TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

# Phân tích quá trình điện từ của máy biến áp khi đóng vào lưới điện bằng phần mềm Ansys Maxwell

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**TÓM TẮT**

Máy biến áp khi đóng vào lưới điện, sinh ra dòng điện cao trong cuộn dây và từ thông trong mạch từ tăng lên gây bão hòa mạch từ. Thời gian bão hòa mạch từ xảy ra có thể lên đến vài chu kỳ dòng điện. Đồng thời, dạng sóng dòng điện sơ cấp chứa thành phần sóng hài và có thể gây ra sự tác động nhầm cho các thiết bị rơle hoặc ảnh hưởng đến sự làm việc cho các thiết bị điện xung quanh khác. Bài báo đã xây dựng một mô hình Máy biến áp có công suất 250kVA bằng phần mềm Ansys Maxwell 3D để tính dòng điện đóng vào lưới điện trong trường hợp định mức và không tải. Kết quả về các giá trị dòng điện, điện áp và từ cảm của máy lần lượt được phân tích. Từ đó giúp cho các kỹ sư thiết kế, chế tạo và vận hành, lựa chọn phương án phù hợp trong trường hợp máy biến áp đóng điện vào lưới điện.

**Từ khóa:** *Ansys Maxwell, máy biến áp, từ cảm, bão hòa mạch từ, dòng điện không tải.*

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# Analysis of electromagnetic on transformer due to inrush power system by Ansys Maxwell

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**ABSTRACT**

A current in the winding and a flux in the magnetic circuit increase very high when a transformer is connected to the grid. This is the cause of the magnetic circuit saturation. The time of magnetic circuit saturation can occur up to some the frequency of alternating electric current. At the same time, the primary current waveform contains a harmonic component and may cause malfunction of relay devices or impair operation of other surrounding electrical equipment. The paper has built a simulation model using Ansys Maxwell 3D to calculate the transformer inrush current with a power of 250 kVA to the grid in the case of load and no load. The results of the current, voltage and inductance values of the machine which are analyzed one after another help engineers to design, manufacture and operate, choose the appropriate plan in case the transformer is connected to the grid.

**Keywords:** *Ansys Maxwell, transformer, self-induction, magnetic circuit saturation, no-load current,*

## 1. INTRODUCTION

When the transformer is working, there is a sudden change in the working mode of the machine. It is a transient process in the transformer. Actions occur when the transformer to the mains is closed, when the load changes or when a sudden short circuit occurs, etc. The transient process consists of two main phenomena called overcurrent, surge current and overvoltage, surge voltage. These transients occur in a very short time. It causes the circuit from the transformer to saturate, or large currents, high voltages to appear suddenly, which damage the windings of the transformer.[1,2]

In transformers, the relationship between the magnetic flux in the magnetic circuit and the no-load current is one of the nonlinear magnetization curve relationships. When the transformer is connected to the grid at no-load, the no-load current increases tens of times higher than the rated current in microseconds and the magnetic flux in the magnetic circuit will reach its maximum value. Even the flux saturation value reaches to 2 Tesla.[1,3-5]

In this paper,[6] the author proposed an approach to calculate the closing current to the grid of a three-phase transformer. Nonlinear inductance is used to simulate core saturation. This article has used electrical and magnetic circuit models. The author performed by using both experiments and simulations. Experimental and simulation results show the current waveforms closed to the grid and methods to reduce this current. Then, the author uses the magnetic circuit model proposed in the article.

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The paper also makes recommendations in this way to reduce the cost of designing and manufacturing three-phase transformers.

Article[7] discussed digital models of common single-phase transformers. The addition of mathematical relationships helps to determine the closing current to the grid and the working current in different processes. The article calculates and compares the waveforms and pulses of the inrush current of the transformer. In addition, the article also calculates the heat released in the transformer windings.

This paper implements a transformer of closing to the grid with a capacity of 250 kVA using the finite element method with Ansys Maxwell 3D software. First, the transformer to the grid in the case of rated load to check the correctness of the theoretical model. Then executing the model in the case of no-load transformer. Model analysis results in current, voltage and inductance values. Since then, the study of using this method for the overvoltage or overheating phenomena of transformers creates an alternative approach for further research.

