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Analysis of Short-Circuit Impedance in Multi-Winding Transformer

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Abstract

Due to green energy policies, investments in renewable energy are rapidly increasing, which in turn raises the demand for efficient power plant integration into electrical grids. Multi-winding distribution transformers are crucial in this process, as they enable operation at various voltage levels to match different grid requirements. However, designing such transformers, mainly calculating short-circuit impedance in accordance with industry standards, is a highly complex and challenging task when using conventional analytical methods. This study investigates the short-circuit impedance of a multi-winding transformer and presents an efficient approach to accurately calculating the short-circuit impedance. The study uses Finite Element Method simulations to calculate the short-circuit impedance for different winding configurations. Experimental testing is performed on a prototype transformer to validate the results, ensuring its performance and reliability. The proposed method offers researchers and manufacturers a reliable approach to accurately determine short-circuit characteristics, improving transformer design and reducing reliance on costly test processes. This approach supports the determination of the necessary characteristics of the transformer before producing prototypes.

Keywords: Transformer, Multi-Winding, Short Circuit Impedance, Test, Simulation.

1. Introduction

Standard distribution transformers are typically designed with a single primary winding that steps down a specified input voltage to achieve a desired secondary output voltage within a limited range. However, large power transformers can accommodate voltage fluctuations of up to ±20% in the grid by incorporating special tap changers. This functionality enables transformers to maintain a consistent output voltage. To effectively operate under varying supply voltages, transformers with different primary-to-secondary voltage ratios are required. For example, a 10/0.4 kV transformer has a primary-to-secondary winding ratio of 1:25. In comparison, a 20/0.4 kV transformer involves a ratio of 1:50. This highlights the necessity for transformers with multiple winding configurations to manage the complexities of diverse grid voltages. Dual-voltage and multi-voltage transformers have recently gained popularity among manufacturers and utilities. The main reasons for the demand for multi-winding transformers include the following:

- Supplying multiple voltage levels: Multi-winding transformers can provide different voltage levels, making them ideal for systems requiring diverse voltage levels for various loads.
- Efficient power distribution: They allow power distribution to multiple locations or substations without needing separate transformers, reducing infrastructure costs and system complexity.
- Integration of renewable energy sources: Multi-winding transformers are widely used in renewable energy systems (solar or wind farms) to connect multiple generators or energy sources to the grid at different voltage levels.
- Cost and space efficiency: A single multi-winding transformer saves space and installation costs compared to using multiple transformers for different purposes.
- Mobile testing stations: Multi-voltage transformers are essential components in mobile testing stations, allowing for tests and measurements at different grid locations.

Numerous studies and research efforts have been conducted in various aspects of transformer technology, including design optimization, material improvements,

efficiency enhancement, and the analysis of operational characteristics, as reviewed below.

Study [1] aims to enhance modeling techniques for multi-winding transformers in short-circuit analysis. It focuses on improving accuracy in impedance calculations, developing effective equivalent schemes, addressing manufacturers' data limitations, and increasing the understanding of transformer modeling in power systems.

Using the Finite Element Method (FEM), study [2] investigates electromagnetic forces on a 12-pulse converter transformer during short-circuit and normal conditions. This aims to enhance transformer design and prevent mechanical failures. Findings show that the axial forces are higher during inrush currents and single-winding short circuits compared to both windings short-circuited. The study emphasizes that inrush currents, which can last longer than short circuits, must be considered in a transformer design to avoid damage and financial losses.

In [3], electromagnetic forces in a 25 MVA power transformer are analyzed under both normal and short-circuit conditions using the finite element method. The study finds that short-circuit currents reach 11.11 times the rated current, resulting in forces over 123.5 times greater than under normal operation. The research highlights the need to consider these forces in transformer design to prevent damage and ensure reliability.

