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Load Insertion Influence on the Hysteresis Loop of a Single-Phase Transformer under Transients

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Abstract: The hysteresis cycle is one of the main parameters that define the characteristics of materials used in the design of transformer. This parameter is strongly influenced by the transient regime of the transformer which has a great influence on the operating point of the transformer. The idea of this paper is original and represents an initiation to a research project aimed at visualizing the effect of load insertion on the characteristics (hysteresis loop) of the iron core. The main objective of this article is to address the influence of this load on the hysteresis loop of a single-phase transformer in transient mode, i.e. in inrush current, in terms of position, surface or size. First, a general study of the electromagnetic characteristics of the transformer iron core will be presented. Then, using the ATP_EMTP program, the simulation is performed to visualize the relationship between the hysteresis loop and the load insertion on the secondary side of the transformer in transient mode. Finally, the results show the decrease in the surface of the hysteresis loop and their shift from the origin of the axes following the increase in the load.

Keywords: Transformer, Inrush current, Transient regime, Hysteresis loop, Load, ATP_EMTP

Introduction

The hysteresis cycle is one of the main parameters that define the characteristics of materials used in the design of transformer. This parameter is strongly influenced by the transient regime of the transformer which has a great influence on the operating point of the transformer. Transformer transient phenomenon are caused by the saturation of a power transformer due to variations in the magnetization voltage (Yahiou, 2012; Yahiou et al.,

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2018a). When an unloaded transformer is energized, a transient phenomenon called inrush current may appear in the excited circuit side. Therefore, all necessary studies and investigations must be carried out in order to anticipate a suitable protecting system for the transformer.

There are many works in the literature that fall into this framework, such as those studied by the authors in Bertagnolli (1996), Specht (1951), Holcomb (1961). Where many numerical and analytical tools have been developed. Furthermore, the majority of studies on the field of transformer transient study are in the context of finding effective and inexpensive techniques to reduce this inrush current. Among these methods, the technique proposed in Cano-González et al. (2015, 2017). Where four different methods to reduce the inrush current are compared; The obtained result from the four techniques is to collect the ability to use the circuit breakers with an independent pole, as well as the ability to deem the residual flux in the iron core of the transformer. The measurement and simulation studies performed in Brunke et al. (2001a, 2001b) is one of the pioneering works, simulation and measurements, in the area of reducing the inrush current in three and single phase transformer. Taking into account the residual flux values, the authors propose three schemes in this technique, by closing the circuit breakers in a synchronous, quick, and delayed manner. In Cheng et al. (2004) the authors utilize the technique of making a modification in the transformer bobbin. This is intended to decrease the inrush current peaks by increasing the transient inductance value. Taking into account the phase shift between the three phases of the transformer during its energization, the authors introduce in the work presented in Arand (2013); Abdulsalam et al. (2017); Abdelsalam et al. (2015); Cui et al. (2005), a resistance between the ground and the transformer neutral. The authors in Xu et al. (2005) with taking into account the switching moment, are used the reversed flux technique for investigating the reduction of the inrush current using an existed photovoltaic generator.

In Schramm et al. (2011), the authors present several methods to protect and reduce the various interactions of transformer relays as well as the introduction and removal of the load in a random or studied manner by the circuit breakers in Rudez et al. (2016) have depended on differential equations and formal methods for solving them, based on the equivalent circuit represented using the state space equation. Pontt et al. (2007) have raised the resistance value of the transformer winding, using the transformer tap changer to reduce the effect of the inrush current power system as well as mitigating its peak value. The main contribution of paper Yahiou et al. (2018d) is to apply the technique proposed by the same authors of Yahiou et al. (2019) in the laboratory using a real-time measurement setup to eliminate the sympathetic inrush current, the latter results from the interaction of two transformers, one is energized and the second is already supplied. Moreover, there is a comparison of the results (measurement and simulation) to prove the efficacy of the proposed technique found in Yahiou et al. (2019). To mitigate also this sympathetic inrush current. Abdelsalam et al. (2016) presented an important technique in the field of inrush current mitigation, especially by using renewable energies (photovoltaic (PV)), where the reverse flux is applied. The authors in Danikas et al. (2020) presented a review of some factors which affect the resistance during breakdown of transformer oil. In (Le & Vu, 2019), the authors have exposed a generator differential protection relay system, its disadvantages and its advantages. This system is dual slope from Areva P343, ABB REG670, SEL300G and GE G60. The authors in Fan et al. (2016) a real power transformer is used in experiments, also the authors built a UHF-PD detection system.

Because the supply of the transformer primary, under its nominal voltage is accompanied by a transient regime during which the intensity of the inrush current can take values much higher than those of the nominal intensity, depending on the instant of appreciation of the voltage and the induction remanence of the magnetic circuit. Hence, the need to predetermine through the study of the transient regime, the approximate value of this inrush current which may be greater than or equal to several times the current of the transformer (Sahoo et al., 2019). Holcomb (1961) is considered among the first who raised the idea of the inrush current calculation, but without going far, where the author have studied only a method to compute the peak inrush current for the first and any succeeding cycle, without considering its effect on hysteresis loop.

In reference Faiz and Saffari (2010) the authors used a developed model to estimate the inrush current and hysteresis loop. However, the authors did not make a comparison between the relationships of the position of the hysteresis loop wave according to the corresponding inrush current. Even in (Abdulsalam et al., 2005b; Oyanagı et al., 2018). It is the same weakness observed in this works, where the authors estimate the saturation curve from the inrush current waveform. This major drawback of this previous works has been studied and accomplished in the present work, where the comparison has been made between different effects of transformer energization on the nature of iron core.The authors in Altun et al. (2021). Have exploited a real model of a transformer to study different phenomena such as the application of the nonlinear load. However, the authors have not totally studied the load influence in all operational modes. In other words, the authors limit their study to the load effects on the steady-state regime.

