Effects of Inrush Current on the Hysteresis Loop and Load Influences on the Transient Current of a Single-Phase Transformer

Abdelghani Yahiou
Automatic Laboratory of Sétif (LAS)
Department of Electrical Engineering
University of Bouira
Bouira, Algeria
abdelghani.yahiou@univ-bouira.dz

Hacene Mellah
Automatic Laboratory of Sétif (LAS)
Department of Electrical Engineering
University of Bouira
Bouira, Algeria
h.mellah@univ-bouira.dz

Abdelhafid Bayadi
Automatic Laboratory of Sétif (LAS)
Department of Electrical Engineering
University of Sétif-1
Sétif, Algeria
a_bayadi@univ-setif.dz

Mokhtar Abid
Department of Automatic and Electrical Engineering
University of Blida-1
Blida, Algeria
oussama.electrotechnique@gmail.com

Received: 15 July 2022 | Revised: 4 August 2022 | Accepted: 7 August 2022

Abstract-When putting any unloaded transformer into service, a high-value current that can be very dangerous, called the inrush current, appears. The latter may cause problems and consequences in the electrical system. The challenges of visualizing the effects of transient regimes on the iron core's characteristics and the influence of the type of load on inrush current characteristics are covered in this study. The main purpose of this paper is to treat the influence of this transient phenomenon on the hysteresis loop of a single-phase transformer, in terms of its size, area, or position, and therefore, the influence of the load on the transient regime. A general study of the electromagnetic characteristics of the transformer iron core will be presented. Then, using the ATP-EMTP program, the purpose of the realized simulations is to visualize the relationship between the hysteresis loop and the magnetizing inrush current in the transient state. The results show the decrease of the hysteresis loop area and their shift with respect to the origin of the axes following the increase in the transient inrush current peak. As the second part of this article, there is a study of the influence of the load on the transient regime, i.e. inrush current. This is accomplished by adding a load with different configurations and various connections. The purpose is to find the effect of the load on the reduction of the transient inrush current phenomenon.

Keywords-transformer; inrush current; transient regime; hysteresis loop; load influence; ATP-EMTP

I. INTRODUCTION

Inrush current is caused by the saturation of a power transformer due to variations in the magnetization voltage [1, 2]. When an unloaded transformer is energized, a transient phenomenon called inrush current may appear in the excited circuit side. Therefore, necessary research 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 [3-5], 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, there is the technique proposed in [6], in which four different methods to reduce the inrush current were compared. The required result is 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 [7, 8] consist pioneering work, simulation, and measurements, in the area of inrush current reduction in three- and single- phase transformers. 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. Authors in [9] utilized 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 in [10-13] introduce a resistance between the ground and the transformer neutral. Authors in [14], while taking into account the switching moment, used the reversed flux technique to investigate the reduction of the inrush current using an existed photovoltaic generator. The idea proposed in [15], is in the

Corresponding author: Abdelghani Yahiou

same context with what was accomplished in [10-13], where the residual flux is taken into account, and a controlled circuit breaker is used to isolate the neutral of the three-phase transformer with respecting of the three phases sequential. Authors in [16] 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. Authors in [17] depended on formal methods to solve differential equations based on the equivalent circuit represented using the state space equation. Authors in [18] 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 in [19] is the application of a technique 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 [20] to mitigate also this sympathetic inrush current. Authors in [21] presented an important technique in the field of inrush current mitigation, especially by using renewable energies, where the reverse flux is applied. Authors in [22] presented a review of some factors which affect the resistance during breakdown of transformer oil. Authors in [23] exposed a generator differential protection relay system, its disadvantages and its advantages. In [24], a real power transformer was used in the experiments, and a UHF-PD detection system was built.

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 [25]. Holcomb in [5] is considered among the first who raised the idea of the inrush current calculation, but without going far. The author 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 [25], the authors used a developed model to estimate the inrush current and hysteresis loop. However, they did not make a comparison between the relationships of the position of the hysteresis loop wave according to the corresponding inrush current. The same weakness was observed in [26, 27], where the authors estimated the saturation curve from the inrush current waveform. This major drawback of these previous works has been studied and dealt with in the present work, where the comparison has been made between different effects of transformer energization on the nature of the iron core. Authors in [28] exploited a real model of a transformer to study different phenomena such as the application of the nonlinear load. However, limited their study to the load effects on the steady-state regime.