Study [4] analyzes electromagnetic forces and winding deformation in a 3-phase, 66/11 kV transformer due to short-circuit currents. Findings reveal that transient currents create significant axial and radial forces, causing mechanical stress and potential distortion in the windings. This understanding is crucial for improving transformer design and insulation to minimize damage during abnormal conditions.

In [5], a new method is developed for calculating the short-circuit impedance of square foil winding phase-shifting transformers, addressing challenges from eddy currents. Findings show that the planar energy density equivalence method achieves high accuracy (errors under 2%) and reduced computation time (under 20 minutes), surpassing traditional 3D finite element methods and meeting engineering design needs.

Study [6] provides a comprehensive analysis of electromagnetic forces and deformations in transformer windings caused by excitation inrush and short-circuit currents. The findings revealed that the electromagnetic forces generated by short-circuit currents affect both high and low-voltage windings, while those from excitation inrush primarily impact the high-voltage winding. The study validated the reliability of simulation results through experimental comparisons, highlighting the need for effective preventive measures to enhance the operational efficiency and lifespan of power transformers.

In [7], an equivalent circuit model is developed and validated for a transformer with two primary windings and one secondary winding, specifically designed for a spot-welding machine application. The findings from experiments demonstrated that the developed equivalent circuit accurately predicted the currents in the primary windings, confirming its effectiveness and physical relevance in transformer design, particularly in scenarios involving multiple primary winding sections and their impact on performance.

Study [8] presents an accurate model for multi-winding high-voltage transformers considering leakage inductance, winding resistance, and parasitic capacitance. Findings indicate that all parameters, except stray capacitance, can be measured using an LCR meter, consistent with simulated and measured results across 10 kHz to 200 kHz, validating the model's effectiveness.

Investigations into transformer design and performance analysis conducted in [9-13], aiming to optimize the electrical and thermal design of the transformer and evaluate its field behavior during unbalanced conditions.

Study [14] analyzes the distribution of electromagnetic forces and the resulting deformation in transformer windings during short-circuit events using FEM simulations. Findings indicate that maximum radial force occurs at the center of the low voltage (LV) winding and near the tapings of the high voltage (HV) winding, with the LV winding experiencing significantly greater axial force. This highlights the need to understand these forces to prevent mechanical failures in power transformers.

In [15], a novel method is proposed to achieve balanced short circuit impedance in multi-split rectifier transformers. The method simplifies the design process and ensures accurate impedance balancing, which is validated through experimental results.

Study [16] applies FEM modeling to examine transient electromagnetic forces in photovoltaic (PV) transformers under short-circuit conditions. Understanding these forces is essential to prevent mechanical failures and improve transformer reliability.

In [17], a simulation is conducted to analyze the short-circuit performance of a large single-phase yoke-type transformer. The simulation results are validated through experimental testing, providing insights into design optimization and emphasizing the influence of yoke compression on magnetic leakage.

A review of existing studies indicates that the analysis of short circuit impedance in multi-winding transformers, which can operate at three different primary voltage levels to provide a stable secondary output, has not been extensively analyzed.

The main objective of this study is to reliably analyze and evaluate the short-circuit impedance of a four-winding transformer configuration during the

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transformer design stage using FEM. The transformer accommodates primary voltages of 22 kV, 11 kV, and 6.3 kV while providing a secondary output voltage of 0.42 kV. This unique design, featuring four separate windings, allows the transformer to operate effectively across all three primary voltage levels, ensuring a reliable secondary voltage output. The study includes simulations conducted using Ansys and experimental analysis. The results from both approaches are in good agreement.

2. Specification of the Proposed Transformer

This study focuses on the short circuit impedance calculation of a 1600 kVA, 22-11-6.3/0.42 kV four-winding transformer to improve performance and adaptability in varying grid conditions in compliance with EU regulations [18,19]. The transformer is designed to operate efficiently at three different primary voltage levels while ensuring a stable secondary voltage output. Such transformers are essential for enhancing flexibility in power distribution systems, reducing energy losses, and simplifying inventory management for utilities and suppliers. The required specifications for the proposed transformer are outlined in Table 1.