The study presented in this article is a continuation of the study presented in the articles (Yahiou, 2022a; Yahiou et al., 2022b). The main objective of this work is to study the influence of the load on the hysteresis cycle of a single-phase 2 kVA transformer. This study will carried out using a no-load and load simulation circuit under the software ATP/EMTP (Alternative Transient Program). Firstly, using measurement setup with a data acquisition system, the parameters of the transformer and the characteristics of the magnetizing branch (inductance and resistance) will identified. After a simulation will be carried out to arrive at a specific study of the influence of the load on the surface and the position of the hysteresis cycle of a single-phase transformer using the software ATPDraw. In order to observe the changes in the shape and location of the hysteresis loop caused by different values of the resistive load (R), for the transformer under transient inrush current.

Transformer Parameters Identification and Iron Core Characteristic

The Figure 1 shows real transformer used in the simulation this transformer.

Figure 1. Real used transformer

Table 1 shows the characteristics of the used transformer.

Table 1. Nameplate data of the transformer

Power	Frequency	Phase	Voltage Ration	Turn	current Ration	Class (isol)
2000 VA	50 Hz	01	0.22/0.25 kV	0330/0037 tr	9.10/080A	E

The calculated parameters of equivalent circuit for the transformer of figure 1 are presented in the following Table 2.

Table 2. Equivalent circuit parameters

Parameter	Value
Magnetizing resistance R_m	2847,05 Ω
Magnetizing reactance X_m	609,72 Ω
Series resistance $R_{éq}$	3,48 Ω
Series reactance $X_{éq}$	2,69 Ω

The study of any transformer transient regime such as inrush current requires careful modeling of the iron core nonlinearities.

Iron Core Nonlinearities

The dynamic behavior of a transformer can be characterized in different ways. Taking into account the saturation of the core, and therefore the non-linearity, implies that the functions to be solved will be more complicated in comparison with linear models. Figure 2 presents the magnetizing curve $\lambda = f(i_l)$ which presents the iron core inductance. Figure 3 shows the resistance characteristic $v = f(i_{lr})$. These figures are used as data in the realized work found in (Yahiou et al., 2018d).

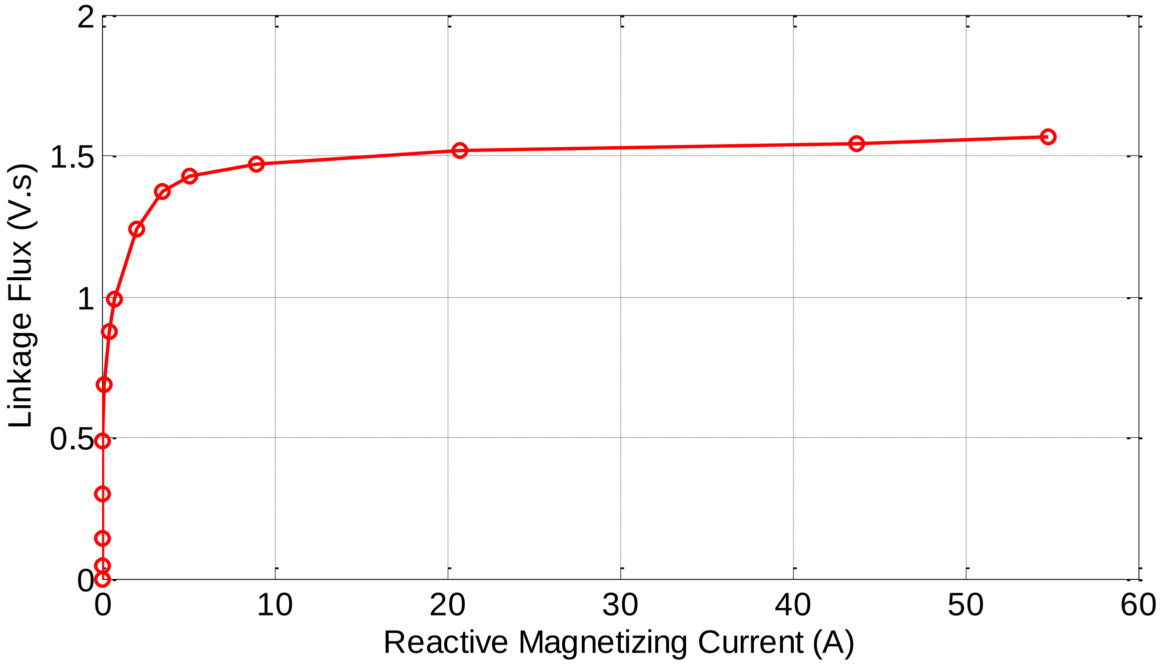


Figure 2. Saturation curve (nonlineair inductance) $\lambda = f(i_l)$ (Yahiou et al., 2018d).

