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Research Article

Investigation of Ferroresonance Phenomenon under Different Conditions in Power System

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ABSTRACT

Introduction: Ferroresonance is a nonlinear oscillatory phenomenon that occurs in electrical power systems when a capacitance interacts with a nonlinear inductance such as a transformer's magnetic core. This interaction can produce high overvoltages, distorted waveforms, and potential damage to equipment. Understanding ferroresonance behavior under various conditions is crucial for ensuring power system stability and protection, especially in networks containing single-phase transformers and capacitive components.

Objectives: The main objective of this study is to investigate the ferroresonance phenomenon using a real single-phase transformer under different operating conditions. The work aims to analyze how changes in loading conditions (no-load, resistive load, and R-L load) and variations in series capacitance values influence the occurrence, magnitude, and waveform of ferroresonance overvoltages. The ultimate goal is to identify conditions that minimize or suppress ferroresonance effects in power systems.

Methods: The investigation combines experimental measurements and numerical simulations. A 2 kVA single-phase transformer was modeled, taking into account nonlinear magnetic characteristics and core saturation effects. The simulations were performed using **ATPDraw** software to model the circuit comprising a voltage source, line impedance, transformer, and varying capacitors. Different scenarios were tested for steady-state and transient regimes, under both unloaded and loaded conditions, to observe the voltage behavior and harmonic distortions induced by ferroresonance.

Results: Simulation results revealed that ferroresonance leads to significant overvoltages and distorted, non-sinusoidal voltage waveforms when the transformer operates in both steady-state and transient conditions. Increasing the series capacitance reduces the amplitude of these overvoltages and improves waveform stability. For loaded transformers, especially with resistive or R-L loads, the phenomenon is less pronounced. When the series capacitance reaches 100 µF, the voltage waveforms become nearly identical and sinusoidal, indicating a stabilized system response.

Conclusions: The study confirms that ferroresonance is highly sensitive to system parameters such as load and capacitance. Small capacitance values intensify overvoltages, whereas larger capacitances mitigate them. Proper selection and control of capacitance can effectively limit ferroresonance and protect electrical equipment. These findings emphasize the importance of considering ferroresonance during the design, modeling, and operation of power transformers and distribution networks.

Keywords: Transformer, Nonlinear inductance, Ferroresonance, Transients, Load.

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INTRODUCTION

Ferroresonance is a phenomenon that occurs in electrical systems when magnetic resonance occurs between a capacitance and a ferromagnetic material (nonlinear inductance). This phenomenon can be observed in a variety of devices, such as transformers, induction coils, magnetic circuits, and electric motors. When an electromagnetic system operates near the resonant frequency of a ferromagnetic material, the magnetic response of that material becomes very high. This can cause a significant increase in current and voltage in the system, which can have undesirable consequences, such as surges, energy losses, and component damage [1].

To better understand ferroresonance, it is necessary to:

- Specify the factors that influence this phenomenon.
- Identify real situations that can cause ferroresonance.
- Perform a ferroresonance analysis using existing methods such as numerical methods and the bifurcation method.

Using these approaches, it is possible to assess and anticipate the risks of ferroresonance, and to implement preventive measures to minimize its adverse effects on the electrical network [2,3].

Over the past decades, many studies and research works have been conducted on ferroresonance. These studies have contributed to deepening our understanding of this complex phenomenon and to developing more advanced methods of analysis and prevention. Researchers have explored different aspects of ferroresonance, such as its fundamental mechanisms, risk factors, effects on electrical equipment, and modeling and simulation techniques to assess and prevent its adverse consequences. This research has led to progress in the management and mitigation of risks related to ferroresonance in electrical networks [4 - 6]. Among these works it is found: Horak John in [4] have presented a study, bringing together 25 references published from 1950 to 2003, mainly deals with the confusion about what constitutes a ferroresonance circuit. Hassan et al. in [5] have developed a study grouping together 14 references, published from 1950 to 1993. This deals with ferroresonance in power distribution networks and the various conditions which give rise to the appearance of this ferroresonance, the most widespread of which results from undesirable voltage conditions. It also proposes the prevention of the appearance of ferroresonance. Bickford et al in [6] also addressed the case of transient overvoltages on power systems. This study of 175 references published from 1955 to 1985 covers a wide range on the dynamics of transient voltages from which stability problems arise in low voltage power distribution. Since 2003 to date, a large number of publications have appeared and we only cite a few of them in relation to the theme we are studying, [7, 8, 9].

The literature published on ferroresonance in distribution circuits primarily focuses on three-to-phase connected single-phase distribution transformers [10, 11] or phase-to-ground connected single-phase transformers on a three-phase distribution circuit [12]. Underground cable is one of the contributors to the capacitive nature of the circuit [13, 14]. Shunt capacitor bank use for reactive power compensation is another source of the capacitive nature [15, 16].

Some ways to mitigate ferroresanonce in distribution network have been listed below from the available literature.