Table 1. Specification of the transformer

Power	1600 kVA, 50 Hz
Cooling system	ONAN
HV/LV Voltage [kV]	22-11-6.3 / 0.42
HV/LV Current [A]	41.99-83.98-146.63 /2199
HV/LV Conductor	AL / AL
Vector group	(D)(D)Dyn11
No Load Loss [W]	1080 + 15 %
Load Loss [W]	12000 + 10 %
Short circuit impedance	6% ±10%

The winding configuration of the transformer under investigation is illustrated in Figure 1.

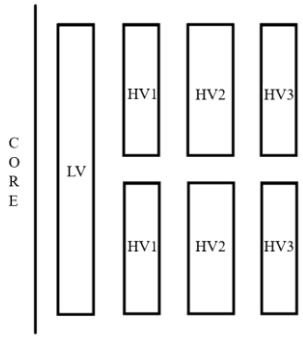


Figure 1. Winding configuration of the transformer

2. Electromagnetic Simulation

An electromagnetic simulation study is carried out to demonstrate the transformer's electromagnetic behavior, including calculating short-circuit impedances for different winding configurations. Figure 2 shows the 3D model of the transformer's active part, displaying its three phases, each with vertically separated upper and lower high-voltage windings.

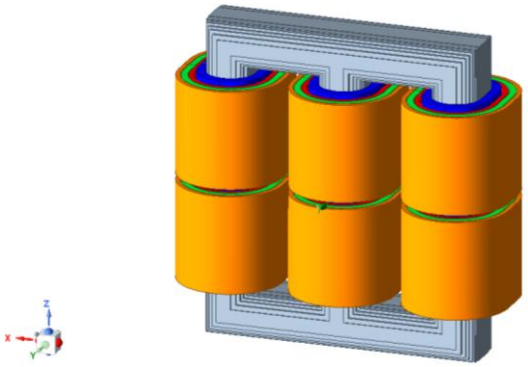


Figure 2. Transformer active part model

The simulation study is carried out in two steps. First, the voltage and current characteristics of the primary and secondary windings are evaluated using Ansys simulation under full-load operating conditions. Next, the simulation model was established to analyze the transformer's short-circuit impedance. In this analysis, the low-voltage side of the transformer is short-circuited while the rated voltage is applied to each winding configuration from the high-voltage side. The electric circuit used for this analysis is shown in Figure 3.

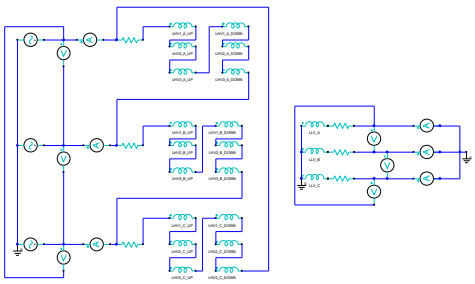


Figure 3. The electric circuit used for calculating short circuit impedance

Equation 2.1 demonstrates how the short-circuit impedance is calculated based on simulation results.

$$\%Z_k = \frac{Rated\ current\ of\ the\ winding \times 100}{Short\ circut\ current\ of\ the\ winding} \quad \textbf{(2.1)}$$

Figure 4 illustrates the current waveform for the low-voltage winding during this condition. The analysis reveals that the low-voltage winding's average short-circuit current value is 39.75 kA. This value highlights the significant magnitude of the current during short-circuit conditions, which is critical for evaluating the

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thermal and mechanical stresses imposed on the winding. Understanding this behavior is essential for ensuring the design integrity and operational reliability under fault conditions.