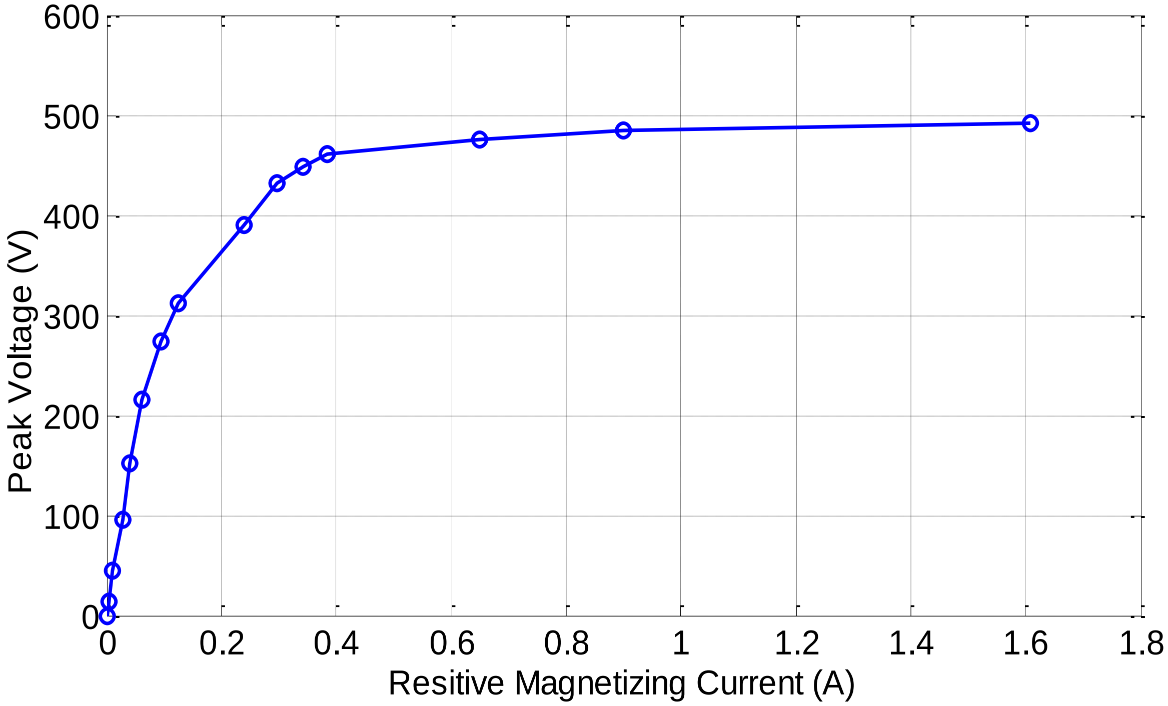


Figure 3. Resistance characteristic $\lambda = f(i_r)$ (Yahiou et al., 2018d)

The data found in Figures 2 and 3 are calculated by the improved technique presented by the authors in (Yahiou et al., 2019; Yahiou & Bayadi, 2012). And they have been inserted in the saturable transformer found in ATP-EMTP program to simulate the ferroresonance under different conditions.

Experimental Setup and dSPACE Interface

Figure 4 shows a measurement setup photo used to extract the parameters of the used single-phase transformer, as well as for measure the data used to estimate the saturation curve and the curve representing the nonlinear resistance.

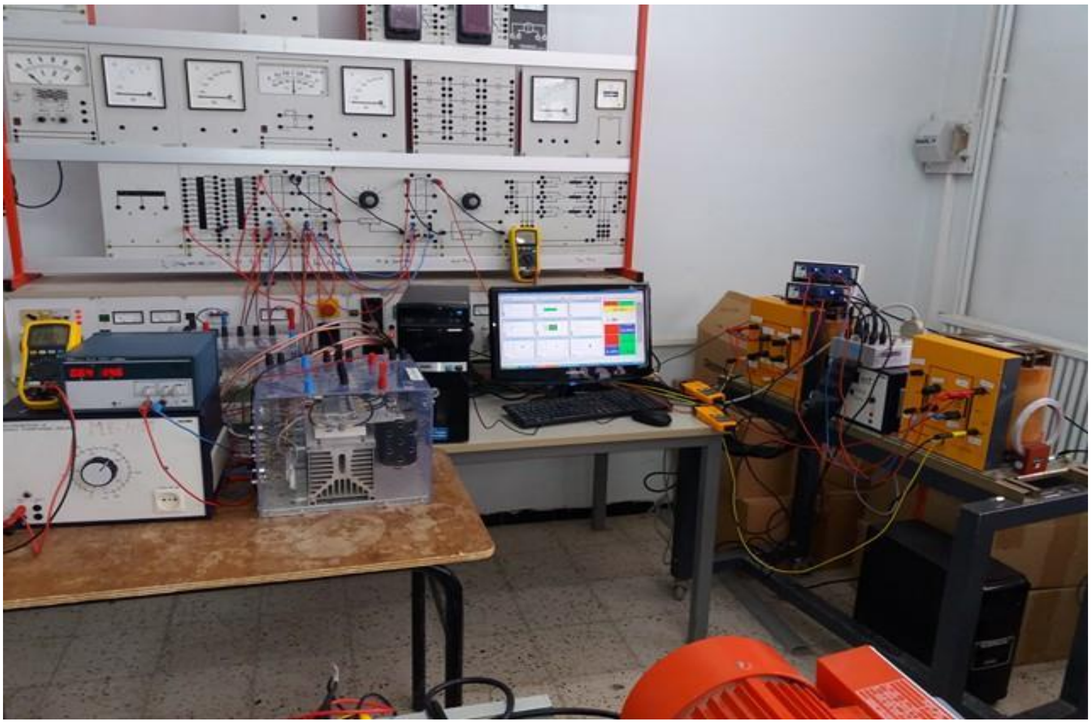
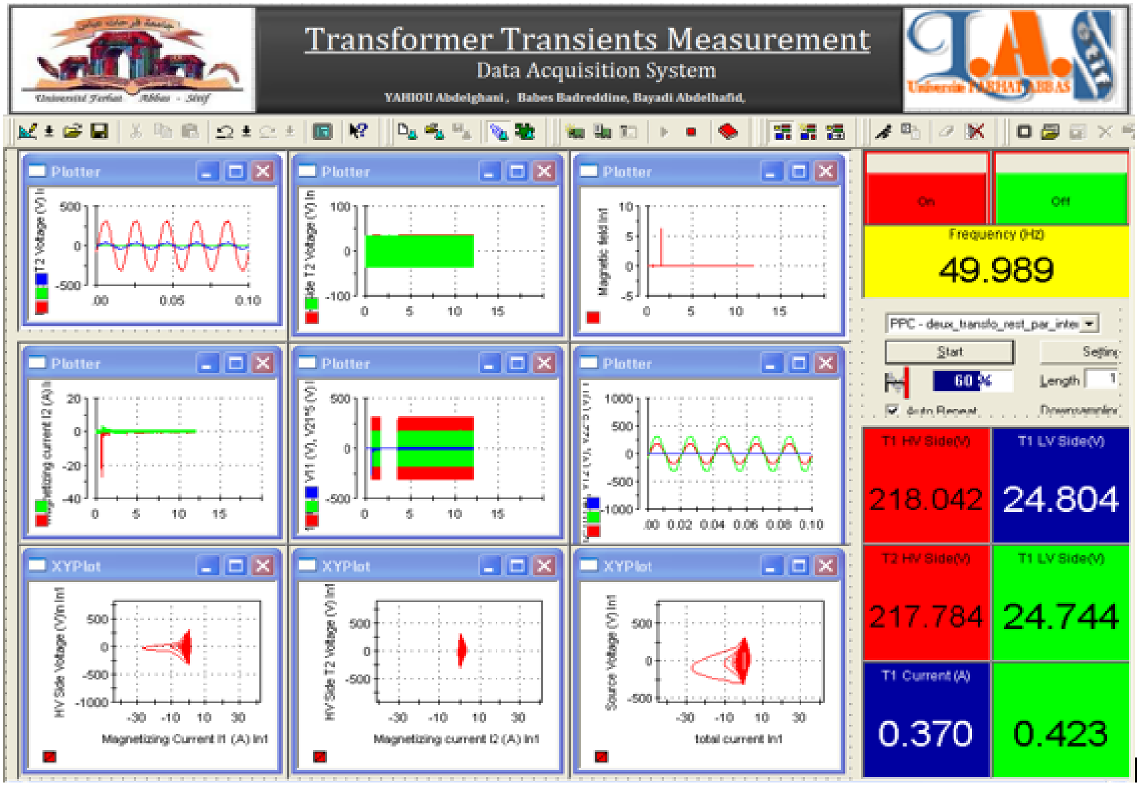