The first part of this paper is devoted to the study of the transient inrush current effect on the hysteresis loop of a transformer. Therefore, a quick rundown is presented on how to identify the equivalent circuit parameters for the used transformer and the iron core magnetizing characteristic (air core-inductance). Then, a simulation using ATP-EMTP program is performed using the nonlinear Type 98 inductance and the nonlinear Type 92 resistance, as well as the system that measures the hysteresis cycle (flux-current). Finally, the presented simulation results show the variation of the area of the hysteresis cycle and the shift of this loop according to the increase and decrease of the inrush current peak. A comparison is made with respect to the hysteresis cycle in the steady state. The next part is devoted to the study of the load insertion effect on the transient inrush current of a transformer. Simulation is done using the same model and the same transformer characteristics, only a load with different values of impedance and different connections is added in the secondary side. The simulation results show the variation of the inrush current waveforms with the application of deferent types of loads.

II. Materials and Methods

This section is devoted to a presentation of the real transformer used in the simulation, the identification of the parameters of its equivalent circuit, and the representation of the model with nonlinear parameters. The single-phase transformer (Figure 1) used in the simulations of this paper is manufactured by the company DELORENZO, Italy and is available at the Laboratory of the Power System, University of Sétif 1. All the experimental tests of this paper were carried out in this laboratory. Table I shows some parameter values of the used transformer. The parameters of the transformer equivalent circuit obtained by applying the classical equations are presented in Table II. The study of any transformer transient regime such as ferro-resonance and inrush current requires careful modeling of the iron core nonlinearities and precision in the equivalent circuit parameters of the transformer determination.

Fig. 1. The used transformer.

TABLE I. TEST TRANSFORMER NAMEPLATE DATA.

Power (VA)	Frequency (Hz)	Phase	Voltage ratio (kV)	Turn (tr)	Current Ratio (A)	Class (isolated)
2000	050	01	0.22/0.025	0330/0037	9.10/080	E

TABLE II. TRANSFORMER PARAMETERS

Parameter	Value
Shunt resistance R_m	2847.05Ω
Shunt reactance X_m	609.72Ω
Equivalent resistance $R_{éq}$	3.48Ω
Equivalent reactance $X_{éq}$	2.69Ω

A. Nonlinearities of the Iron Core

The representation of the transformer model with linear resistors and inductances does not reflect the actual behavior of the electrical transformer. So, the effects of hysteresis and saturation must be introduced using non-linear branch elements. Figure 2 shows the saturation curve $\lambda = f(i_l)$ which represents the air core inductance. The nonlinear resistance characteristic $v = f(i_{lr})$ is depicted in Figure 3. Both figures use the data of [1].

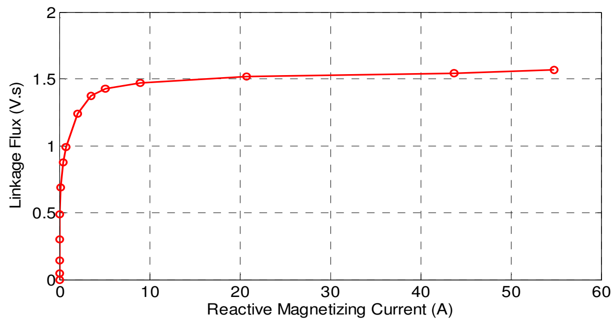

Fig. 2. Air core inductance characteristic $\lambda = f(i_l)$ [1].

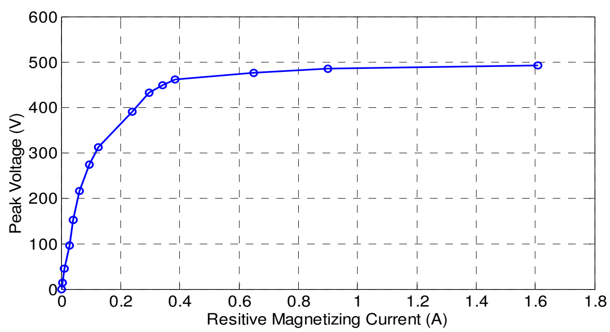

Fig. 3. Nonlinear resistance characteristic $\lambda = f(i_r)$ [1].

The curves of Figures 2 and 3 are computed by the method based on the improved technique presented in [20, 29], and they have been inserted in the transformer models (saturable) found in ATP-EMTP program to simulate the effect of the inrush current phenomenon on the hysteresis loop.

B. Residual Flux

Residual flux plays a basic role in the occurrence of inrush current in an unloaded transformer. It represents a continuous flux value that persists in the magnetic circuit, which can generate an inrush current after switching off if the transformer is not completely demagnetized [30, 31]. The instantaneous equation for flux in the iron core is:

$$\lambda_{core}(t) = \lambda_R + \int_{t_{close}}^{t} u_{coil}(t)dt$$
$$\lambda_{core} = -\lambda_{max}\cos(\omega * t) + \lambda_{max}\cos(\omega * t_{close}) + \lambda_R \quad (1)$$

C. Simulation of the Influence of the Inrush Current on the Hysteresis Loop

In this section, the simulation and the results will be presented in detail. Figure 4 shows the simulation diagram using the ATP-EMTP program to visualize the influence of the transient inrush current on the hysteresis loop.

