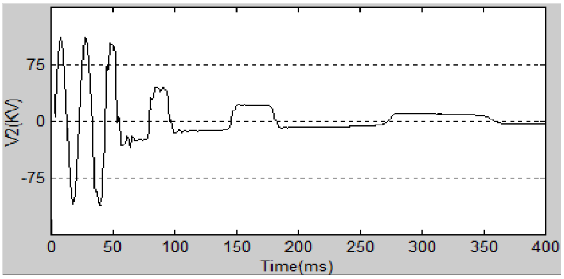


Figure 1 . Square pulses waveform during transformer-capacitor interaction causing virtual de-magnetization.

The aforesaid nature of DC voltage tends to de-magnetize core of the transformer. Depending upon quantum of capacitance connected to transformer, different levels of natural de-magnetization can be observed. Consequently, the de-magnetization of power transformers can be categorized into three modes viz Full-demagnetization, Partial Demagnetization and Nil-demagnetization based on level of energy dissipated through L-C oscillations post de-energization of the transformer. As per existing methods, residual flux is evaluated at the time of de-energization of transformer and status of de-magnetization is fixed/ locked considering this instant.

But actual de-magnetization process takes longer time and final level of core de-magnetization can only established after lapse of number of cycles.

A. *Full De-magnetization*

Full de-magnetization of power transformers can take place in event of large capacitive component (ex. very long cable) is connected to the transformer winding; or a filter bank is directly connected to the transformer. Energy is stored in connected capacitance and contributes in ringdown phenomena when transformer is de-energized. Upon, de-energization the inductive current supplied by transformer is reduced and in meanwhile, the capacitive current start flowing towards the inductor. This flow of capacitive current toward inductor accomplished by appearance of voltage at the transformer terminals. This results into dissipation of energy stored in the capacitor towards the transformer inductance and vice versa. This leads to successive square shaped voltage oscillations across the transformer terminals. These oscillations will be progressively reducing magnitude but having same time period as shown in Figure 1, resulting into full de-magnetization of transformer core. Generally, filter banks are used for harmonic minimization in HVDC systems. Moreover in special applications like aluminum smelters, they are connected on tertiary winding of the transformer to compensate for high reactive current drawn, especially in case of weak grids. This is done to avoid voltage dip and harmonic distortion on the grid. Said type of configurations would lead to fully de-magnetization of the transformer core. One of such system configuration is shown in Figure 2

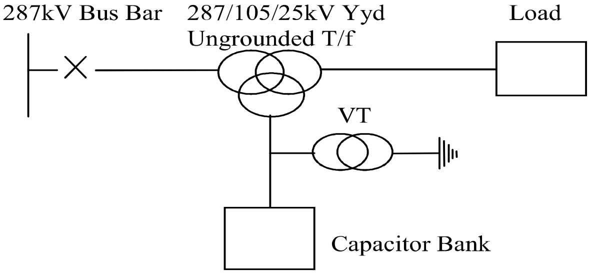


Figure 2. Network diagram indicating Filter bank directly connected on tertiary of the transformer.

B. *Partial De-magnetization*

A cable of moderate length connected to any one or more winding of a transformer results into partial de-magnetization of the core. In this case, some of the energy stored in inductance of transformer is counter-balanced by capacitive component of the HV cable. Moreover, due to insufficient capacitance of the cable, energy will not be fully dissipated and thus core, still be partially de-magnetized. Figure 3 shows a two winding transformer (15/0.2kV) directly connected with a moderate length cable on its own secondary winding leading to partial de-magnetization.

Consequently, Figure 4 shows typical voltage waveform during de-energization of this transformer. In such cases, the ringdown transient continues only for couples of cycles after de-energization of transformer, which is governed by quantum of connected capacitance. Other components like circuit breaker grading capacitors may also contribute to partial de-magnetization.

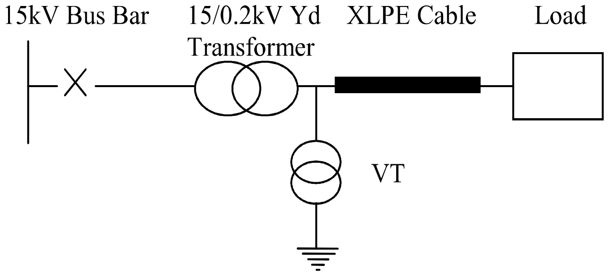


Figure 3 Single line diagram indicating connection of HV cable in series with the transformer.