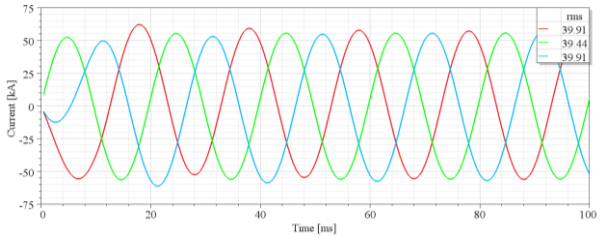


Figure 4. Short circuit current of low voltage winding

Figure 5 illustrates the waveform of the current recorded in the high-voltage winding during a short circuit. While the high-voltage winding operates at a voltage of 22 kV, it has been established that the average value of the short-circuit current in the winding is approximately 0.758 kA.

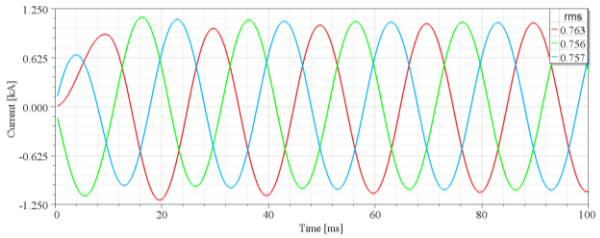


Figure 5. Short circuit current of HV winding while operating at 22 kV

Figure 6 shows the current waveform in the high-voltage winding during a short circuit, with an average current of 1.5 kA at 11 kV.

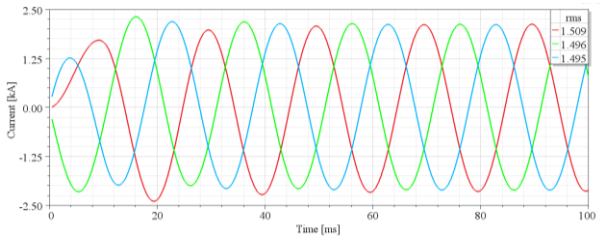


Figure 6. Short circuit current of HV winding while operating at 11 kV

Figure 7 illustrates the current waveform measured in the high-voltage winding under short-circuit conditions at a voltage level of 6.3 kV. An average short-circuit current of approximately 2.8 kA is measured in the winding. This current value reflects the winding's behavior during fault scenarios and provides essential insights into its electrical performance.

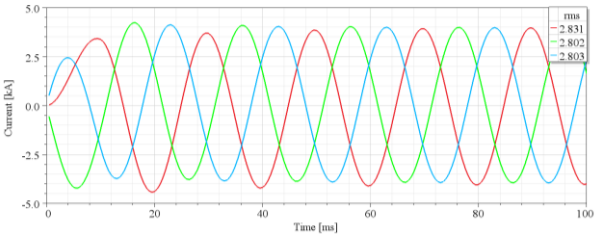


Figure 7. Short circuit current of HV winding while operating at 6.3 kV

Using equation 2.1, the short circuit impedances for 22 kV, 11 kV, and 6.3 kV windings are calculated as 5.467%, 5.514%, and 5.256%, respectively, from the simulation results.
It's worth noting that the simulation results are based on approximate calculations and are not related to the reference temperature.

3. Experimental Results

The experimental study was conducted to validate the proposed methodology. The prototype transformer was submitted to a comprehensive series of routine tests and successfully passed all evaluations. The results fully comply with the required technical specifications and regulatory standards.
Load loss and short circuit impedance are typically assessed during transformer testing as part of routine tests, following established standards [20,21].
The test starts with a voltage applied to the terminals of the primary winding, while the secondary winding terminals are short-circuited. The voltage is then adjusted carefully to generate the rated current through the windings. The supplied current should match the relevant rated current, but must not be less than 50 %.