Figure 4. Laboratory setup for data measurement.

To visualize the different signals and acquisition values, an interface is created in the PC as shown in figure 5.



Transformer Transients Measurement

Data Acquisition System

YAHIOU Abdelghani , Babes Badreddine, Bayadi Abdelhafid,

Frequency (Hz) 49.989

PPC - deux_transfo_rest_par_inte

60 %

☑ Auto Repeat

T1 HV Side(V) 218.042

T1 LV Side(V) 24.804

T2 HV Side(V) 217.784

T1 LV Side(V) 24.744

T1 Current (A) 0.370

0.423

Figure 5. Data acquisition interface.

Simulation of Load Influences on Hysteresis Loop

The study of this paper consists of carrying out numerical simulations for a 2 kVA transformer, i.e. nonlinear phenomenon, which is supplied with a voltage of 220V, as shown in figure 6. The elaborated model in an electrical circuit to observe the behaviour of the transformer is implemented for both next cases:

First Case: Unloaded Transformer

The goal is to visualize the hysteresis cycle of a 2 kVA transformer without load (no-load) and its waveform for transient and steady state. Figure 6 shows the simulation block under ATPDraw software, which contains a sinusoidal power supply, a transformer, the magnetizing branch which includes a nonlinear inductance and resistance (its characteristics are those of Figure 2 and 3 respectively) and the series elements of the transformer.

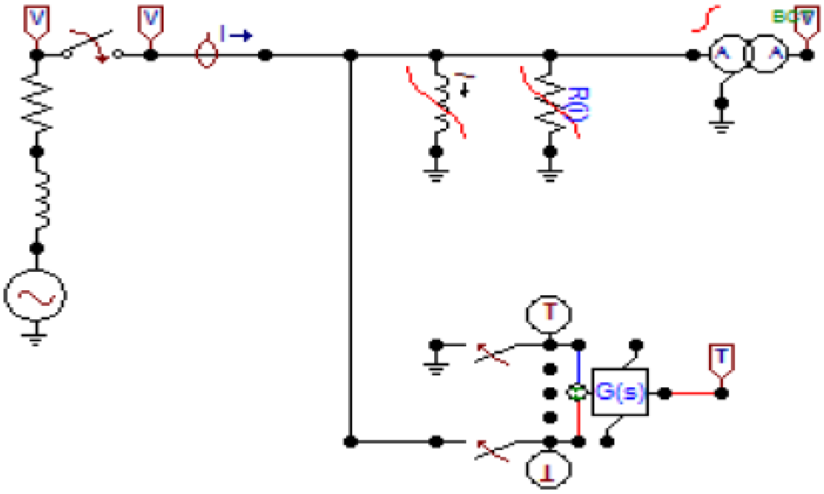


Figure 6. ATPDraw simulation diagram for unloaded transformer.

In steady state, when using a voltage source at the primary of the test transformer with the secondary in open circuit, we obtain the magnetizing current waveform presented in Figure 7.

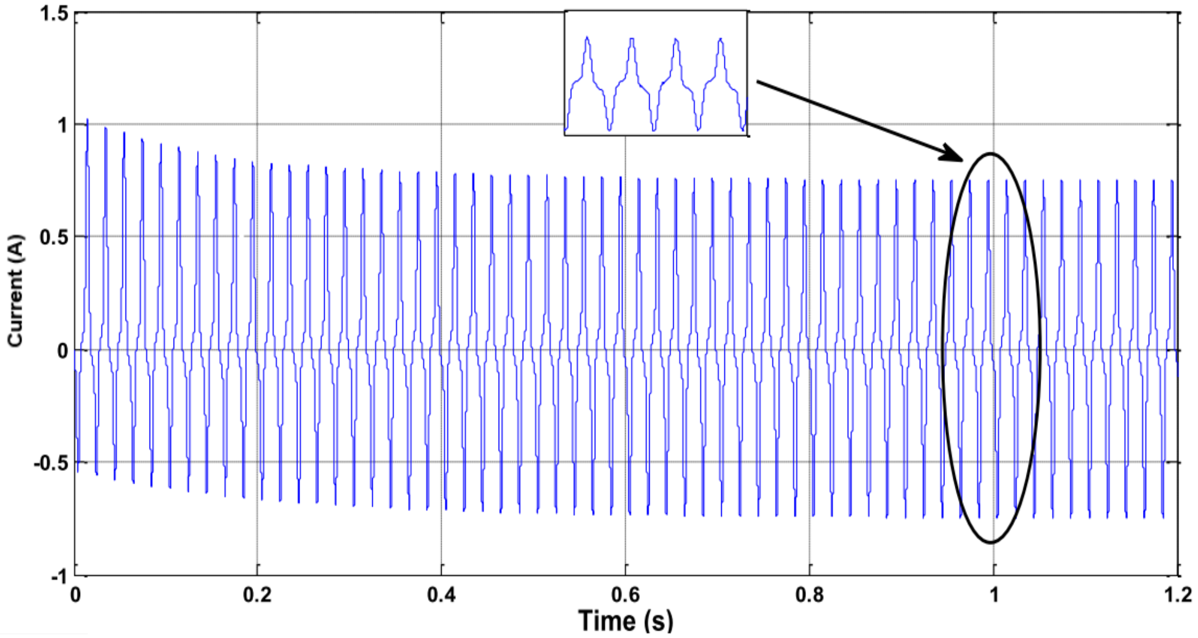


Figure 7. Magnetizing current for steady state with unloaded transformer.