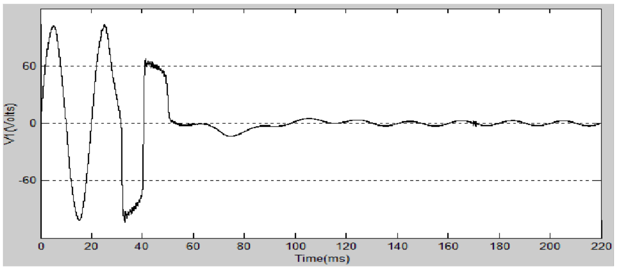


Figure 4. Voltage waveform during partial de-magnetization.

C. *No De-magnetization*

When Power Transformer is connected to bus bar/grid where large capacitive elements are not connected to any of the transformer winding directly, the de-magnetization effect will not be present. In this case, energy stored in its inductance will remains in its core and will lead to considerable amount of residual flux. The level of residual flux depends upon the magnetic state of the transformer during very previous de-energization of the transformer. As an example, if the capacitor bank shown in Figure 2 is disconnected for maintenance purpose, the core will not be de-magnetized during next de-energization operation due to absence of large capacitive element as shown in Figure 5. Figure 6 shows voltage oscillation observed during real transformer de-energization operation in this scenario.

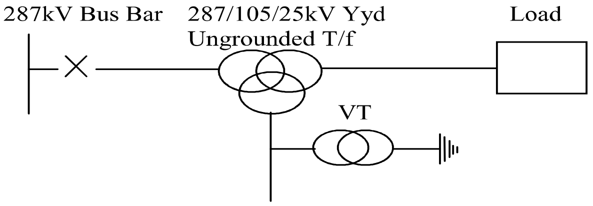


Figure 5. Network diagram indicating transformer without filter bank.

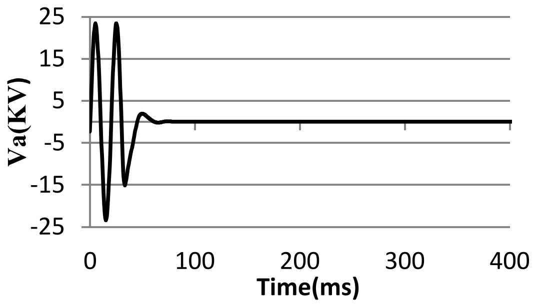


Figure 6. Voltage waveform during nil de-magnetization.

In next section, the proposed methodology for discriminating the nature of de-magnetization of transformer core among above mentioned three categories is discussed in detail.

3. SUGGESTED METHODOLOGY

Area under the curve method is proposed in this paper for evaluating the cumulative residual flux in a core. This method approximates the definite integral on prescribed limits. As shown in Figure 7, the whole contour is divided into equal sub-intervals depending upon the sampling rate of transformer side voltage measuring device for individual phases. Upon integration, the aforesaid area under curve in this case, presents average flux linking with individual winding for the transformer over a specified time period. The trapezoidal integration method is used for determining the flux from transformer side voltages for individual phases.

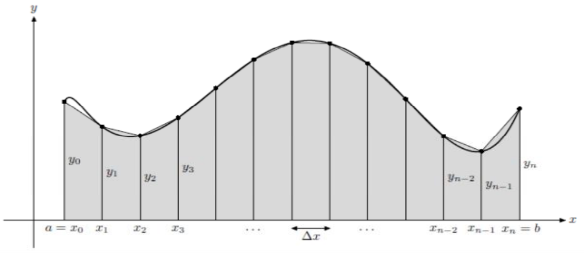


Figure 7. Integration using trapezoidal method.

$y_0, y_1, y_2 \dots\dots y_n$ presents the flux magnitude (obtained upon integration of the voltage), presented on y-axis with time interval $x_0, x_1, x_2 \dots\dots x_n$ on x-axis respectively. Points on x-axis are equi-spaced with interval Δx defined by the sampling rate of sample. The area between two points a and b for function f(x) is given by equation (22) as:

$$\int_a^b f(x)dx = \frac{\Delta x}{2}(y_0 + y_1) \tag{2}$$

Consequently, the cumulative area under the curve is evaluated in following equation (3):-

$$\int_a^b f(x)dx = \frac{\Delta x}{2}(y_0 + y_1) + \frac{(y_1+y_2)\Delta x}{2} \dots \frac{(y_{n-1}+y_n)\Delta x}{2} \tag{3}$$

The suggested methodology can be clearly understood from flow chart shown in Figure 8. Upon de-energization of power transformer, voltage samples are captured from individual phases of voltage transformer available on any one transformer winding side and converted to voltage across individual winding of three phase transformer if needed. In the first step, correction for error due to measurement device inaccuracy is performed by normalization method.