The following equations are used to calculate the short circuit impedance at ambient and reference temperatures using measured values for a 22 kV winding [22,23].

$$\%Z_{k@23\,^{\circ}C} = \frac{U_{Test} \times I_N \times 10^2}{I_{Test} \times U_N} = \frac{1244 \times 41.99 \times 10^2}{41.99 \times 22000} = 5.652 \quad \textbf{(3.1)}$$

$$\%R_{k@23\,^{\circ}C} = \frac{Power@23\,^{\circ}C \times 10^2}{P_N} = \frac{11183 \times 10^2}{1600000} = 0.699 \quad \textbf{(3.2)}$$

$$\%X_k = \sqrt{Z^2_{k@23\,^{\circ}C} - R^2_{k@23\,^{\circ}C}} = \sqrt{31.92 - 0.488} = 5.61 \quad \textbf{(3.3)}$$

$$\%R_{k@75\,^{\circ}C} = \frac{Power@75\,^{\circ}C \times 10^2}{P_N} = \frac{13046 \times 10^2}{1600000} = 0.815 \quad \textbf{(3.4)}$$

$$\%Z_{k@75\,^{\circ}C} = \sqrt{R^2_{k@75\,^{\circ}C} + X^2_k} = \sqrt{0.664 + 31.47} = 5.668 \quad \textbf{(3.5)}$$

Where, U_{Test} and I_{Test} represent the average phase-to-phase voltage and current of the winding measured during the test , P_N , U_N , I_N denote the rated power, voltage and current of the winding, respectively, and

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$\%X_k$ and $\%R_k$ represent the short-circuit reactance and resistance, respectively.

The experimental setup used to measure the load losses and the short circuit impedance is shown in Figure 8.



Figure 8. The experimental setup used to measure load losses and short circuit impedance

Figure 9 illustrates the impedance and load loss measurements conducted on the 22 kV high-voltage winding.

	A	B	C	Sum/Avg
P	3.79 kW	3.96 kW	3.44 kW	11.19 kW
Q	29.59 kVAR	30.12 kVAR	30.04 kVAR	89.75 kVAR
I rms	41.525 A	42.351 A	42.101 A	41.99 A
f	50.00 Hz			
	A-N	B-N	C-N	Sum/Avg
U rms	718.38 V	717.41 V	718.09 V	717.96 V
	A-B	B-C	C-A	Sum/Avg
U rms	1.243 kV	1.244 kV	1.244 kV	1.244 kV
	Power [In]	SC Voltage [%]	Rk[%]	Zk[%]
@ 23.0 °C	11.183 kW	5.652 %	0.699 %	5.652 %
@ 75.0 °C	13.046 kW	5.668 %	0.815 %	5.668 %

Figure 9. Short circuit impedance measurement while the HV winding is operating at 22 kV

This figure displays the screen of the test equipment. As shown, when an average primary current of 41.99 A (I_{rms}), corresponding to the rated current of the 22 kV winding, flows through the winding, the short-circuit impedance is measured to be 5.668%.
Similarly, the test was conducted for the windings at 11 kV and 6.3 kV, with the results illustrated in Figures 10 and 11, respectively.

	A	B	C	Sum/Avg
P	3.85 kW	3.98 kW	3.61 kW	11.44 kW
Q	29.93 kVAR	30.32 kVAR	30.28 kVAR	90.53 kVAR
I rms	83.385 A	85.041 A	84.547 A	84.32 A
f	50.00 Hz			
	A-N	B-N	C-N	Sum/Avg
U rms	361.874 V	359.638 V	360.64 V	360.72 V
	A-B	B-C	C-A	Sum/Avg
U rms	624.278 V	624.918 V	624.522 V	624.573 V
	Power [In]	SC Voltage [%]	Rk[%]	Zk[%]
@ 23.0 °C	11.336 kW	5.655 %	0.708 %	5.655 %
@ 75.0 °C	13.226 kW	5.671 %	0.827 %	5.671 %

Figure 10. Short circuit impedance measurement while the HV winding is operating at 11 kV

As shown in Figure 10, under 11 kV operating conditions, when the rated current, approximately 84.32 A, flows through the winding, the short-circuit impedance is measured to be 5.671%.