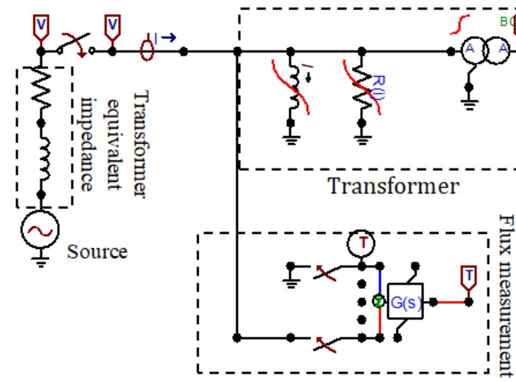

Fig. 4. Simulation diagram.

III. RESULTS

A. Steady State

In the steady state, a voltage source is placed in the primary of the test transformer while the secondary is unloaded. The obtained simulated magnetizing current curve is shown in Figure 5 and the corresponding hysteresis loop curve is shown in Figure 6.

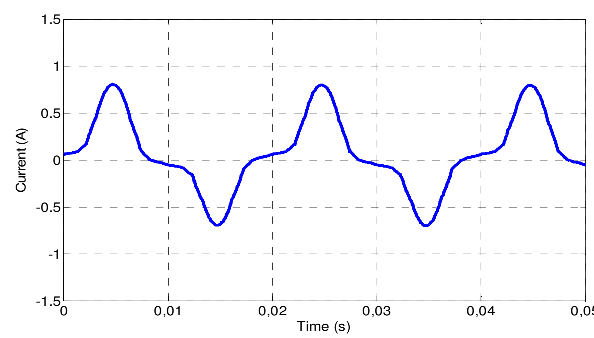

Fig. 5. Unloaded steady state current waveform.

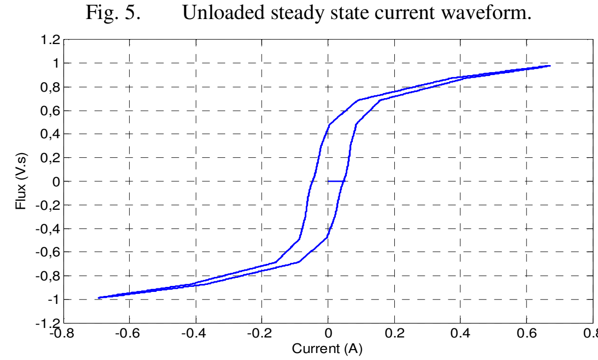

Fig. 6. Unloaded steady state hysteresis loop.

It should be noted that the current waveform in the no-load state is distorted non-sinusoidal due to the harmonics caused by the non-linearity of the transformer core. Figure 6 represents the variation of the flux as a function of current in the unloaded test. It should be noted that the hysteresis loop is symmetrical with respect to the origin of the reference. The surface occupied by this loop is approximately bounded from -1.2 to 1.2A and beyond this interval we enter the saturation phase. This area represents the losses in the iron core.

B. Transient Regime (Inrush Current)

In these applications, the simulation time is fixed to 2s, and a controlled circuit breaker is exploited to vary the closing time and see the first peak of the inrush current and its attenuation up to the magnetizing current until reached the steady state. The hysteresis loop corresponding to each closing time of the circuit breaker will be drawn.

1) Closing Time t_f = 0.5808s

When the circuit breaker closes at t_f = 0.5808s, the first peak of inrush current is reached at 2.25A, and continue to decrease until the steady state current, as shown in Figure 7. The hysteresis loop is distorted and asymmetrical with respect to the origin. The saturation phase in the positive part follows the inrush current peak of 2.25A corresponding to a flux value of 1.26V.s. While the current of the negative part does not exceed the value of -0.2A and the flux the value of -0.3V.s. Figure 8 shows the complete hysteresis loop.

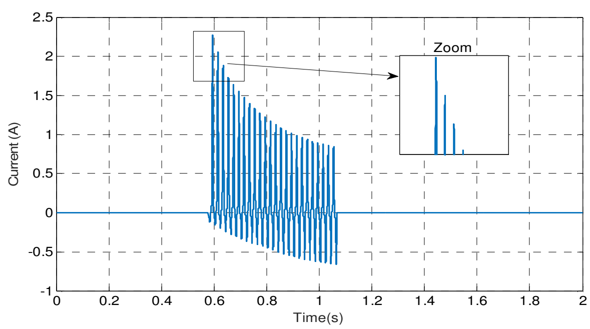

Fig. 7. Transient inrush current for closing timet_f = 0.5808 s.

