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Investigation of Increasing Accuracy Distributed Voltage on the Power Transformer Disks Considering Mutual Induction and Different Grounding System Models

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Abstract- *Power equipment are subjected to multiple shock voltages during their operations that are generally caused by a lightning strike, switching of electronic power devices, or transient voltages which across available in the power system. These impulses have a frequency range from several kHz to several MHz, which take pulses at very short intervals in several microseconds. Also, the equipment experiences the peak voltage and subsequently peak currents than their nominal values. These variations in voltage and current values, in very short intervals, have destructive effects on these equipment insulated systems as well as on the accuracy of measuring ground impedance. The primary purpose of this study is to investigate the effect of standard and non-standard voltage impulse on power transformers windings by considering the mutual induction of transformer windings. Furthermore In this paper, by applying lightning pulse on power transformer windings for different models of ground voltage distribution system on different disks of transformer windings terminal (20/0.4KV, 100KVA, 9 disks continuous winding) and the disks voltage are calculated as outputs in MATLAB/Simulink. In previous studies, the calculations were in the time domain, while in this study, the ground impedance was measured in the frequency domain. The simulation results show that considering the model RC and considering the mutual induction, the voltage distribution on the disks is higher than other models. This study provides functional information for improving the design of insulations that are installed between windings and core the results of the present research may lead to the minimization of the dielectric failures. Furthermore, the results of this study can be used in future studies about non-standard impulse voltages. This investigation can certainly lead to modifying available standards or creating new standards in power transformers.*

Keyword: Power Transformer, Disk, Impulse, mutual induction, Ground, winding.

1. INTRODUCTION

The overvoltage impression on windings of the transformer Fourier Transform is one of the critical issues that the transformers designers and manufacturers are encountered. In this regard, Impulse voltages generated by switching operation in high voltage substations and lightning strikes on transmission lines are significant. If one of the present frequencies in Fourier Transform impulse voltage be coordinated with one of the transformer winding natural frequencies, the electrical resonance occurs. In this case, there is a possibility that the winding parts become exposed to severe electrical stresses, and the insulation gets damaged. To reduce the risk of these stresses on transformer windings, it is necessary to investigate the various aspects of transient voltages distribution on transformer windings.

When impulse voltages affect the transformer windings, the amount of the voltage will be distributed on winding disks [1]. The insulation life estimation of transformer windings is examined through an impact impulse application and a transformer monitoring review has been studied [2, 3]. The study of oil transformer windings insulation is carried out by considering the impulse curve slope, including interruption, fall time, frequency fluctuations, and other parameters. [2, 4]. The power transformer details model have been performed through using FEM, MATLAB and ATP software, and eventually, the results have been acquired by comparing the results of the mentioned methods [5]. The effects of over voltages via applying lightning and switching impulses insulation systems is investigated [6]. Mitra et al. [7] have carried out via a

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computational study on the transformer winding response under voltage stresses. Their report demonstrates the effect of the voltage stresses at the worst case of the lightning impulses, intermittent lightning impulse, or front section of the switching curve length. In another study, the investigation of internal stresses that are made due to voltage shocks has been accomplished by using patterns added to the power grid [8]. A comparison of the swept frequency and low voltage impulse methods has been performed [9]. The positive and negative polarity effect of the disk dielectric curve is removed [10]. A novel technique for detecting winding displacement in power transformers has been performed by applying the frequency response analysis method [11]. Various suitability models of transformer windings for frequency response analysis in different applied over voltages have been investigated [12]. The prediction of transient operations in transformer cable interferences and switching over voltages on the transformer cable is discussed [13-15]. Application of vector fitting to high frequency transformer modeling and wide band modeling of power transformers and high Voltage test techniques are investigated [16-22]. The sensitivity analysis process for transient frequency response of transient voltages on the structure of the power transformer disk respect to the ground has been investigated [23]. The lightning impulse test based on the IEC 60076-4 standard with the front side of the standard impulse voltage curve also half rise time 1.2/50 μs, and the switching impulse test of the voltage curves used by 250/2500 μs were illustrated [24]. The standard lightning impulse curve from 1.2/50μs was presented at the beginning of the IEC in 1962 [25]. Specific information on the lightning wave frequency ranges is shown through transformer design methods [26]. In another research, a high-frequency model simulation of a simple transformer has been investigated [27].