In this method, the cumulative area under voltage curve for individual phase is calculated and then, corrected for average error prior to transformer de-energization. In next step, numerical integration of voltage samples is carried out one cycle prior to de-energization till end of pre-defined time duration. Consequently, the area under flux curve is calculated and expressed with reference to the peak flux observed prior to transformer de-energization.

Lastly, specific threshold are defined to discriminate between levels of de-magnetization among partial, full and no-demagnetization. It has been observed that the nil demagnetization will have quite high ratio compared to the partial and full de-magnetization cases. Furthermore, due to measuring equipment (CT & PT) inaccuracy and signal processing limitations, there exists challenge to discriminate between full and partial de-magnetization [28]. Moreover, for partial de-magnetization case; the numbers of square wave pairs are one or two, whereas, for the full de-magnetization case they are more than two and can have quite a large number of pulses. Therefore, the discrimination of partial and full demagnetization is performed with area under curve in conjunction with square wave pairs of flux post de-energization of the transformer. The choice of thresholds for partial, full and nil de-magnetization cases are discussed in the next section (section 4) in detail.

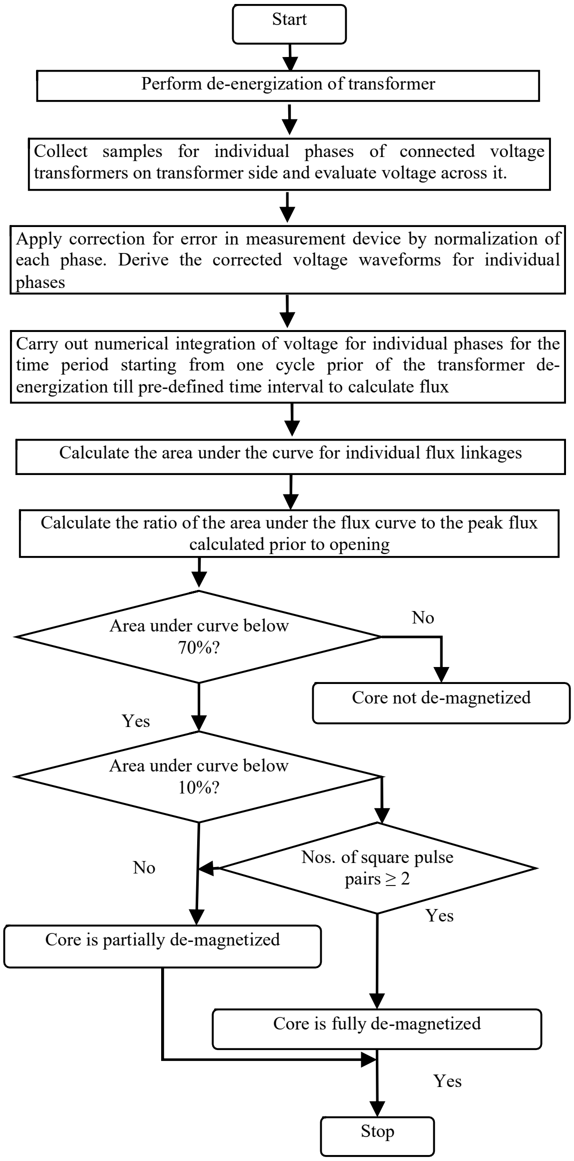


Figure 8. Proposed methodology

4. CASE STUDY AND RESULT DISCUSSION

In this section, the proposed method is applied for a number of field cases where transformers with different design and connection configurations are considered. In this paper, different designs considered are: -

- Three winding transformer with tertiary delta connected as shown in Figure 1. This delta connected tertiary winding behave like coupled system and is commonly used in power systems.
- When capacitor bank is connected to tertiary side of 287/105/25kV Yyd transformer, it exhibits full de-magnetization of core and residual flux lies less than 0.1 Pu. The capacitance of capacitor bank is quite larger as compare to inductance of transformer. And when capacitor bank is removed from arrangement, transformer core will be fully de-magnetization with residual flux lies greater than 0.7 p.u.
- Two winding transformer 15/0.2kV Yd transformer connected with directly terminated XLPE cable of moderate length as compared to transformer MVA capacity as shown in Figure 3. Its de-energization shows partial de-magnetization case and residual flux lies in range 0.1 to 0.7 pu. The considered cases include partial, full and no de-magnetization effects.