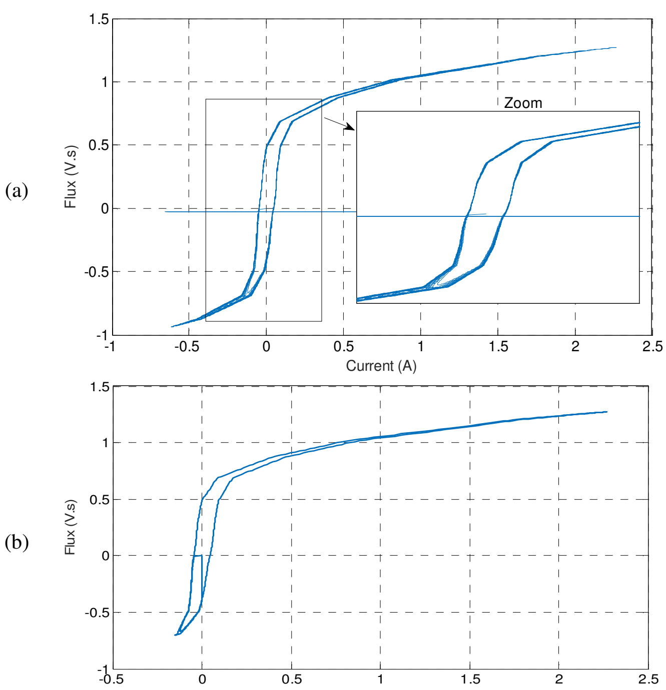

Fig. 8. Hysteresis loop at t_f=0.5808s for (a) several periods, (b) one period.

2) Closing Time t_f = 0.5828s

When the circuit breaker closes at t_f = 0.5828s, the first peak of inrush current is reached at 18.72A and continues to decrease until the steady state current, as shown in Figure 9. The inrush current peak is very large in this application compared to the peak in the first application. This leads the hysteresis loop to withdraw completely to the positive part according to the direction of the inrush current. For the positive part, it follows the inrush current peak of 18.72A corresponding to a flux value of 1.52V.s, while that of the negative part does not exceed the values of -0.03A and -0.38V.s. Figure 10 shows the complete hysteresis loop.

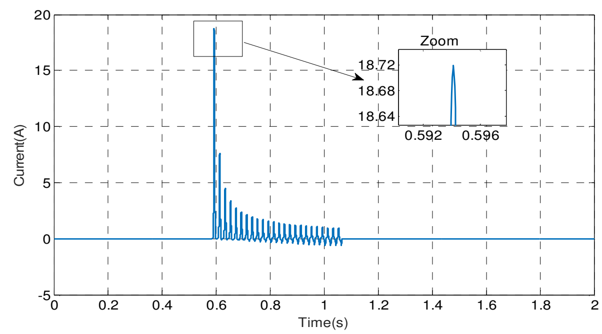

Fig. 9. Transient inrush current for closing time t_f = 0.5828s.

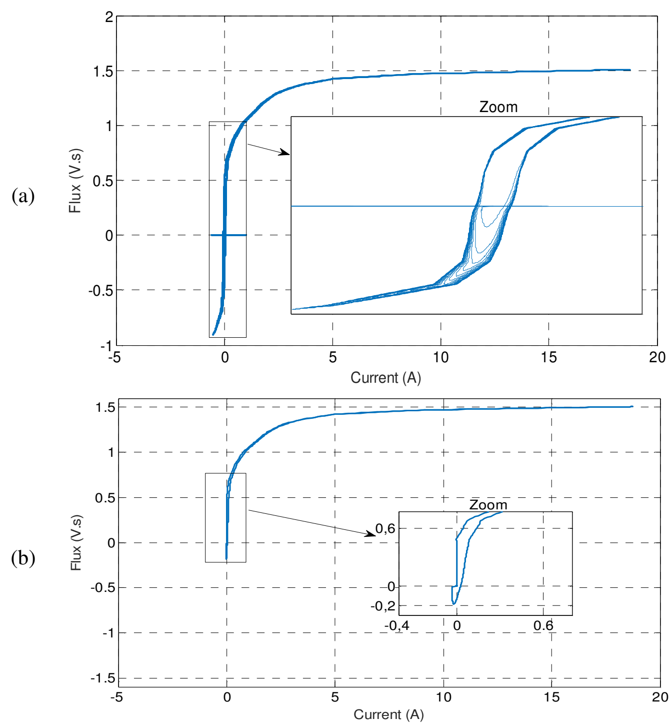

Fig. 10. Hysteresis loop at t_f=0.5828s for (a) several periods, (b) one period.