	A	B	C	Sum/Avg
P	1.81 kW	1.83 kW	1.87 kW	5.51 kW
Q	10.47 kVAR	10.40 kVAR	10.44 kVAR	31.31 kVAR
I rms	87.454 A	88.833 A	88.558 A	88.28 A
f	50.00 Hz			
	A-N	B-N	C-N	Sum/Avg
U rms	121.522 V	118.832 V	119.802 V	120.05 V
	A-B	B-C	C-A	Sum/Avg
U rms	208.089 V	207.804 V	207.944 V	207.946 V
	Power [In]	SC Voltage [%]	Rk[%]	Zk[%]
@ 23.0 °C	15.184 kW	5.482 %	0.949 %	5.482 %
@ 75.0 °C	17.742 kW	5.512 %	1.109 %	5.512 %

Figure 11. Short circuit impedance measurement while the HV winding is operating at 6.3 kV

Figure 11 illustrates that when a voltage is applied to the 6.3 kV winding and a current of 84.32 A, corresponding to approximately 57% of the rated current (146.6 A), flows through it, the short-circuit impedance is measured as 5.512%. This complies with IEC 60076-1, which requires the test current to be at least 50% of the rated current.

4. Discussion

The analysis presented in this study emphasizes the crucial need to accurately determine the short-circuit impedance of multi-winding transformers, especially those designed to operate at multiple primary voltage levels. Using FEM simulations proved to be a reliable and efficient way to address this complex design challenge, with results validated by experimental data.

The simulation results closely match experimental data, confirming the effectiveness of the FEM-based method in capturing electromagnetic behavior during short-circuit conditions. This agreement demonstrates the proposed approach's ability to accurately predict short-circuit characteristics, which is crucial for ensuring transformer reliability and safety during faults. Table 2 compares the short-circuit impedance values from simulations with those obtained from experiments. The findings demonstrate a remarkable degree of consistency, with an average error of 3.6%, confirming the reliability of the simulation analysis.

Table 2. Comparison of simulation and experimental results

	Simulation [%]	**Test [%]**	**Difference [%]**
Z_k - 22 kV	5.467	5.668	-3.5
Z_k - 11 kV	5.514	5.671	-2.8
Z_k - 6.3 kV	5.256	5.512	-4.6

5. Conclusion

This research outlines a comprehensive study on the short circuit impedance of a transformer with novel high-voltage winding configurations.
The investigation employs an innovative approach that combines advanced computational techniques with empirical validation. This simulation method facilitates the identification of short circuit design parameters during the design stage, offering valuable insights into the performance characteristics of the transformer.
Experimental validation was conducted using standard testing procedures to confirm the accuracy of the simulation results, ensuring the proposed transformer's reliability under expected operating conditions.
The proposed solution aims to assist in the design of multi-winding transformers by improving their ability to withstand short-circuit effects and facilitating the design and short-circuit impedance calculation of these transformers, thereby enhancing their adoption and widespread use in electrical networks to achieve the following objectives:

- Improve flexibility in power distribution networks to ensure operation with varying voltages of the different grids.
- Reduce the number of required transformers with different voltage classes to minimize the investment costs.
- Reduces costs associated with testing and prototype validation processes.
- Enables the evaluation of transformer short-circuit impedance, even for complex winding configurations, to ensure compliance with desired or standard-specified values before manufacturing.
- Facilitates the evaluation of various winding configurations, allowing for cost optimization and improved design efficiency.

Developing an innovative multi-winding transformer is essential for modern energy distribution and grid management challenges. This advancement enhances transformer performance and creates more sustainable and efficient energy systems.

Author's Contributions

Emir YÜKSELEN: Drafted and wrote the manuscript, performed the experiment, and conducted the simulation analysis.

Ethics

There are no ethical issues after the publication of this manuscript.

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