- Elimination of asymmetrical switching [14, 05, 17]
- Coordinated operation of cable and transformer [14]
- Maintain transformer loading during energization [14, 05, 17]
- Modifications in circuit configuration [14, 05]
- Voltage controlled resistor in neutral [05, 18, 19]

The work done in this article is a continuation of previous work done in the field of transformers transient study found in [20-22].

In this paper, the single-phase saturable transformer is used in different operating conditions, no-load or on-load for ferroresonance simulations. In these different regimes, the interaction of the non-linear transformer with a capacitor can lead to overvoltages and ferroresonance disturbances.

In order to better understand the effect of ferroresonance, a simulation was carried out on a transformer model using ATPdraw software. The different simulations realized are:

Study the phenomenon of ferroresonance for the steady and transient regime. Study the phenomenon of ferroresonance for the case of the loaded transformer. When the transformer is subjected to resistive loads, study if

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the ferroresonance overvoltages occurring. Increasing the value of the capacitor in series with the transformer. Show the influence of the capacitance values on the ferroresonance phenomenon.

METHODS AND MATERIALS

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	0330/0037tr	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 ferroresonance 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 [23]

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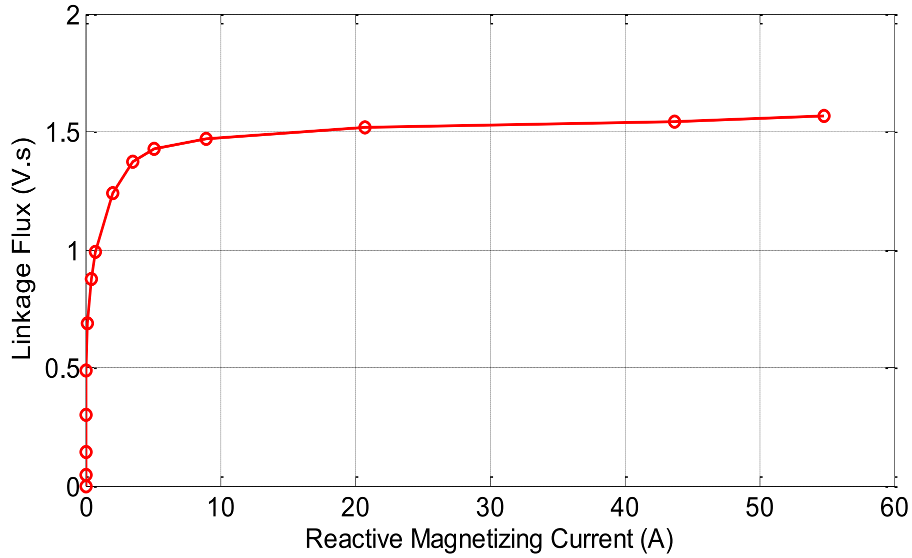

Figure 2. Saturation curve (nonlineair inductance) $\lambda = f(i_l)$ [23].

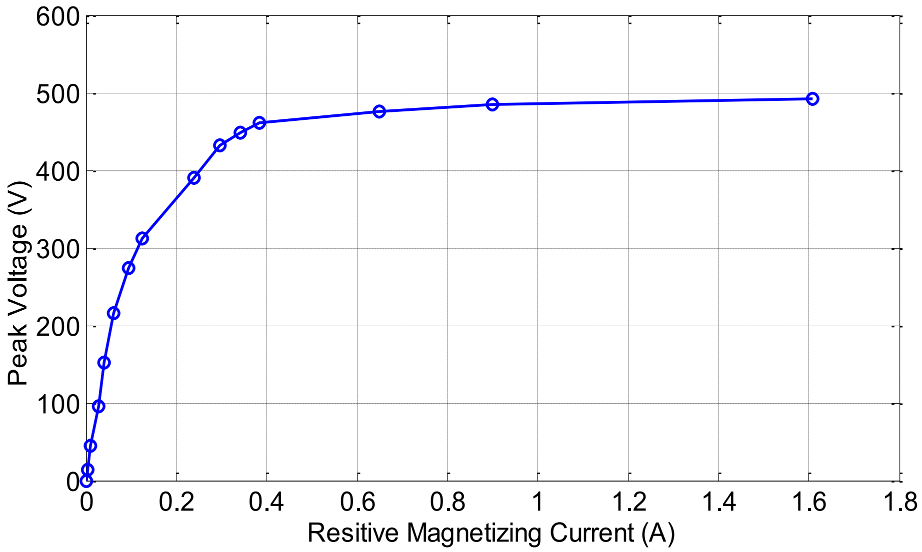

Figure 3. Resistance characteristic $\lambda = f(i_r)$ [23].

The data found in Figures 2 and 3 are calculated by the improved technique presented by the authors in [24, 25], and they have been inserted in the saturable transformer found in ATP-EMTP program to simulate the ferroresonance under different conditions.

EXPERIMENTAL SETUP AND TEST PROCEDURE

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.