3) Closing Time t_f = 0.5848s

When the circuit breaker closes at t_f = 0.5848s the first peak of inrush current reached 26.50A and continued to decrease until the steady state current, as shown in Figure 11. When compared to the peak in the previous application, the inrush current peak is considerably large. According to the direction of the inrush current, this causes the hysteresis loop to entirely retreat to the positive part. The inrush current peak of 26.50A, corresponding to a flux value of 1.57V.s, is followed by the positive portion. The negative component, on the other hand, does not surpass the current value of -0.03A and flux value of -0.18V.s. The whole hysteresis loop is shown in Figure 12.

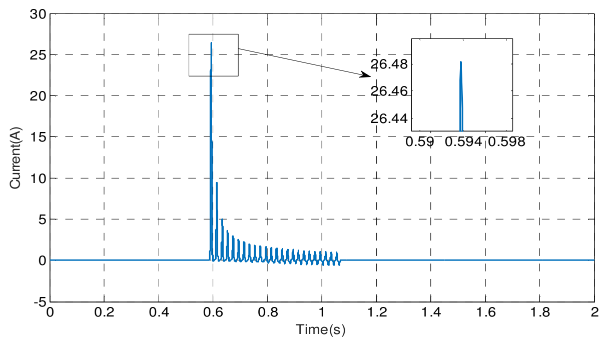

Fig. 11. Transient inrush current for closing time t_f = 0.5848s.

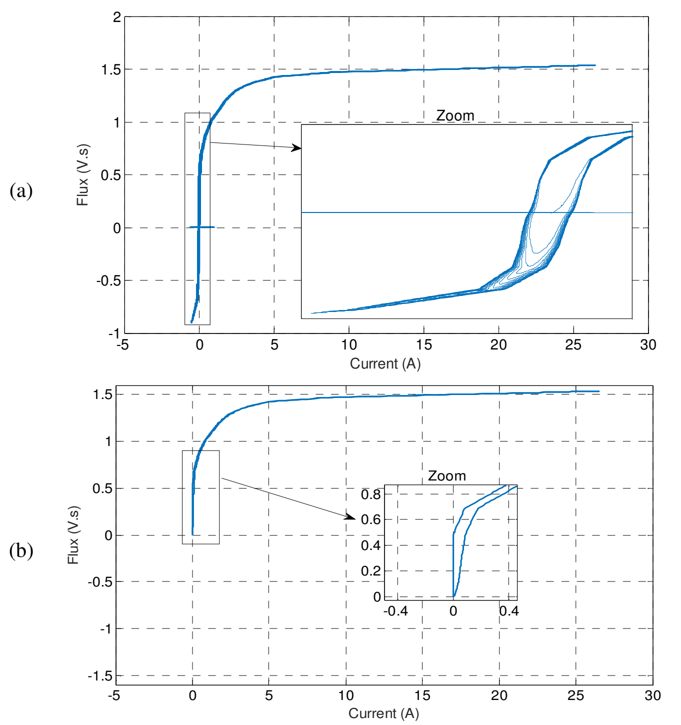

Fig. 12. Hysteresis loop at t_f=0.5848s for (a) several periods, (b) one period.

IV. LOAD EFFECTS ON THE INRUSH CURRENT

The goal is to apply different loads with different values in the secondary side of the transformer to observe the influence of this variation on the transient inrush current phenomenon. The simulation is carried out using the model of Figure 4, and the same transformer characteristics, but with adding load.

A. Resistive Load

In the first application, and after the unloaded operating of the transformer as seen in the first part of this article, a pure resistance load is added in the secondary side. Figure 13 shows a comparison between transient current waveforms with different proportions of resistive load (100%, 50%, and 120% of the nominal resistive load).

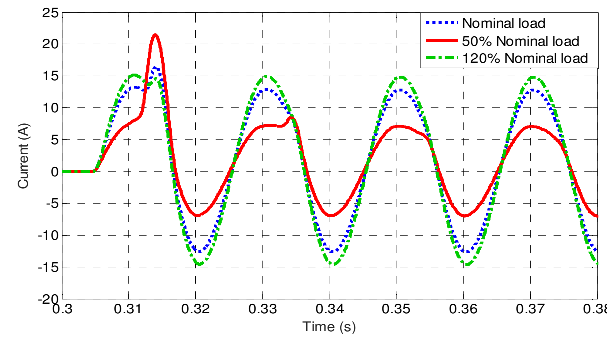

Fig. 13. Primary current waveforms for the resistive load.

B. R-L load

In the second application, a resistance-inductance (R-L) load is added in the secondary side. Figure 14 shows a comparison between transient current waveforms with different proportions of R-L load.