Noting that the current waveform in the no-load steady state is non-sinusoidal distorted due to harmonics caused by the transformer core nonlinearity. In transient regime (using the circuit breaker), when using a voltage source at the primary of the test transformer with the secondary in open circuit, we obtain the simulated transient inrush current waveform presented in Figure 8.

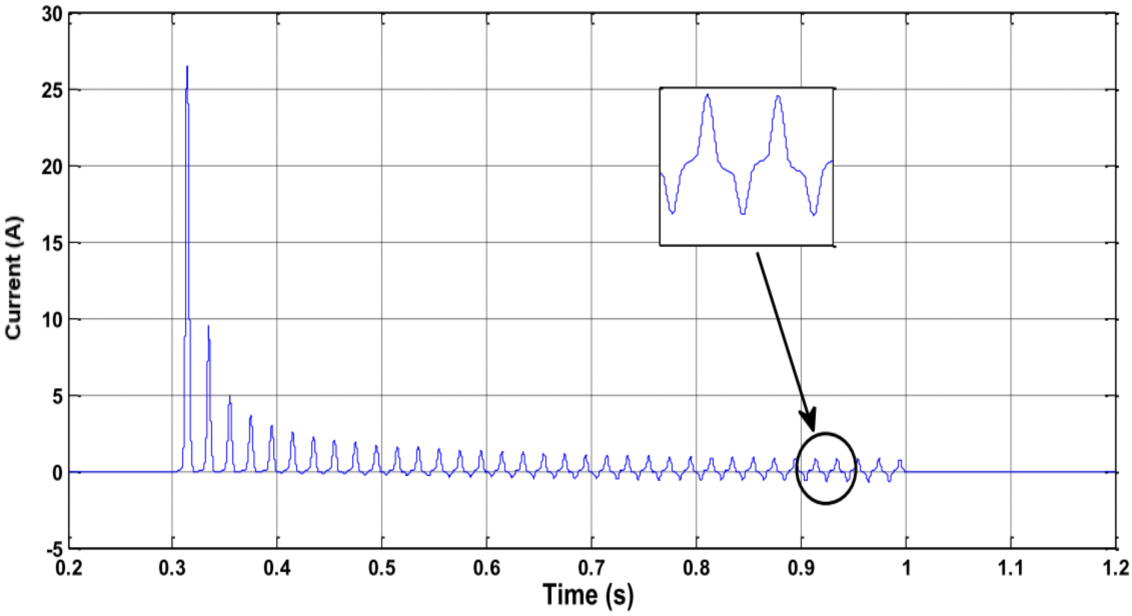


Figure 8. Transient inrush current for unloaded transformer

An important observation is that the inrush current during the transient regime has much higher peaks compared to the magnetizing current in the steady state. These simulations highlight the non-sinusoidal waveforms of the currents during the transient regime, as well as during the steady state for the unloaded transformer, due to the presence of harmonics. These harmonics are the result of the non-linear behavior of the transformer magnetic circuit. Figure 09 shows the hysteresis loop in steady state for a 2 kVA unloaded transformer, this cycle is the variation of the flux as a function of the magnetizing current.