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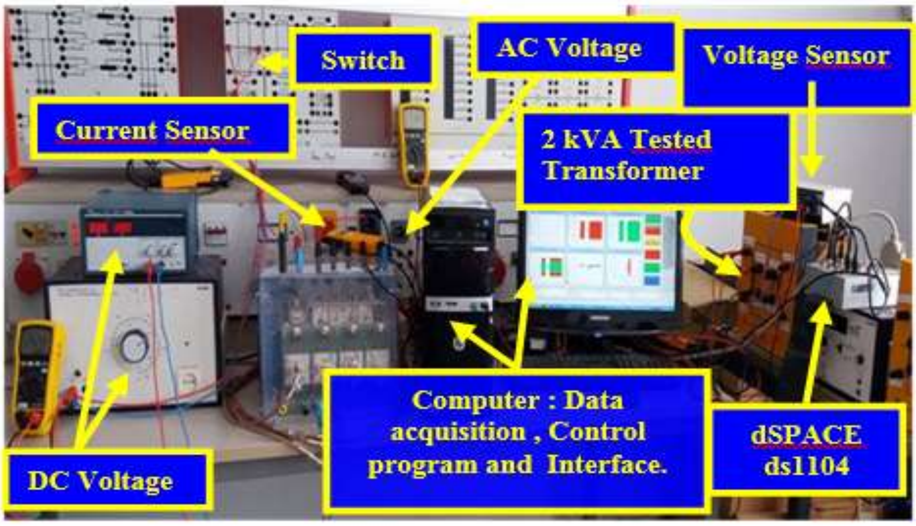

Figure 4. Laboratory setup for data measurement.

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

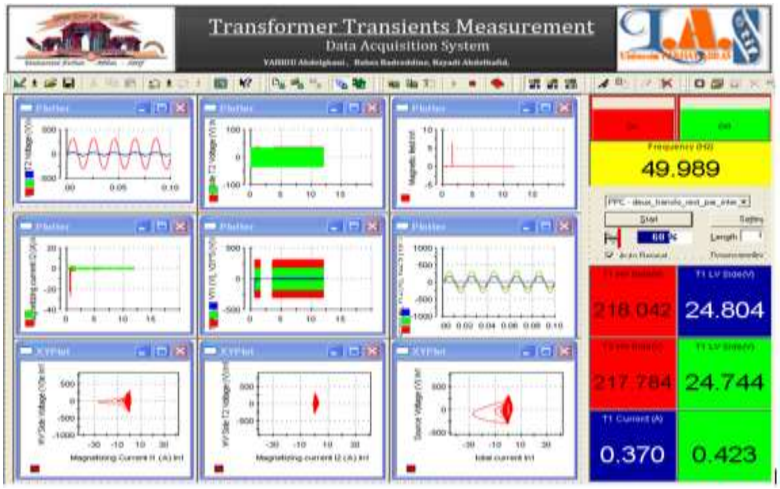

Figure 5. Data acquisition interface.

MODEL DESCRIPTION

The study of this paper consists of carrying out numerical simulations on a line which is supplied with a voltage of 220V, containing a resistance, an inductance and a capacitances, in the presence of a 2 kVA power transformer, i.e. nonlinear phenomenon, as shown in figure 6.

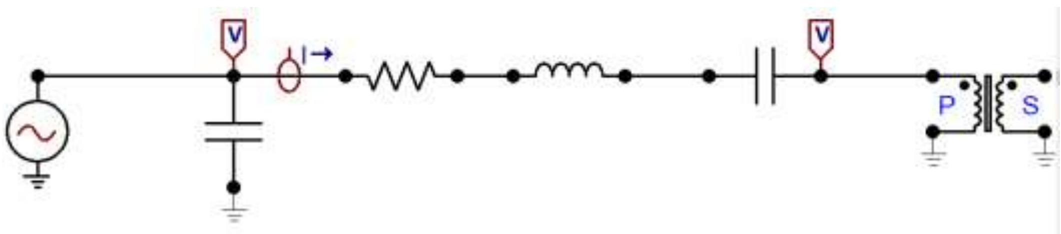

Figure 6. Model representation on ATPDraw.

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The following diagrams represent the three modes to be studied, such as: ferroresonance with no-load mode on steady state (Figure 7) and transient state (Figure 8), as well as in the presence of the load (Figure 9).