The winding voltage distribution constant (α) indicates the uniformity rate of the Impulse Voltage Distribution along the transformer winding [29]. The value of this coefficient depends on the collective series and parallel capacitance of winding. The total series capacitance of the winding is equal to the capacitances of turn-turn, also total parallel capacitance of the winding is equal to the capacitances of turn-core. The current study investigates the impulse response of a power transformer with specifications of 100kVA and 20/0.4kV, three phases, 50Hz, and a continuous winding with 9 disks.

In previous studies, a developed model for transformer winding has been proposed without considering the mutual induction effect. Moreover, a comparative study which examines the transient response using standard and non-standard waveforms is performed and a significant differences in the characteristics of impulse voltages that have to be considered for the correct assessment of insulation resistance in power transformers is observed. In the present paper, it is attempted to consider the effect of various impulses of actual lightning waves and other waveforms that may practically occur in the power systems. Standard and non-standard impulse waveforms that are different in the slope characteristics, the moment of chopping, the time of the collapse, oscillation frequency and other parameters, are used to analyze the stroke wave. The non-standard stroke voltages applied in this study are formed based on the previous study in power systems.

This paper is composed of the following sections: In the second, third and fourth sections, modeling of full standard voltage shock waveform and modeling of power transformers are expressed, respectively. In the fifth and sixth sections, the different graphs of the measured voltages along with the ground impedance will be compared.

2. CREATING THE WAVEFORMS OF IMPULSE VOLTAGE

First, the characteristics of the waveforms are presented, and then how the waveforms are generated in the MATLAB/Simulink are introduced.

The main characteristics of this waveform are expressed in the IEC-60060-1 standard. The peak of the waveform is generated at the time of 1.2μs, and the wave tail is reduced to 50% of the peak value in the period of 50μs. This form can be created from the addition of two exponential functions, as follows.

$$V = v_0[\exp(\alpha t) - \exp\,(\beta t)] \quad (1)$$

Where α=0.0146*106 , β=2.467*106 , V0=50000

The generated waveform using MATLAB/Simulink is shown in Fig. 1.

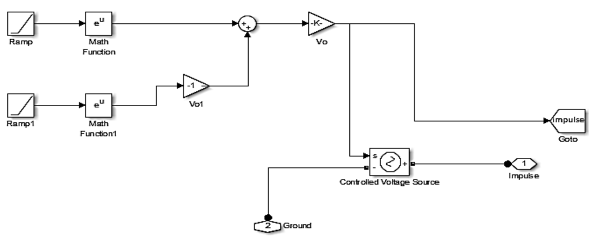


Fig. 1. How to produce a full standard voltage impulse waveform in the MATLAB/Simulink

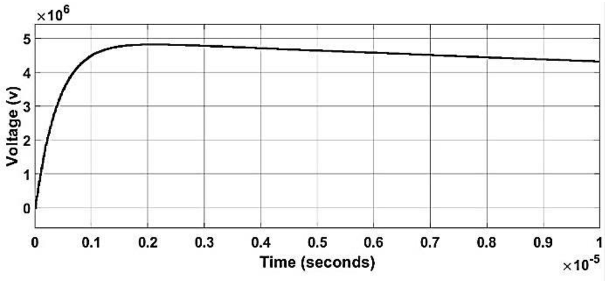


Fig. 2. The standard impulse voltage waveform is simulated

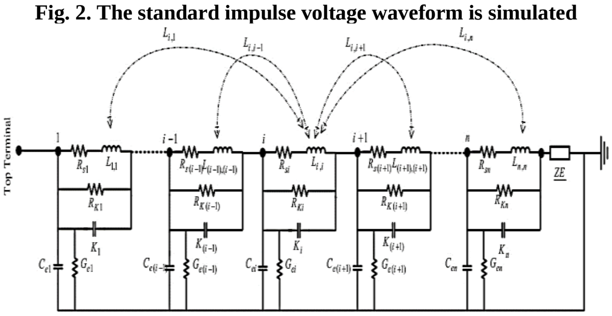


Fig. 3. Winding lumped detailed model of a power transformer [30]