A. Full De-magnetization.

In case of power transformer full-demagnetized, the area under the curve shall ideally be zero. Moreover, the error in measuring devices, sampling rate and number of cycles considered for detecting the de-magnetization effect may result into non zero area under the curve. Consequently, a level of 10% with reference to average maximum flux prior to its de-energization is found to be discriminating level for fully de-magnetized cases.

Figure 9 demonstrates voltage waveform recording of power transformer during its full de-magnetization for one of the field cases. As observed, a voltage having square wave shape with alternating polarity and reducing magnitude in successive cycles is present for all three phases of the transformer. It is observed that, full-demagnetization process may require a number of square voltage pulses depending upon the time constant of L-C circuit. Figure 10 indicates the corresponding flux of R Phase and it also exhibits same behavior as that of the voltage waveform for each phase.

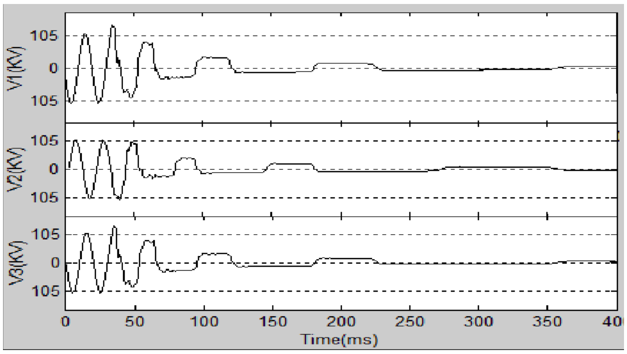


Figure 9. Field recording showing voltage waveform for full demagnetization of power transformer

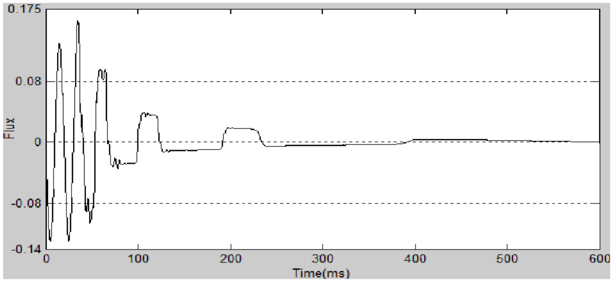


Figure 10 Flux waveform for full-demagnetization of power transformer.

B. Partial De-magnetization.

Due to insufficient capacitive component, the energy oscillations across inductance of transformer and capacitance do not create adequate number of square pulses and hence, the core remains partially de-magnetized. It is observed that, considering all inaccuracies discussed in previous section, the total area under the curve remains in the range of 10-70% with respect to maximum flux prior to de-energization.

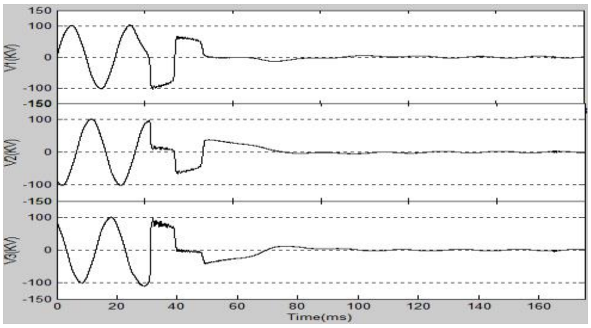


Figure 11. Voltage waveform for partial-demagnetization of power transformer.

Figure 11 shows the 3-phase voltages across transformer windings post to its de-energization for partial de-magnetization case. In this case, the numbers of positive or negative cycles are limited to two or three, which are insufficient to fully de-magnetize the core. Corresponding flux of R phase by numerical integration is shown in Figure 12 exhibiting similar behavior.