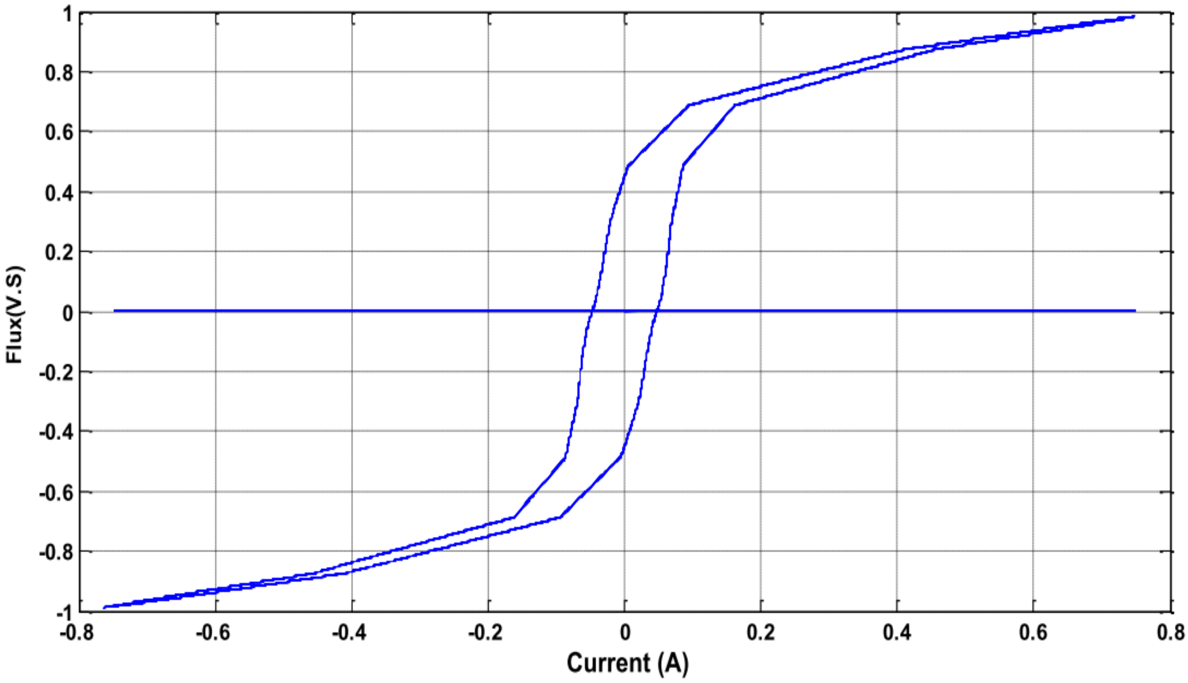
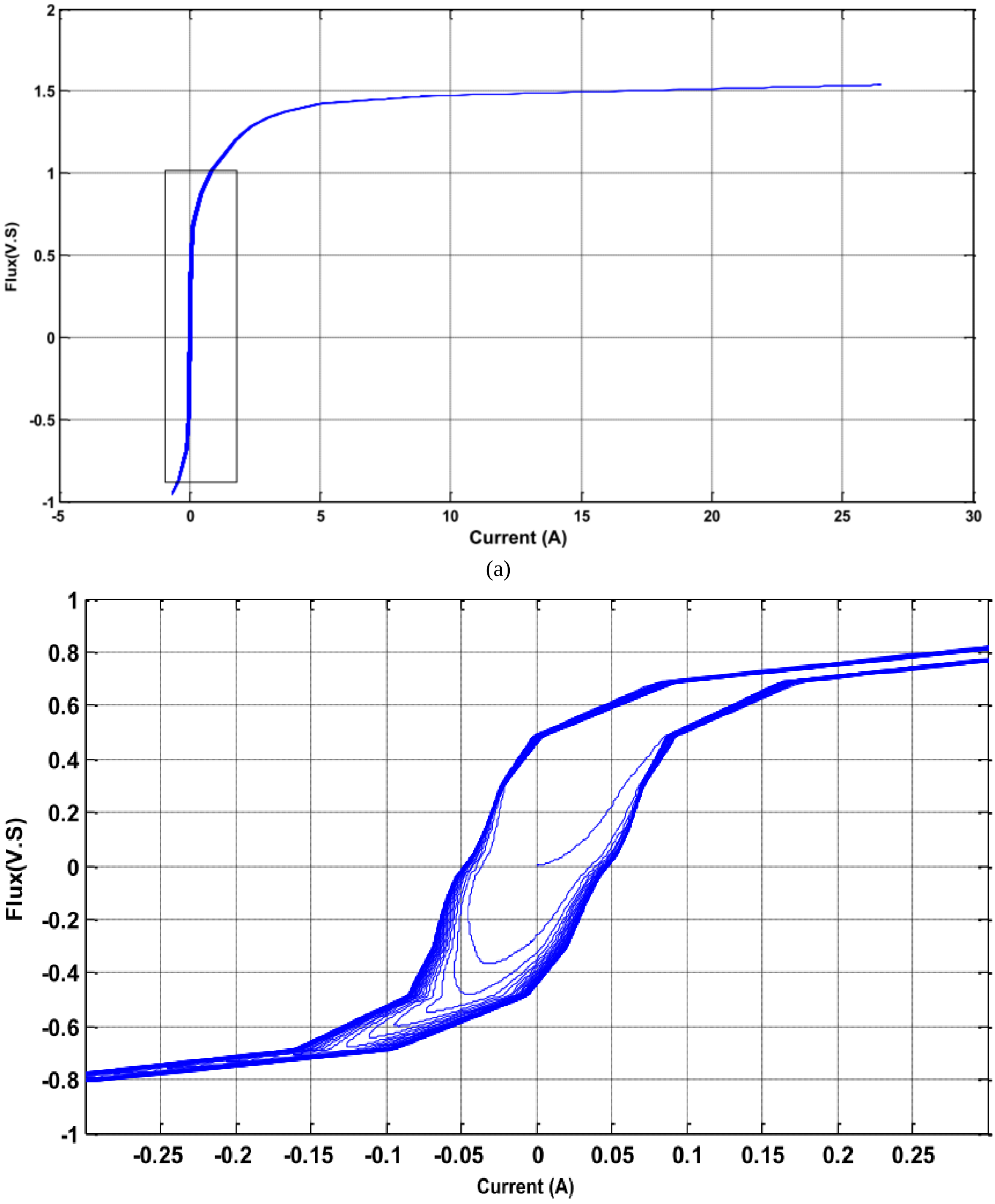


Figure 9. Hysteresis loop in steady state for unload transformer.

Figure 10 shows the hysteresis loop in transient regime for a 2 kVA unloaded transformer, this cycle is the variation of the flux as a function of the magnetizing current.



(a)

(b)

Figure 9. Hysteresis loop in transient regime for unload transformer.
(a) Total hysteresis loop (b) Zoom for hysteresis loop

Second Case: Loaded transformer

The aim is to apply different loads with different values to observe the influence of this variation on the transformer hysteresis loop in transient regime. Figure 10 shows the simulation block under ATPDraw software, which contains a sinusoidal power supply, a transformer, the magnetizing branch which includes a nonlinear inductance and resistance (its characteristics are those of Figure 2 and 3 respectively) and the series elements of the transformer. Here the resistive load is added to the secondary of the transformer.

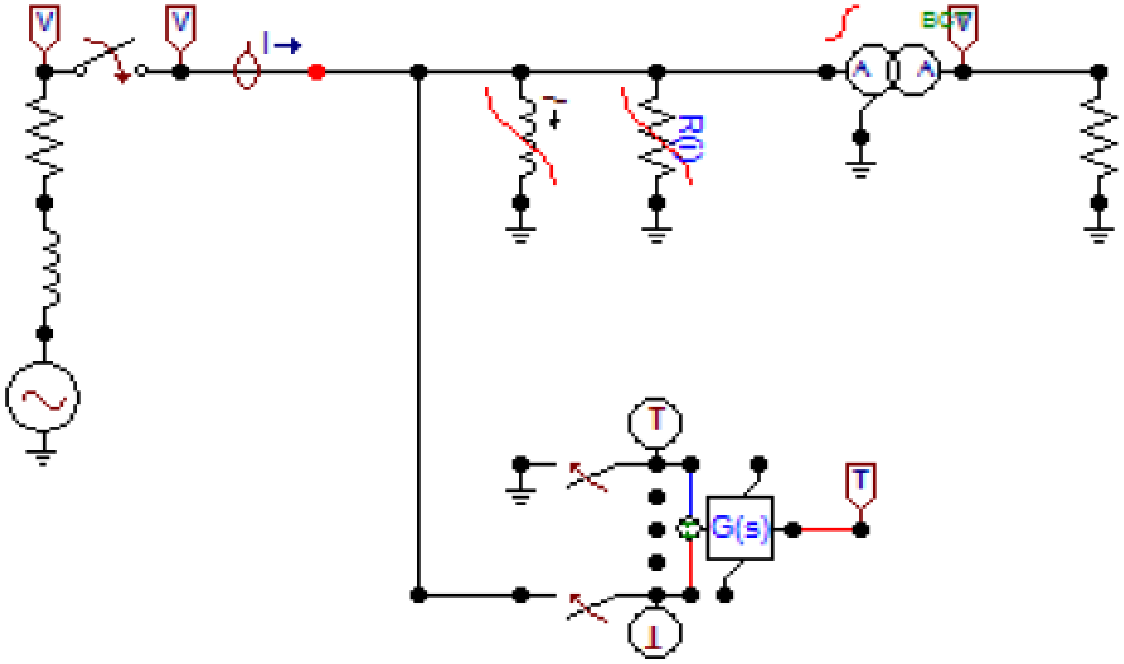


Figure 10. ATPDraw simulation diagram for loaded (resitiance) transformer.