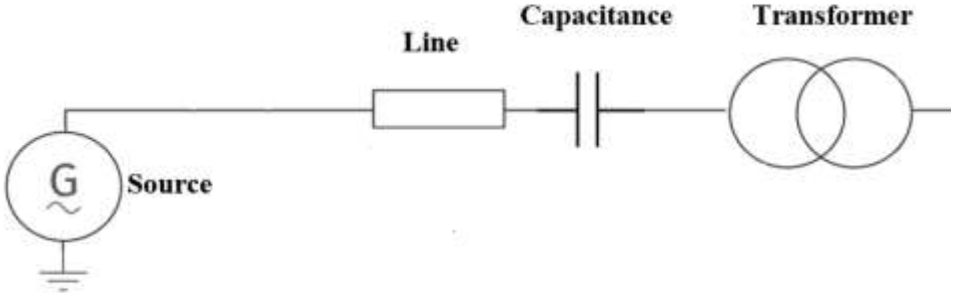

Figure 7. Ferroresonance study in steady state with unloaded transformer

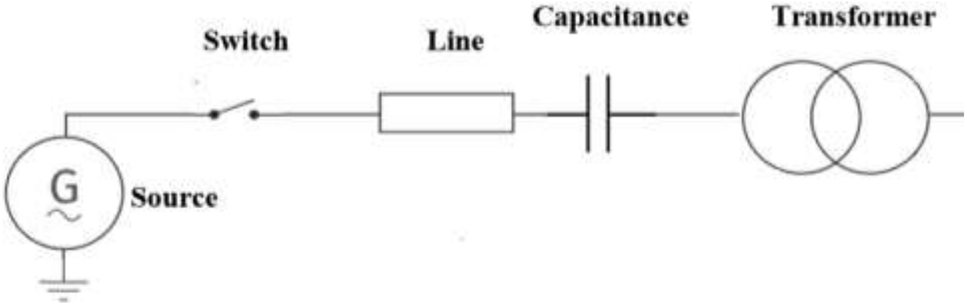

Figure 8. Ferroresonance study in transient regime with unloaded transformer

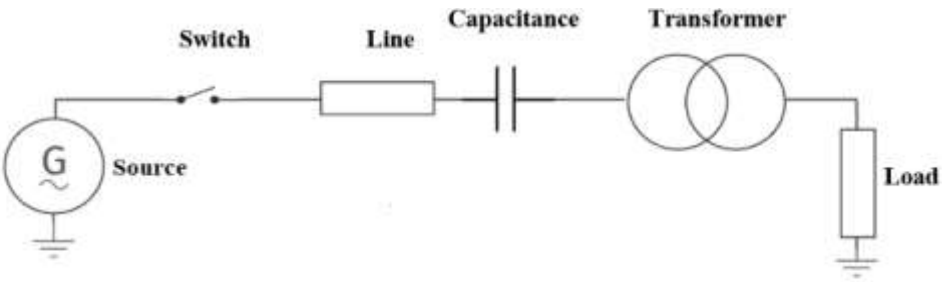

Figure 9. Ferroresonance study in transient regime with load.

FERRORESONANCE SIMULATION FOR UNLOADED TRANSFORMER

A) *FERRORESONANCE STUDY IN STEADY STATE WITH UNLOADED TRANSFORMER*

Simulation of the unloaded transformer circuit in steady state changing the value of capacitor C2 have been performed (Figure 10). The objective of this simulation is to analyze the effects of ferroresonance and to study how these effects manifest themselves in the behaviour of the circuit.

The parameters values are:

R: resistance of the line (R=10 Ohms)

L: inductance of the line (L=0.0001 mH)

C_1: capacitance of the line (C=10)

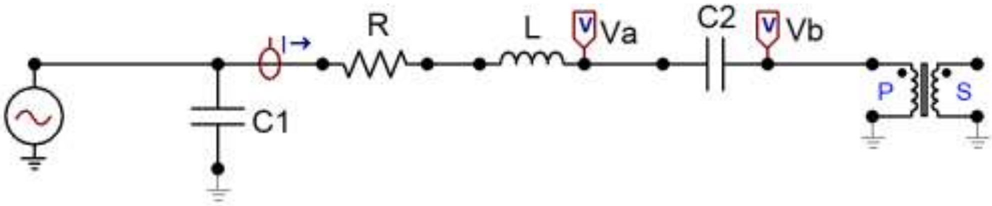

Figure 10. ATPDraw simulation block for first application.

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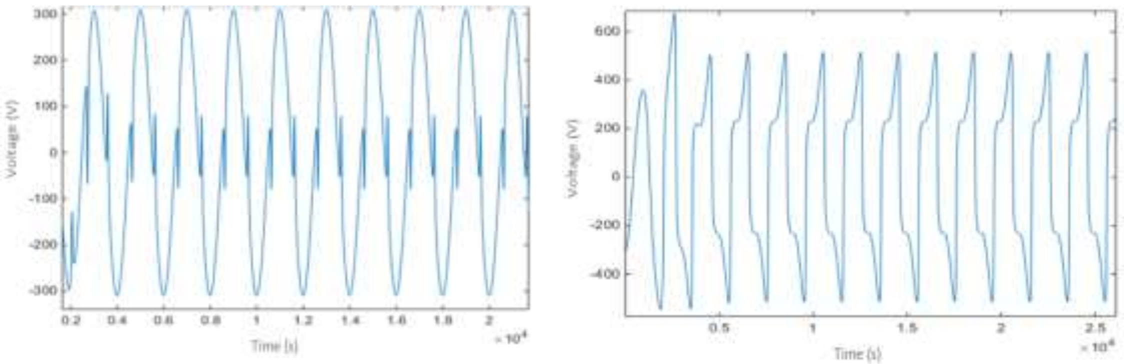
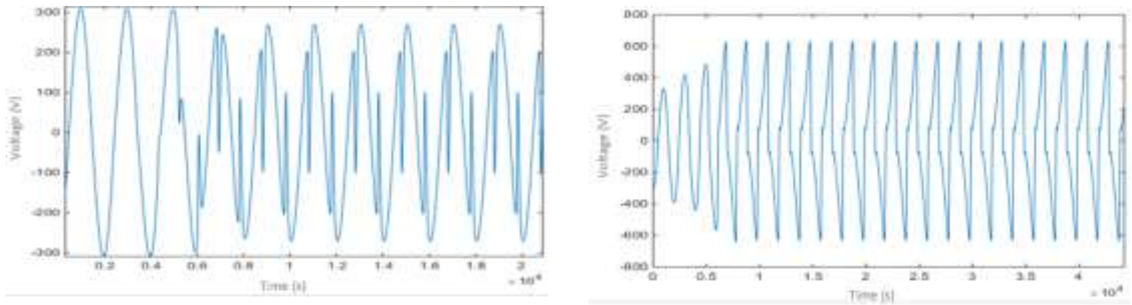
Figures 11 represent the voltage curves V_a and V_b obtained by simulation of the ferroresonance phenomenon with unloaded transformer in steady state with a value of C_2 equal to 20 µF.