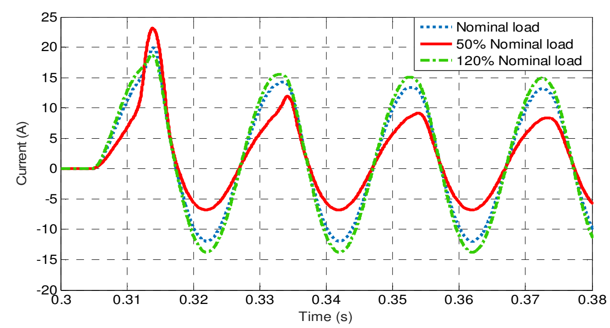

Fig. 14. Primary current waveforms for the R-L load.

C. R-L-C Load

In the last application, a resistance-inductance-capacitance (R-L-C) load is added in the secondary side. Figure 15 shows a comparison between transient current waveforms with different proportions of R-L-C load (100%, 50%, and 120% of the nominal R-L-C load). The values of Figures 13-15 are summarized in Table III.

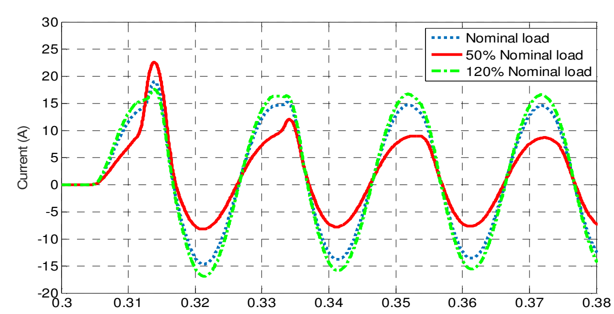

Fig. 15. Primary current waveforms for the R-L-C load.

TABLE III. CURRENT VALUES FOR DIFERENT LOAD VALUES

	Resistive load	R-L load	R-L-C load	
Inrush current first peak (A).	16.48	19.9	18.4	**Nominal load**
Steady state current (A)	12.73	12.04	13.8	
Inrush current first peak (A)	21.45	23.13	22.57	**50% of nominal load**
Steady state current (A)	7.037	6.82	7.9	
Inrush current first peak (A)	15.14	18.70	17.5	**120% of nominal load**
Steady state current (A)	14.74.	14.74	15.79	

V. DISCUSSION

From the obtained results in the first part, it can be concluded that the transient inrush current of the transformer has a direct influence on the hysteresis loop waveform. This impact results in the reduction of the area of this loop according to the increase of the inrush current peak, therefore it can explain the reduced iron core losses with the inrush current appearance. Moreover, there is a withdrawal of the hysteresis loop according to the direction of the transient inrush current, which means that the hysteresis loop shifts towards the value and direction of the peak inrush current.O n the other hand, Figures 13-15 represent the transient currents waveforms when different types of loads at 50% and 120% of the nominal values are inserted. The figures show that the energization of transformer lightly loaded causes transient inrush current almost similar to that of energizing an unloaded transformer. Moreover, the energization of a highly loaded transformer causes transient inrush current much less to that acquired after energizing an unloaded transformer .The above applications, by adding load in its various forms and values, prove that a decrease in the load leads to an increase in the transient inrush current. On the other hand, the current in the steady state (after removing the transient regime) is proportional to the value of the load. In the unloaded test, when the current waveform takes its permanent regime, it was not sinusoidal. However, adding load leads to the return of the sinusoidal waveform after crossing the transient regime. These simulations prove that the transformer loading decreases the amplitude of the transient inrush current. So, it can be concluded that the inrush current exists only at energization of an unloaded or lightly.

VI. CONCLUSION

This work is concerned with the visualization of the effect of transient regimes on the characteristics of the iron core, as well as the influence of the load on the inrush current characteristics. In the present paper, a summary of the parameter identification method of the transformer equivalent circuit has been presented and a magnetizing characteristic representing the transformer iron core has been illustrated. Parameter identification was achieved using classical tests such as open circuit and short-circuit. A simulation using ATP-EMTP was performed using the Type 98 nonlinear inductance and the Type 92 nonlinear resistance, and a system that measures the hysteresis cycle (flux-current). Finally, the simulation results were presented and show the variation of the area of the hysteresis cycle and the shift of this loop according to the increase and decrease of the inrush current peak. The comparison was conducted with respect to the hysteresis cycle in steady state. Energizing an unloaded transformer causes transients at large amplitudes, with the effect of the non-linear behavior of the magnetic circuit on the current waveform occurring in this mode of operation. Increasing the load value decreases the transient regime. Therefore, the application of the load restores the sinusoidal waveform of the steady state current. Regarding future research, we intend to concentrate on experiments in order to confirm the present simulation results and to adopt this approach to large power transformers.