Figure 11 shows a comparison between the current waveforms and their values in the transient and steady state after applying a resistive load with different values (the nominal load multiplied by 0.5, 0.8 and 1.2).

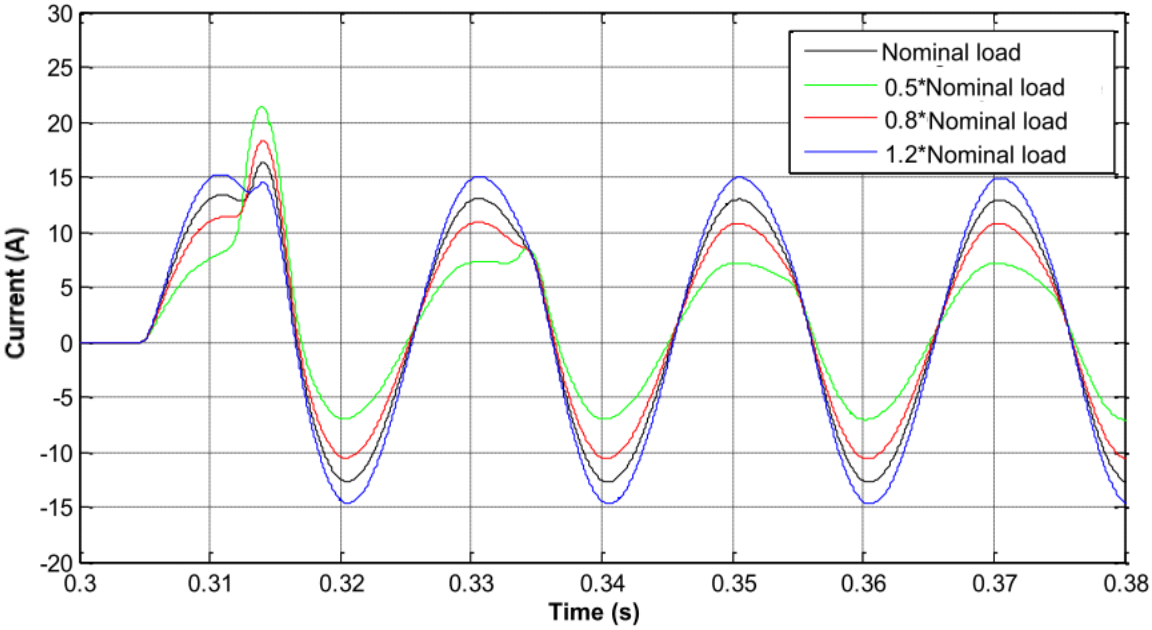


Figure 11. Primary current waveform with a resistive load.

- If the load is at nominal value, the peak inrush current in transient state is 16.37 A, and 12.87 A in steady state.
- If the load is 50 % of the nominal load value, the peak current in transient state equal to 21.39 A, and 7.128 A in steady state.
- If the load is 80 % of the nominal load value, the peak current in transient state equal to 18.35 A, and 10.72 A in steady state.
- If the load is 120 % of the nominal load value, the peak current in transient state equal to 15.25 A, and 14.86 A in steady state.

Figure 12 shows the hysteresis loop waveform for purely resistive load in transient operation.

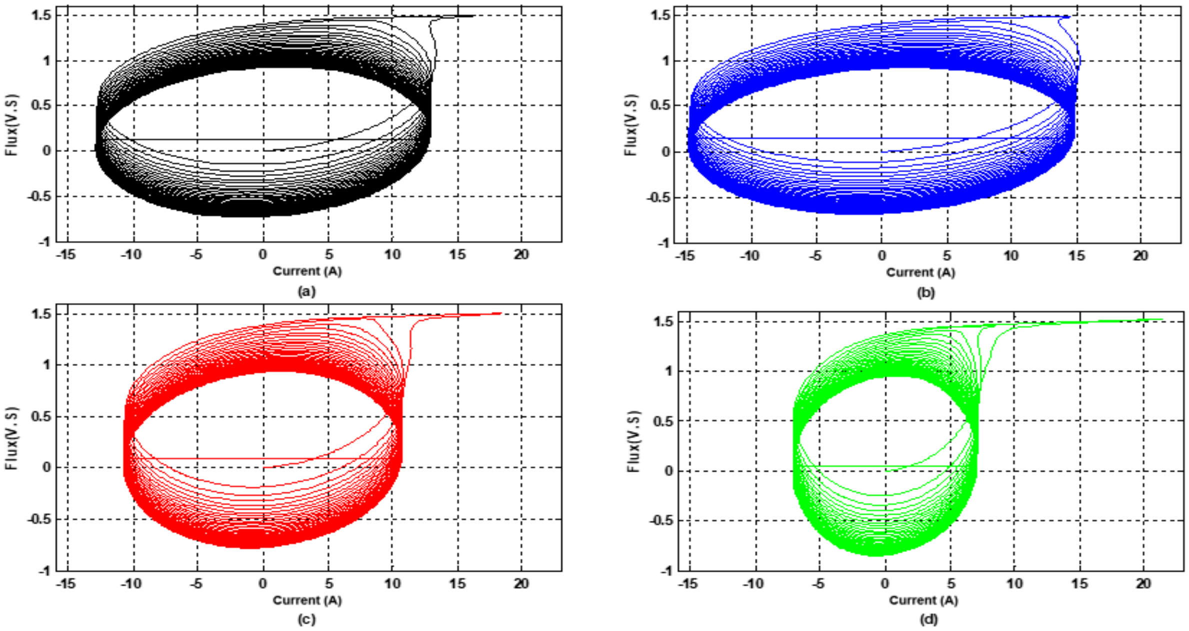


Figure 12. Hysteresis loop of 2 kVA transformer for resistive load.
(a) Nominal load value. (b) 120 % of the nominal load value.
(b) 80 % of the nominal load value. (d) 50 % of the nominal load value.