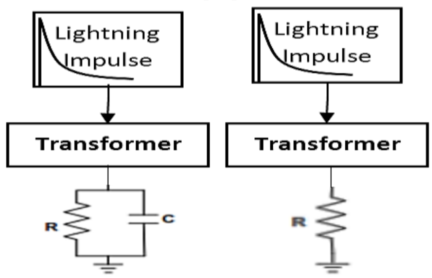


Fig. 4. Single line diagram of the whole circuit in two different modes of ground system connection (resistive and RC parallel)

As shown in Fig. 1, the β and α value are defined as the slope size for generating the slope mathematical functions. Then the output of this slope generators will be entered into the generating blocks of exponential functions and the exponential function exp(βt) is changed using a gain function with the value (-1) and summed with the exponential function exp(αt). Finally, as shown in Fig. 1, to apply the voltage waveform to the transformer simulated model, it is also necessary to use a controlled voltage source block. In Fig. 2, the simulated waveform can be seen in the MATLAB software.

3. THE TOPOLOGY OF WINDING DETAILS MODEL

The voltage in any specific points of the capacitive network during the strike time of the impulse voltage, U, is deduced from Eq. (2) by assuming that the transformer winding is grounded [28]:

$$V(x) = U\left(\frac{e^{\alpha x} - e^{-\alpha x}}{e^{\alpha l} - e^{-\alpha l}}\right) \quad (2)$$

Where,

$$\alpha = \sqrt{Cg/Cs} \quad (3)$$

In Eq. (2), U represents the applied impulse voltage amplitude to the winding terminal, l and x indicate the total winding length and the coordinates of the intended point for the voltage calculation respectively. Additionally, in Eq. (3), Cs and Cg are the total series capacitance and the total parallel capacitance of the winding, respectively. To study the response of power transformer windings to the standard voltage, a power transformer with the following specifications is considered.

Power of the transformer: 100KVA

Number of disks: 9

Transformer voltage: 20/0.4kv

The topology provided for the circuit is equivalent to the windings of a three-phase transformer phase as, shown in Fig. 3.

To produce a modular model in the MATLAB/ Simulink, the power transformer winding consists of 9 disks. This will make the simulation file more orderly and more comfortable to troubleshoot. It should be noted that according to the topology of the equivalent circuit for creating 9 disks in the Simulink, a capacitors between the windings and the ground is needed, each module for each loop is separated. These modules are connected in series.

4. TRANSFORMER MODEL IN MATLAB/SIMULINK

The single-line diagram of the whole circuit in two different ground system connection modes, which includes resistor and RC parallel, is shown in Fig. 4. The resistance value is 50Ω and the capacitor capacity is 1µf. The power transformer consists of 9 disks connected in series. Also, for convenience in the simulation, only one phase of a three - phase transformer is modeled due to the three-phase windings; the examination of only one phase of the transformer is enough. To produce a suitable model of the desired transformer, different parameters of the windings can be considered as Table 1 [31].

Due to the distance between the disks, the following relationships must be established:

L11=L22=L33=L44=L55=L66=L77=L88=L99 (4)

L12=L23=L34=L45=L56=L67=L78=L89 (5)

L13=L24=L35=L46=L57=L68=L79 (6)

L14=L25=L36=L47=L58 (7)

L15=L26=L37=L48 (8)

L16=L27 (9)

L11>L12>L13>L14>L15>L16>L17>L18>L19 (10)

Table 1. Transformer Constants

Conductor Layers	Capacitance (pf)		Inductance	Resistance
(from-to)	Cs	Cg	(mH)	(Ohm)
L1-1	8.4×10-3	3.4×10-4	1.1	4
L1-2	8.5×10-3	3.5×10-4	1.1	4
L1-3	8.7×10-3	3.7×10-4	1.1	4
L1-4	9.0×10-3	3.8×10-4	1.1	4
L1-5	9.2×10-3	4.0×10-4	1.1	4
L1-6	9.5×10-3	4.2×10-4	1.1	4
L1-7	9.7×10-3	4.4×10-4	1.1	4
L1-8	1.0×10-2	4.6×10-4	1.1	4
L1-9	1.02×10-2	4.8×10-4	1.1	4

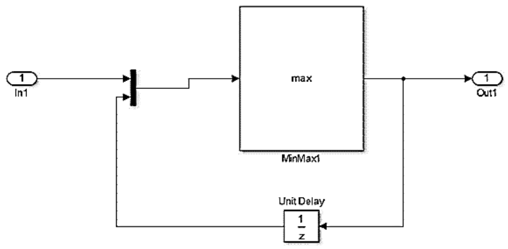


Fig. 5. How to save the maximum voltage

5. INFORMATION COLLECTION AND COMPARE THE RESULTS

The obtained results is categorize in three parts.