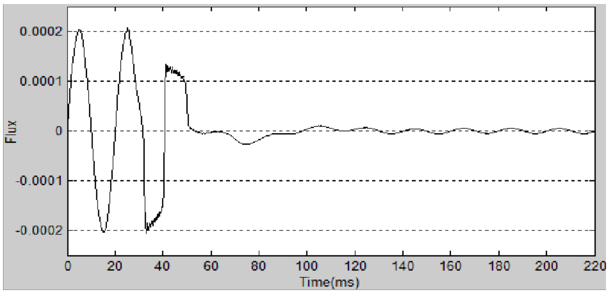


Figure 12. Flux waveform for partial-demagnetization of power transformer.

Another case of partial de-magnetization having superimposed L-C micro oscillations in voltage and flux waveforms is shown in Figure 13 and Figure 14 respectively.

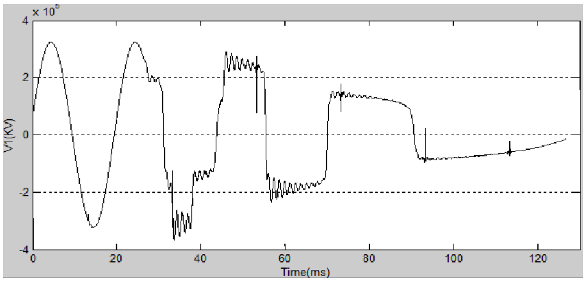


Figure 13. Voltage waveform for partial-demagnetization of power transformer.

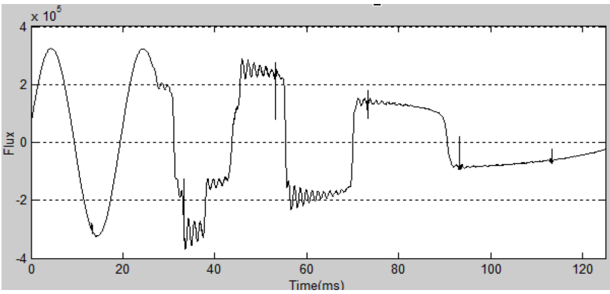


Figure 14. Flux waveform for partial-demagnetization of power transformer.

C. Nil de-magnetization.

In absence of noticeable capacitive component, the energy trapped in the transformer inductance have no path to dissipate and core remains in the fully magnetize state. In this case, it is observed that the area under the curve remains more than 70% with respect to maximum amount of core flux prior to its de-energization. Figure 15 represents the three phase voltages across transformer windings post its de-energization for no demagnetization case. Corresponding flux of single phase is shown in Figure 16.

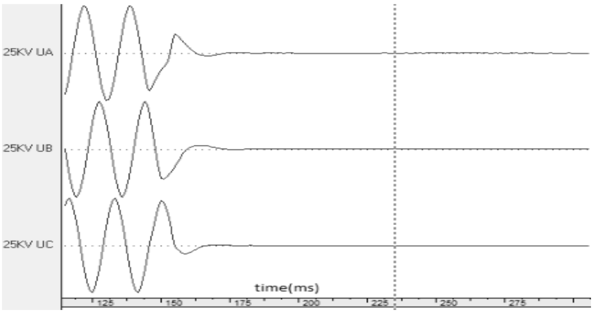


Figure 15. Voltage waveform for nil-demagnetization of power transformer.

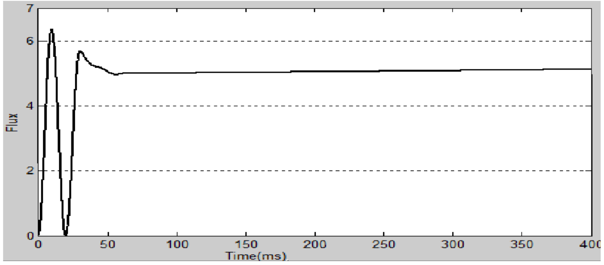
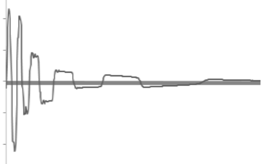
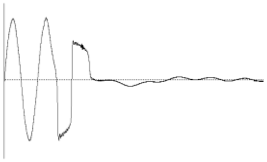


Figure 16 Flux waveform for nil-demagnetization of power transformer.

Moreover, it shall be noted that, the area under curve varies with level of residual flux. Table 1 depicts results obtained for a large number of field cases each category of transformer de-magnetization. The sampling rate of 162 samples per cycle has been chosen for all cases.