Since the aim is to observe the hysteresis loop during the appearance of transient inrush current, it was sufficient to show only three cycles of hysteresis loop (Figure 13).

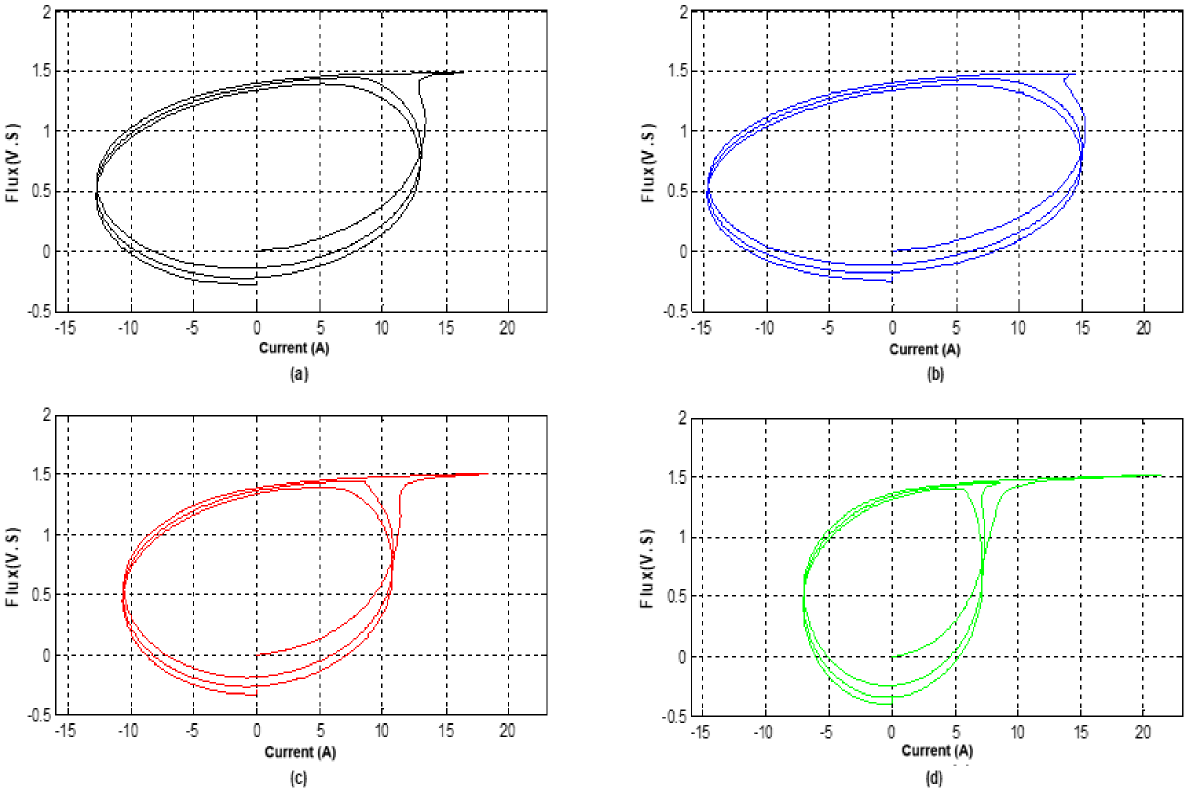


Figure 13. Hysteresis loop of 2 kVA transformer for resistive load (three cycles).
(a) Nominal load value. (b) 120 % of the nominal load value.
(c) 80 % of the nominal load value. (d) 50 % of the nominal load value.

1. Nominal load

The distorted hysteresis cycle with a positive saturation phase follows the inrush current peak (16.37A) corresponding to a flux value (1.49 V.s)

2. 120% of the Nominal load value

The distorted hysteresis cycle with a positive saturation phase follows the inrush current peak (15.25A) corresponding to a flux value (1.4851 V.s)

3. 80% of the Nominal load value

The distorted hysteresis cycle with a positive saturation phase follows the inrush current peak (18.35A) corresponding to a flux value (1.5044 V.s)

4. 50% of the Nominal load value

The distorted hysteresis cycle with a positive saturation phase follows the inrush current peak (21.39A) corresponding to a flux value (1.5173 V.s)

By applying different values of the resistive load (100%, 120%, 80% and 50%), it is clear that each time the load value is reduced, the transient regime increases, resulting in a decrease in the cycle area. The simulation results show that the value of the resistive load has an influence on the surface and the positioning of the hysteresis cycle according to the origin. This suggests that the transformer load has a direct influence on the hysteresis cycle waveform.

Conclusion

The work presented in this article makes a study on the influence of the load on the hysteresis loop of a 2 kVA transformer. To visualize this influence it is necessary to identify the transformer parameters and determine the iron core characteristics. Using the ATPDraw program, the simulations results are extracted with adding the resistive load at their nominal value, and for some percentage (120%, 80% and 50%). The results show that it is clear that the load directly affects the hysteresis cycle, and this is explained by the restriction and the shift of the hysteresis cycle caused by the load, this relationship results in a decrease in the surface and a displacement of the hysteresis cycle following the decrease in the load. The results of these simulations show that the value of the load driven has an influence on the surface and the positioning of the hysteresis cycle. The results of the simulation carried out in this styudy show that each time the value of the load is increased there is a decrease in the surface of the hysteresis cycle. This study can complement by the following perspectives:

- It would be interesting to apply the results of this study in a laboratory environment in order to perform experiments and compare the simulation results with the experimental results. This would allow to validate the models and methods used, as well as to identify possible differences or errors.
- The obtained results could have extrapolated and applied to larger power transformers, which would be of great interest in the field of large-scale power system engineering.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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