- The maximum voltage of each disk to the ground (measured at the time of impulse)
- The peak voltage that applied to each disk
- The time of occurrence of the maximum voltages on the desired disks

Here, to collect the maximum voltages occurring between each disk and ground, these voltages are measured, and the maximum of them is calculated as follows Fig. 5.

To save the maximum voltage for each winding (between the winding and the ground, or on each winding), a comparator block and a delay block is used. The performance of the comparison block (max) is such that by comparing the two inputs, it considers the more significant value as the output. As shown in Fig. 5, using a delay block, this output is again the second input to the max block, and thus, the maximum voltage can be measured for individual disks.

6. COMPARISON OF RESULTS FROM SIMULATION

According to different analyzes and comparison of different modes of the earth network, obtained results have been studied. Fig. 6 shows the plots obtained by the simulation to the maximum possible windings voltage. These results are presented for four parts:

Mode 1: without considering the effect of mutual induction of transformer windings with end circuit RC Parallel.

Mode 2: without considering the effect of mutual induction of transformer windings with end resistance.

Mode 3: Considering the effect of mutual induction of transformer windings with end circuit RC Parallel.

Mode 4: Considering the effect of mutual induction of transformer windings with end resistance.

By examining the results obtained from different modes and measuring the maximum amount of voltage applied on each transformer disk, we can comment on the insulation level of the windings. Then he observed the amount of voltage applied to the first and last disk. Now by measuring the value of ze impedance relative to the reference ground and comparing them at frequencies up to 10KHz, their analysis is examined.

6.1. Mode 1 & 2: without considering the effect of mutual induction of transformer windings

Fig. 6. Shows the maximum voltage changes relative to the ground and other graphs obtained for each of the 9 disks applied standard full lightning impulse voltage. As can be seen, the maximum amount of voltage measured is located on disk 1 of the transformer, and similarly, the amount of decreasing voltage is measured to the end disks. In relation to the measured impedance value, it is observed in two modes 1 and 2, which in mode 1 the impedance value decreases with increasing frequency, while in mode 2 this value increases and reaches 50Ω.

As can be seen, the value of ground resistance at a frequency of 50 Hz is about 25Ω in two different modes, and when the frequency increases, the amount of impedance will also increase.

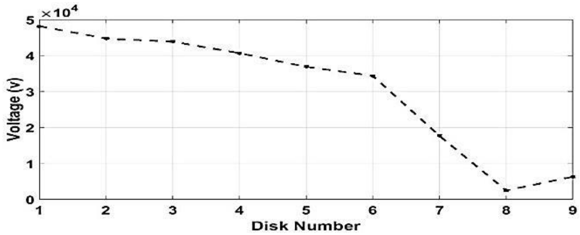
6.2. Mode 3 & 4: Considering the effect of mutual induction of transformer windings

Fig. 7, Shows the maximum voltage changes relative to the ground and other graphs obtained for each of the 9 disks applied standard full lightning impulse voltage. As can be seen in modes 3 and 4, the amount of voltage measured up to disk 6 is incremental and then decreases. The value of the impedance measured in mode 3 reaches the peak value with a frequency delay compared to mode 1 and then decreases, while in mode 4 it reaches 50Ω with a lower slope than in mode 2.

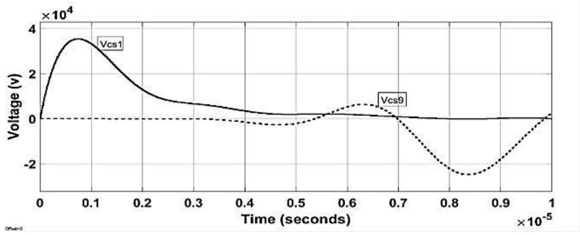
6.3. Comparison of measured voltage in modes from 1 to 4

According to Fig. 8, and comparison of voltage diagrams applied to the transformer windings in different modes; desirable, results can be achieved to reduce the impulse voltages applied to the windings. As can be observed in various simulations, the maximum amount of voltages distributed to the windings disk, was acquired in mode 3,4 (with mutual induction).