REFERENCES

[1] A. Yahiou, "Contribution a l'etude et a l'analyse du regime transitoire dans les transformateurs de puissance : cas du courant d'appel," M.S. thesis, Universite Ferhat Abbas de Setif, Setif, Algeria, 2012.

[2] A. Yahiou, A. Bayadi, and B. Babes, "Point on Voltage Wave Switching for Sympathetic Inrush Current Reduction," in *International Conference on Applied Smart Systems*, Medea, Algeria, Nov. 2018, pp. 1–4, https://doi.org/10.1109/ICASS.2018.8651972.

[3] G. Bertagnolli, *The ABB Approach to Short-circuit Duty of Power Transformers*. Zurich, Switzerland: ABB, 2007.

[4] T. R. Specht, "Transformer Magnetizing Inrush Current," *Transactions of the American Institute of Electrical Engineers*, vol. 1, no. 70, pp. 323–328, 1951, https://doi.org/10.1109/T-AIEE.1951.5060409.

[5] J. E. Holcomb, "Distribution Transformer Magnetizing Inrush Current," *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*, vol. 80, no. 3, pp. 697–702, Apr. 1961, https://doi.org/10.1109/AIEEPAS.1961.4501117.

[6] R. Cano-Gonzalez, A. Bachiller-Soler, J. A. Rosendo-Macias, and G. Alvarez-Cordero, "Controlled switching strategies for transformer inrush current reduction: A comparative study," *Electric Power Systems Research*, vol. 145, pp. 12–18, Apr. 2017, https://doi.org/10.1016/j.epsr.2016.11.018.

[7] J. H. Brunke and K. J. Frohlich, "Elimination of transformer inrush currents by controlled switching. I. Theoretical considerations," *IEEE Transactions on Power Delivery*, vol. 16, no. 2, pp. 276–280, Apr. 2001, https://doi.org/10.1109/61.915495.

[8] J. H. Brunke and K. J. Frohlich, "Elimination of transformer inrush currents by controlled switching. II. Application and performance considerations," *IEEE Transactions on Power Delivery*, vol. 16, no. 2, pp. 281–285, Apr. 2001, https://doi.org/10.1109/61.915496.

[9] C.-K. Cheng, T.-J. Liang, J.-F. Chen, S.-D. Chen, and W.-H. Yang, "Novel approach to reducing the inrush current of a power transformer," *IEE Proceedings - Electric Power Applications*, vol. 151, no. 3, pp. 289–295, May 2004, https://doi.org/10.1049/ip-epa:20040223.

[10] S. J. Arand, M. Saeedi, and S. Masoudi, "Transformer Inrush Current Mitigation Using Controlled Switching and Magnetic Flux Shunts," *International Journal of Energy and Power Engineering*, vol. 2, no. 2, pp. 46-53, Apr. 2013, https://doi.org/10.11648/j.ijepe.20130202.13.

[11] S. G. Abdulsalam and W. Xu, "A Sequential Phase Energization Method for Transformer Inrush Current Reduction—Transient Performance and Practical Considerations," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 208–216, Jan. 2007, https://doi.org/10.1109/TPWRD.2006.881450.

[12] H. A. Abdelsalam and A. Y. Abdelaziz, "A New Strategy for Selection of Switching Instant to Reduce Transformer Inrush Current in a Single-phase Grid-connected Photovoltaic System," *Electric Power Components and Systems*, vol. 43, no. 11, pp. 1297–1306, Jul. 2015, https://doi.org/10.1080/15325008.2015.1027424.

[13] Y. Cui, S. G. Abdulsalam, S. Chen, and W. Xu, "A sequential phase energization technique for transformer inrush current reduction - Part I: Simulation and experimental results," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 943–949, Apr. 2005, https://doi.org/10.1109/TPWRD.2004.843467.

[14] W. Xu, S. G. Abdulsalam, Y. Cui, and X. Liu, "A sequential phase energization technique for transformer inrush current reduction - Part II: theoretical analysis and design guide," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 950–957, Apr. 2005, https://doi.org/10.1109/TPWRD.2004.843465.

[15] R. Cano-Gonzalez, A. Bachiller-Soler, J. A. Rosendo-Macias, and G. Alvarez-Cordero, "Inrush current mitigation in three-phase transformers with isolated neutral," *Electric Power Systems Research*, vol. 121, pp. 14–19, Apr. 2015, https://doi.org/10.1016/j.epsr.2014.11.031.

[16] S. Schramm, C. Sihler, and S. Rosado, "Limiting Sympathetic Interaction Between Transformers Caused by Inrush Transients," in *International Conference on Power Systems Transients*, Delft, Netherlands, Jun. 2011.