Table 1. NATURE OF NATURAL DE-MAGNETIZATION POST DE-ENERGIZATION

Nature of de-magnetization	Nos. of switching records	Nature of voltage and flux waveform
Full de-magnetization	60	
Partial de-magnetization	72	
Nil de-magnetization	99	

Different methods like Graphical determination method [23], Frequency response method [18], voltage accumulator method [19], and voltage integration method [24] have been used to portray the level of de-magnetization status of transformer core. These methods discussed only nil-demagnetization case and other possible states of natural de-magnetization are not addressed. This paper distinguished three different levels of de-magnetization achieved in presence of capacitive component. Real case studies are discussed with large number of samples and different configurations on different voltage levels. This paper addresses all scenario of natural de-magnetization with good accuracy

The number of cycles post transformer de-energization has been 10 for all the cases in each category. Moreover, the impact of variation in sampling rate considered for evaluation post de-energization, on the detection accuracy has been discussed in detail in the next section.

5. IMPACT OF VARIATION OF SAMPLING RATE ON DETECTION ACCURACY

For the results discussed in previous section, the number of cycles post de-energization for all cases had been maintained same as 10. Also, the sampling rate for various field cases had been same (166sample/cycle). The impact of variation in the sampling rate is described in this section. Moreover, for one-to-one comparison, all waveform had been post processed to the same sampling rate.

TABLE 2. IMPACT OF VARYING SAMPLING RATE ON DETECTION OF TYPE OF DE-MAGNETIZATION

Nature of de-magnetization	Sampling rate (Samples/cycle)	Residual flux w.r.t peak flux
Nil de-magnetization	20 166	75.428% 74.434%
Partial de-magnetization	34200 166	45.692% 45.015%

Effect of variation in sampling rate is demonstrated in TABLE 2. The field data contains different sampling rate (20, 166 & 34200 samples per cycles) and proposed methodology is applied in both scenarios and very minute variation is observed in resultant flux. Hence, it can be appreciated that the suggested method is equally effective with a sampling rate, as low as 20 samples/cycle. Due to non-availability of dissimilar sampling rate disturbance records for full de-magnetization cases, the same is not included in this section.

6. IMPACT OF VARIATION IN THE LEVEL OF RESIDUAL FLUX ON DETECTION OF TYPE OF DE-MAGNETIZATION

De-energization is a complex ringdown transient and amount of connected capacitance & de-energization instant play dominant role in deciding residual flux. In case of electrically and/or magnetically coupled transformers, therefore, all phase shows different level of residual fluxes. TABLE **3** demonstrates variation span of area under the flux curve for full, nil and partial de-magnetization for change in level of residual fluxes.

TABLE 3. VARIATION OF AREA UNDER THE CURVE DURING FULL, NIL AND PARTIAL DE-MAGNETIZATION

Nature of de-magnetization	Min. value of area under the curve	Max. value of area under the curve	Average variation
Nil de-magnetization	70.6%	85.5%	± 7.4%
Partial de-magnetization	35.1%	66.2%	±15.7%
Full de-magnetization	2.2%	9.1%	± 5.6%

Area under the flux curve during full de-magnetization case varies from 2.2% to 9.1% and shows average variation of 5.6%, exhibiting fair level of accuracy. Also, average variation in case of nil de-magnetization lies in range 70.6% to 85.5% with average variation of 7.4%. Whereas, area under the curve during partial de-magnetization varies over longer span ranging from 35.1% to 66.2%. Hence, it can be appreciated that, the suggested methodology hasn't significant impact on detection accuracy for variation in level of residual fluxes.

This paper address all possible states of natural de-magnetization of core and its evaluation led to:-

a) Exact status of de-magnetization of transformer core which might be different from existing methods.

b) Effect of large capacitive component directly connected to transformer are not discussed in existing methods

7. CONCLUSION

In this paper, a new methodology has been proposed for detecting the nature of de-magnetization for transformer core post its de-energization using load side voltages with area under the flux curve method. Based on validation for a large numbers of field cases for transformers having different voltage levels, design & connection configurations and nature & level of connected capacitances, the proposed technique successfully discriminates between different types of de-magnetization effects: partial de-magnetization, full de-magnetization & no de-magnetization. The suggested method is found to be equally effective for different sampling rates and variation in level of residual fluxes. Consequently, this classification can be very helpful in improving the accuracy in evaluation of optimum controlled energization targets for controlled switching to mitigate magnetizing inrush current for transformers during its no-load energization.

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