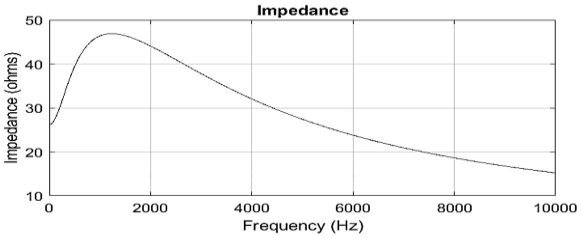
In order to investigate the actual over voltages applied to the transformer disks according to Fig. 8, the calculations and measurements must necessarily take into account the mutual induction of the transformer windings in order to achieve high accuracy results.



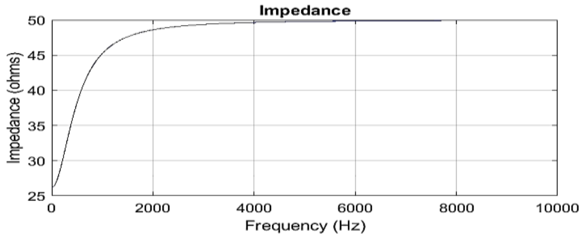
a) Maximum voltage on the disks



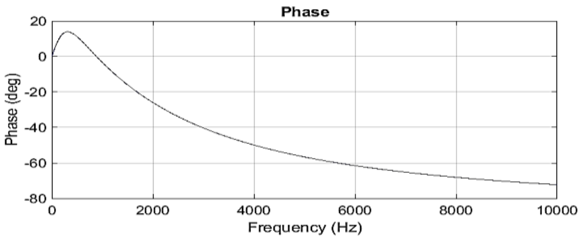
b) Voltage diagram Cs (Between the first and last disk)



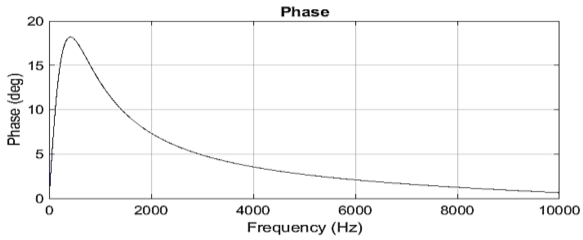
c) Ground impedance diagram on both sides Ze with end circuit RC Parallel



d) Ground impedance diagram on both sides Ze with end resistance

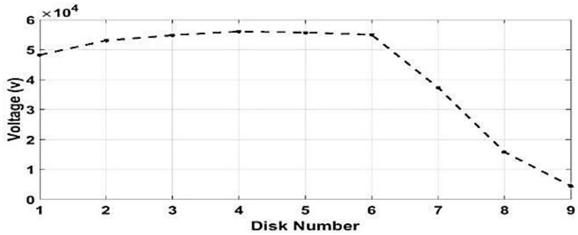


e) Ground impedance phase diagram on both sides Ze with end circuit RC Parallel

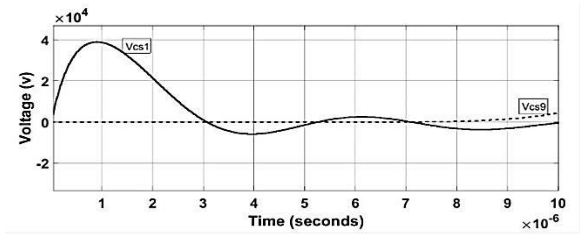


f) Ground impedance phase diagram on both sides Ze with end resistance

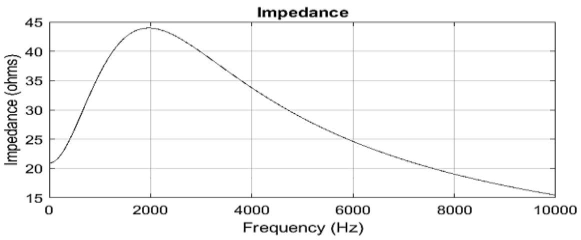
Fig. 6. Results of simulation of maximum voltage changes for the ground of each disk for modes 1 & 2 (Type of Impulses: Standard full lightning impulse voltage)