(a) (b)

Figure 11. Voltage curve with C_2=20 µF, (a): V_a, (b): V_b.

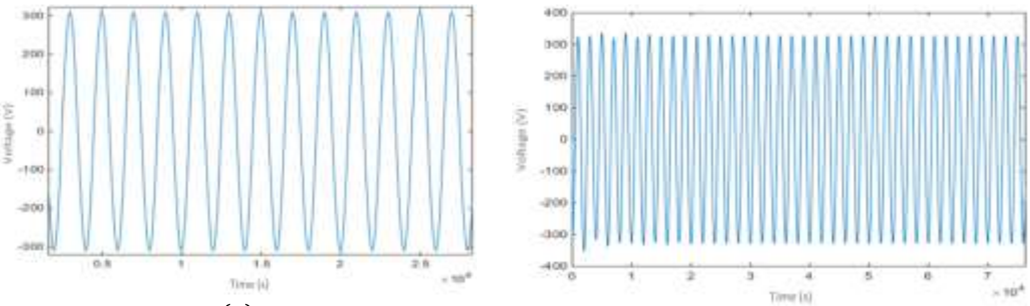
Figures 12 represent the voltage curves V_a and V_b obtained by simulation of the ferroresonance phenomenon with unloaded transformer in steady state with a value of C_2 equal to 60 µF.



(a) b)

Figure 12. Voltage curve with C_2=60 µF, (a): V_a, (b): V_b.

Figures 13 represent the voltage curves V_a and V_b obtained by simulation of the ferroresonance phenomenon with unloaded transformer in steady state with a value of C_2 equal to 100 µF.



(a) (b)

Figure 13. Voltage curve with C_2=100 µF, (a): V_a, (b): V_b.

B) FERRORESONANCE STUDY IN TRANSIENT STATE WITH UNLOADED TRANSFORMER

Simulation of the unloaded transformer circuit in transient regime, with adding the circuit breaker, changing the value of capacitor C_2 have been performed (Figure 14). The objective of this simulation is to analyze the effects of ferroresonance and to study how these effects manifest themselves in the behaviour of the circuit.

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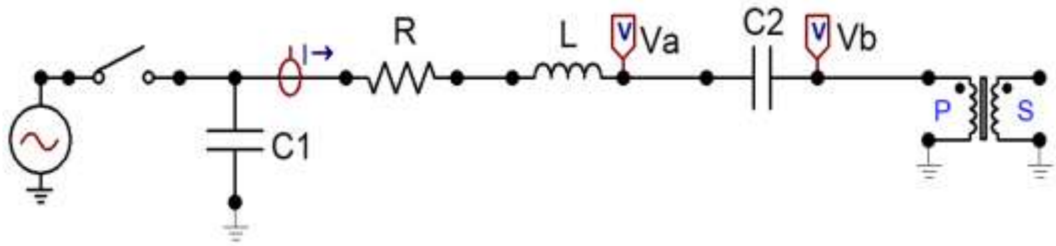
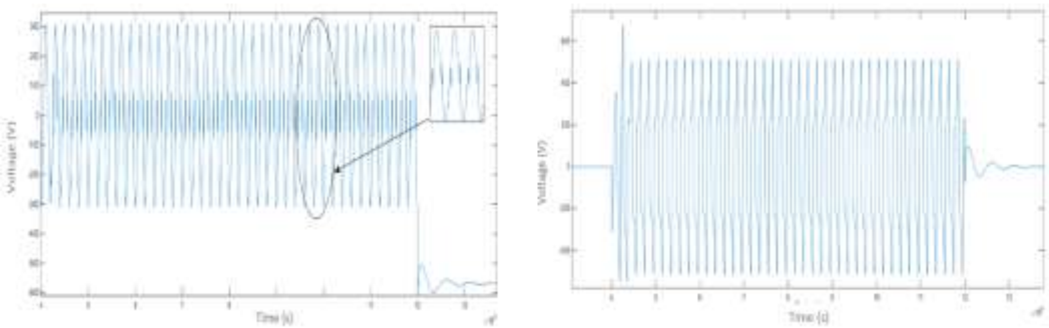


Figure 14. ATPDraw simulation block for second application.