[17] U. Rudez and R. Mihalic, "Sympathetic inrush current phenomenon with loaded transformers," *Electric Power Systems Research*, vol. 138, pp. 3–10, Sep. 2016, https://doi.org/10.1016/j.epsr.2015.12.011.

[18] J. Pontt, J. Rodriguez, J. San Martin, and R. Aguilera, "Mitigation of Sympathetic Interaction between Power Transformers Fed by Long over Head Lines Caused by Inrush Transient Currents," in *IEEE Industry Applications Annual Meeting*, New Orleans, LA, USA, Sep. 2007, pp. 1360–1363, https://doi.org/10.1109/07IAS.2007.211.

[19] A. Yahiou, A. Bayadi, and B. Babes, "Mitigation of Sympathetic Inrush Current in Transformer Using the Technique of Point on Voltage Wave Control Switching," in *International Conference on Communications and Electrical Engineering*, El Oued, Algeria, Dec. 2018, pp. 1–6, https://doi.org/10.1109/CCEE.2018.8634501.

[20] A. Yahiou, A. Bayadi, and B. Babes, "Modified method for transformer magnetizing characteristic computation and point-on-wave control switching for inrush current mitigation," *International Journal of Circuit Theory and Applications*, vol. 47, no. 10, pp. 1664–1679, 2019, https://doi.org/10.1002/cta.2682.

[21] H. A. Abdelsalam, A. Ahmed, and A. Y. Abdelaziz, "Mitigation of Transformer Inrush Current Using PV Energy," *Recent Advances in Communications and Networking Technology (Discontinued)*, vol. 4, no. 2, pp. 95–102, https://doi.org/10.2174/2215081104666150822001924.

[22] M. Danikas, R. Sarathi, and S. Morsalin, "A Short Review of Some of the Factors Affecting the Breakdown Strength of Insulating Oil for Power Transformers," *Engineering, Technology & Applied Science Research*, vol. 10, no. 3, pp. 5742–5747, Jun. 2020, https://doi.org/10.48084/etasr.3554.

[23] K. H. Le and P. H. Vu, "Performance Evaluation of a Generator Differential Protection Function for a Numerical Relay," *Engineering, Technology & Applied Science Research*, vol. 9, no. 4, pp. 4342–4348, Aug. 2019, https://doi.org/10.48084/etasr.2754.

[24] H. Fan, J. Hu, H. Liu, Y. Yin, and M. Danikas, "UHF PD Experiments on Real Power Transformer and its Frequency Characteristics Results," *Engineering, Technology & Applied Science Research*, vol. 6, no. 1, pp. 906–912, Feb. 2016, https://doi.org/10.48084/etasr.608.

[25] S. Sahoo, N. Abeywickrama, T. Bengtsson, and R. Saers, "Understanding the Sympathetic Inrush Phenomenon in the Power Network using Transformer Explorer," in *4th International Conference on Condition Assessment Techniques in Electrical Systems*, Chennai, India, Nov. 2019, pp. 1–5, https://doi.org/10.1109/CATCON47128.2019.CN0031.

[26] J. Faiz and S. Saffari, "Inrush Current Modeling in a Single-Phase Transformer," *IEEE Transactions on Magnetics*, vol. 46, no. 2, pp. 578–581, Oct. 2010, https://doi.org/10.1109/TMAG.2009.2032929.

[27] S. G. Abdulsalam, W. Xu, W. L. A. Neves, and X. Liu, "Estimation of transformer saturation characteristics from inrush current waveforms," *IEEE Transactions on Power Delivery*, vol. 21, no. 1, pp. 170–177, Jan. 2006, https://doi.org/10.1109/TPWRD.2005.859295.

[28] R. Oyanagi, T. Noda, and M. Ichikawa, "A Method for Estimating the Current–Flux Curve of a Single-Phase Transformer for Electromagnetic Transient Simulations of Inrush Currents," *Electrical Engineering in Japan*, vol. 204, no. 2, pp. 13–24, 2018, https://doi.org/10.1002/eej.23102.

[29] H. Altun, S. Sunter, and O. Aydogmus, "Modeling and analysis of a single-phase core-type transformer under inrush current and nonlinear load conditions," *Electrical Engineering*, vol. 103, no. 6, pp. 2961–2972, Dec. 2021, https://doi.org/10.1007/s00202-021-01283-9.

[30] W. L. A. Neves and H. W. Dommel, "On modelling iron core nonlinearities," *IEEE Transactions on Power Systems*, vol. 8, no. 2, pp. 417–425, Feb. 1993, https://doi.org/10.1109/59.260845.

[31] T. Liu, "Manoeuvre controlee des transformateurs de puissance avec flux remanent.," Ph.D. dissertation, Supelec, Paris, France, 2011.