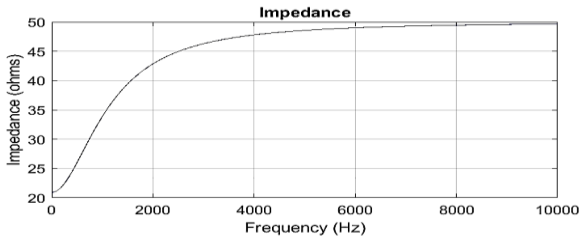
a) Maximum voltage on the disks



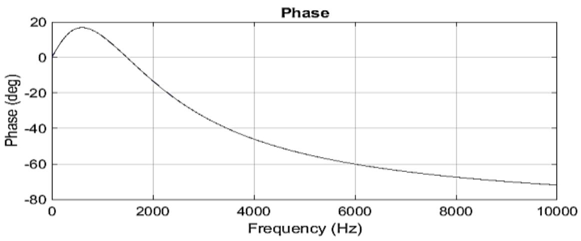
b) Voltage diagram Cs (Between the first and last disk)



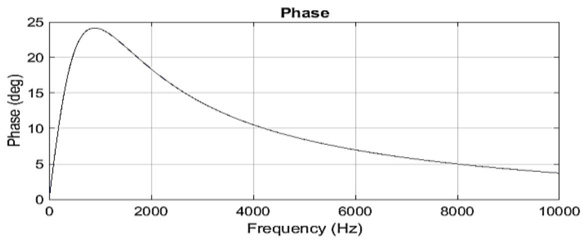
c) Ground impedance diagram on both sides Ze with end circuit RC Parallel



d) Ground impedance diagram on both sides Ze with end resistance



e) Ground impedance phase diagram on both sides Ze with end circuit RC Parallel



f) Ground impedance phase diagram on both sides Ze with end resistance

Fig. 7. Results of simulation of maximum voltage changes for the ground of each disk for modes 3 & 4 (Type of Impulses: Standard full lightning impulse voltage)

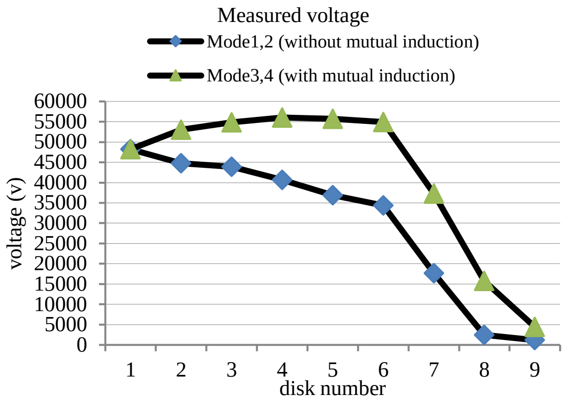


Fig. 8. Comparison of measured disk voltage in modes from 1 to 4

7. CONCLUSIONS

Transient overvoltage analysis due to lightning strike to power transformer should be considered as one of the most important and valuable equipment installed in high voltage power systems. Therefore, the ground model to which the zero point of the transformer should be connected is evaluated. The effects of distributed voltage on the power transformer disks considering mutual induction and different grounding system models on a 3 MVA, 20/0.4 kV, 3-phase, 50 Hz, 9 disks continuous winding power transformer were investigated in this work. The variation of maximum voltage to ground and voltage across the disks along the transformer winding under different grounding system models impulse voltage waveforms were studied using an analog and a simulated transformer model. Modeling and simulations are performed using MATLAB/ Simulink. As can be shown, the transient over voltages on the transformer windings are made due to various voltage pulses lead to insulation stresses on the transformer windings. This important, that the applied voltage to the winding must be able to excite all the frequency modes of the winding such that the application of its results in a wide frequency range would be acceptable. The study investigates the unconsidered variables of previous studies by comparing different modes such as simulations of transformer windings in two states of considering and ignoring the mutual induction effect of the windings and, different grounding system models installed in the measuring circuit in the desired results. This study provides functional information for improving the design of insulations that are installed between windings and core the results of the present research may lead to the minimization of the dielectric failures. Furthermore, the results of this study can be used in future studies about non-standard impulse voltages. This investigation can certainly lead to modifying available standards or creating new standards in power transformers.

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