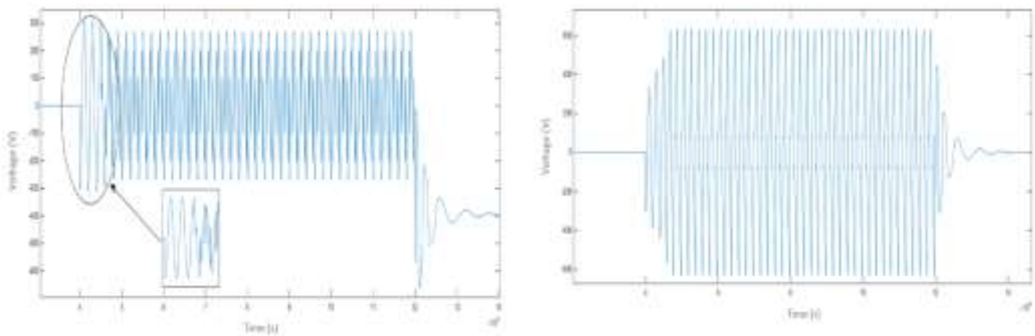
Figures 15 represent the voltage curves V_a and V_b obtained by simulation of the ferroresonance phenomenon with unloaded transformer in transient regime with a value of C_2 equal to 20 µF.



(a) (b)

Figure 15. Transient voltage curve with C_2=20 µF, (a): V_a, (b): V_b.

Figures 16 represent the voltage curves V_a and V_b obtained by simulation of the ferroresonance phenomenon with unloaded transformer in transient regime with a value of C_2 equal to 60 µF.



(a) (b)

Figure 16. Transient voltage curve with C_2=60 µF, (a): V_a, (b): V_b.

Figures 17 represent the voltage curves V_a and V_b obtained by simulation of the ferroresonance phenomenon with unloaded transformer in transient regime with a value of C_2 equal to 100 µF.

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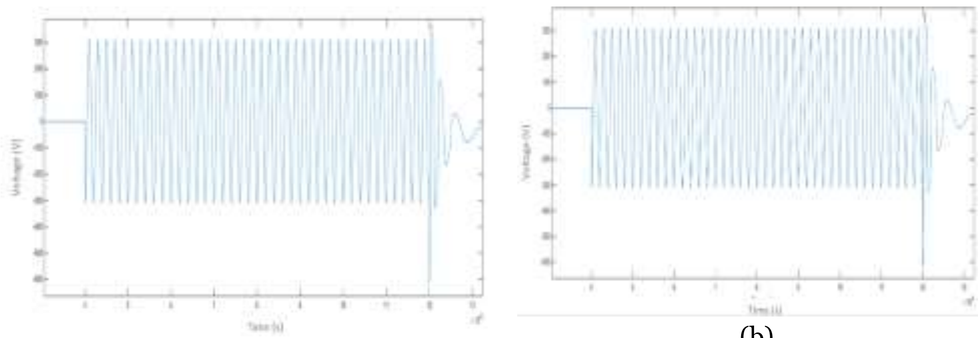

(a) (b)

Figure 17. Transient voltage curve with C_2=100 µF, (a): V_a, (b): V_b.

C) RESULTS INTERPRETATION

When the transformer is operating at no-load in steady and transient regimes, overvoltages are observed. The simulations demonstrate that the voltages during this period do not follow a sinusoidal shape due to the presence of harmonics. These harmonics are generated by the nonlinear behaviour of the transformer magnetic circuit as well as by the interaction with the series capacitance.
By observing the results, it is noticed that each time the value of the capacitor in series with the transformer is increased, the voltage takes a sinusoidal form and the overvoltages are reduced. This suggests that these overvoltages can be eliminated by varying the value of the capacitance.
By adjusting the value of the series capacitance, it is possible to modify the resonance of the circuit and mitigate the harmonics. This allows to stabilize the voltage and reduce the observed overvoltages
When the value of the series capacitance reaches 100 µF, the voltage curves Va and Vb become identical. This indicates that there is a ferroresonance phenomenon between the transformer and the capacitance, which leads to a similar response of the voltages across the two components.

FERRORESONANCE SIMULATION FOR LOADED TRANSFORMER

A)PURELY RESISTIVE LOAD

Simulation of the loaded transformer (resistive load) circuit in transient regime changing the value of capacitor C_2 have been performed (Figure 18).

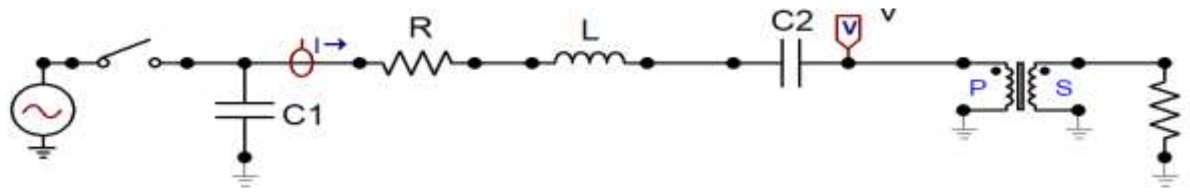

Figure 18. ATPDraw simulation block for resistive load application.

Figures 19 represent the voltage curve V obtained by simulation of the ferroresonance phenomenon with loaded transformer in transient regime with a value of C_2 equal to 20 µF.

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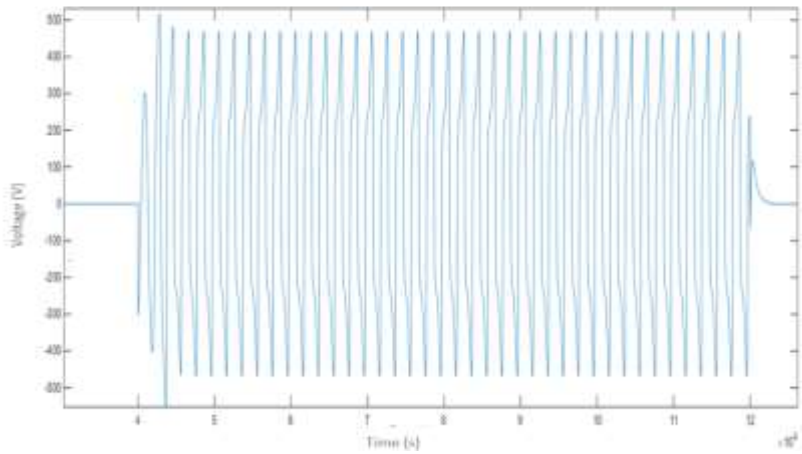

Figure 19. Transient voltage V curve with C_2=20 μF (Case of resistive loaded transformer).

Figures 20 represent the voltage curve V obtained by simulation of the ferroresonance phenomenon with loaded transformer in transient regime with a value of C_2 equal to 100 μF.

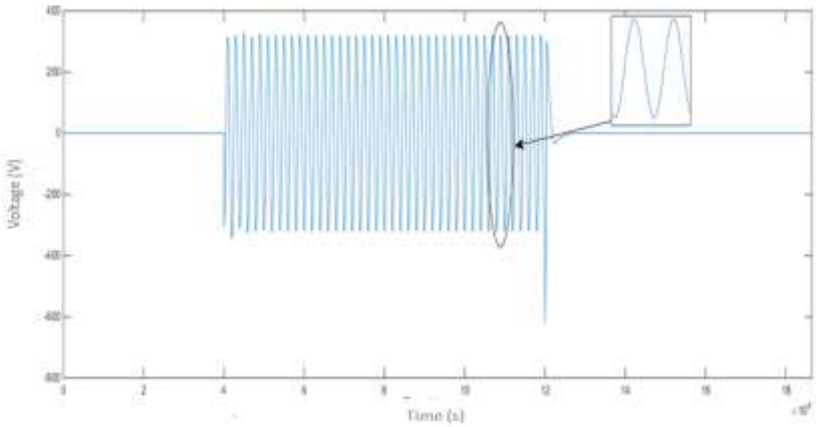

Figure 20. Transient voltage V curve with C_2=100 μF (Case of resistive loaded transformer).

B) RESULTS INTERPRETATION

Indeed, when a transformer is subjected to a purely resistive load, there may be overvoltages and disturbances observed during the transient regime. These phenomena are generally due to the nonlinear behavior of the transformer's magnetic circuit.

When a transformer is excited by an AC power source, the magnetic circuit may exhibit nonlinearities due to magnetic saturation, ferromagnetic losses, and other non-ideal magnetic effects. These nonlinearities introduce harmonics into electrical quantities, including voltages.

The existence of harmonics in voltages can cause distortions and non-sinusoidal waveforms. These distortions can lead to overvoltages and disturbances in the circuit, thus affecting the performance of connected equipment.

That by increasing the value of the capacitance in series with the transformer, overvoltages can decrease in some cases. This is due to the effect of increasing the capacitance on the circuit behavior and reducing ferroresonance phenomenon.

C) R-L LOAD

Simulation of the loaded transformer (R-L load) circuit in transient regime changing the value of capacitor C_2 have been performed (Figure 21).

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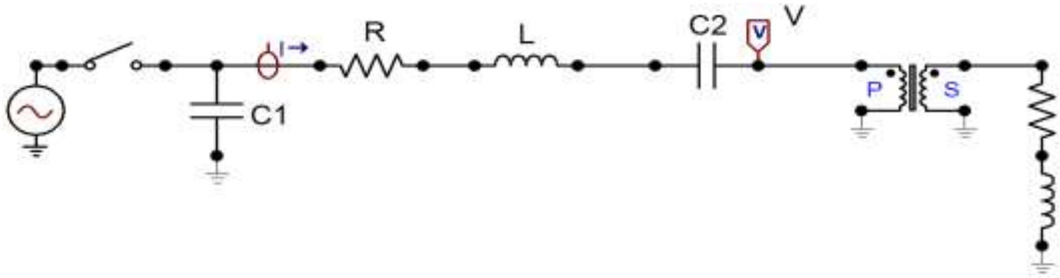

Figure 21. ATPDraw simulation block for R-L load application.

Figures 22 represent the voltage curve V obtained by simulation of the ferroresonance phenomenon with loaded transformer in transient regime with a value of C_2 equal to 20 µF.

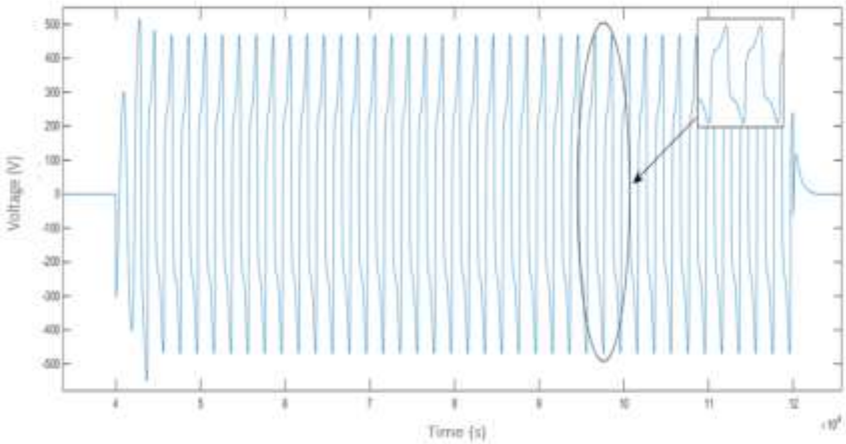

Figure 22. Transient voltage V curve with C_2=20 µF (Case of R-L loaded transformer).

Figures 23 represent the voltage curve V obtained by simulation of the ferroresonance phenomenon with loaded transformer in transient regime with a value of C_2 equal to 100 µF.

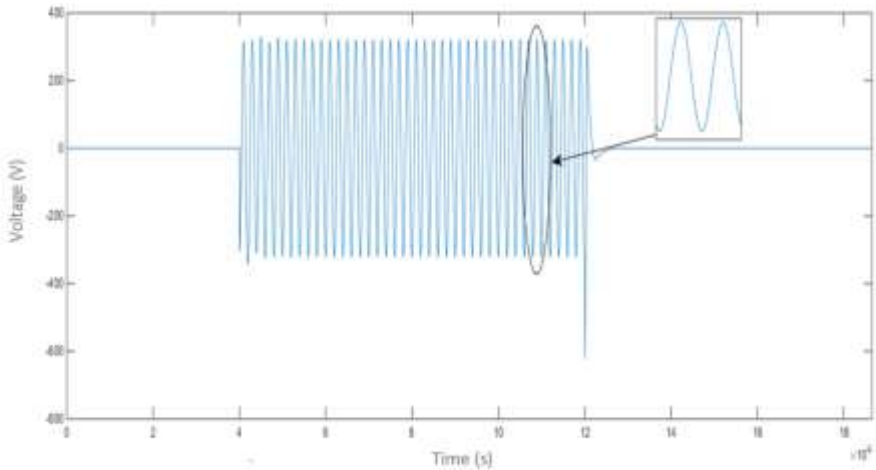

Figure 23. Transient voltage V curve with C_2=100 µF (Case of R-L loaded transformer).

D) RESULTS INTERPRETATION

When a transformer is subjected to a load witch contained resistance (R) and inductance (L), surges and disturbances can occur during the transient state. These phenomena are generally caused by the non-linear behaviour of the transformer's magnetic circuit.

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Increasing the value of the capacitance in series with the transformer can help reduce surges in some cases. This increase in capacitance has an impact on the overall behaviour of the circuit, which can help to mitigate the undesirable effects of ferroresonance.

CONCLUSIONS

The single-phase saturable transformer can be used in different operating conditions, unload or loaded transformer. In these different regimes, the interaction of the nonlinear transformer with a capacitor can lead to overvoltages and ferroresonance disturbances.
Ferroresonance is a phenomenon that occurs in electrical systems when magnetic resonance occurs between a capacitance and a ferromagnetic material (nonlinear inductance)
The aim of paper is to study the ferroresonance phenomenon in presence of a real single-phase transformer, as well as its impact on the electrical network. A study the effect of ferroresonance on a network that consists of a sinusoidal voltage source, a line and a transformer is presented.

The results of simulations revealed that:

- When the transformer is subjected to resistive loads, ferroresonance overvoltages can occur during the transient regime.
- Increasing the value of the capacitance in series with the transformer can reduce ferroresonance overvoltages in some cases.
- Ferroresonance overvoltages are more severe when the value of the capacitance in series is small.
- On the other hand, increasing the value of the capacitance can limit overvoltages and reduce their harmful effects on the electrical network and equipment.

These simulations have illustrated the importance of taking into account the effect of ferroresonance when designing and operating power transformers.

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