## 2. CONTENT

### 2.1. Current and magnetic flux when energizing a single-phase power transformer

Under no load operation, the current flowing in the transformer ($I_0$) has a small value and may not exceed 10% of the rated current. But in the transient period when energizing a power transformer, the inrush current will have an excessive high value, and (???) multiple times of the rated current.[1,2,3]

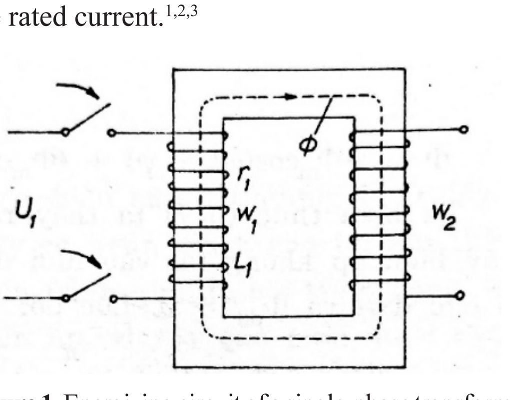


**Figure 1.** Energizing circuit of a single-phase transformer

In Figure 1, when applying a sinusoidal voltage to one of the transformer's windings, based on the Kirchhoff Voltage Law, we have:

$$U_{1m}\sin(\omega t+\psi) = i_0 r_1 + \omega_1 \frac{d\Phi}{dt} \quad (1)$$

Where

$\psi$: voltage phase angle, rad

$\omega$: the velocity angle of the input voltage, rad/s

$i_0$: the instantaneous value of the no load current, A

$r_1$: resistor of transformer winding, Ω

$W_1$: number of turns of the winding

$\Phi$: linkage flux

The relationship between $\Phi$ and $i_0$ is based on the magnetization curve of the transformer, which means (1) is a non-linear derivative equation. For simplification, we assume that the linkage flux proportional to the no load current by the following equation:

$$i_0 = \frac{\omega_1 \Phi}{L_1} \quad (2)$$

Inductance of the primary winding ($L_1$) is constant, from Equation (2) and Equation (1), we have:

$$\frac{U_{1m}}{W_1}\sin(\omega t+\psi) = \frac{r_1}{L_1}\Phi + \frac{d\Phi}{dt} \quad (3)$$

Using the classic integration method or Laplace operator method to obtain the linkage flux $\Phi$ of the transformer. The resulting flux includes two terms which are the steady state term and the transient term:

$$\Phi = \Phi_{xl} + \Phi_{td} \quad (4)$$

The steady state term of the flux is calculated as:

$$\Phi_{xl} = \Phi_m \sin(\omega t + \psi - \frac{\pi}{2}) = -\Phi_m \cos(\omega t + \psi) \quad (5)$$

with: $\Phi_m = \dfrac{L_1 U_{1m}}{W_1\sqrt{r_1^2 + (\omega L_1)^2}}$

And the transient term of the flux is calculated as

$$\Phi_{td} = C.e^{-r_1 t/L_1} \quad (6)$$

The integral constant C is determinded by the initial condition (t = 0). In this condition, the transformer core also remains an amount of flux called residual flux ± Φres which means

$$\Phi_{t=0} = \left[\Phi_{xl} + \Phi_{td}\right]_{t=0} = -\Phi_m \cos\psi + C = \pm\Phi_{du}$$

Then: $C = \Phi_m \cos\psi \pm \Phi_{du}$

$$\text{And } \Phi_{td} = (\Phi_m \cos\psi \pm \Phi_{du}).e^{-r_1 t/L_1} \quad (7)$$

From Equations (4), (5) and (7), we have:

$$\Phi = \Phi_{xl} + \Phi_{td} = -\Phi_m \cos(\omega t + \psi) + (\Phi_m \cos\psi \pm \Phi_{du}).e^{-r_1 t/L_1} \quad (8)$$

From Equation (8), the optimum condition to energize the transformer is when the initial phase angle of the applied voltage ψ equals π/2 and the residual flux is zero ($\Phi_{res} = 0$). Then the transformer linkage flux becomes:

$$\Phi = -\Phi_m \cos(\omega t + \frac{\pi}{2}) = \Phi_m \sin\omega t \quad (9)$$

The flux is purely sinusoid because the transient term has been eliminated, and the steady state operation of the transformer is established immediately.

In contrast, the most undesirable condition to connect a transformer to power grid is when the initial angle of the applied voltage ψ is zero and the residual flux has a positive value. Then the linkage flux becomes:

$$\Phi = -\Phi_m \cos\omega t + (\Phi_m + \Phi_{du}).e^{-r_1 t/L_1} \quad (9)$$

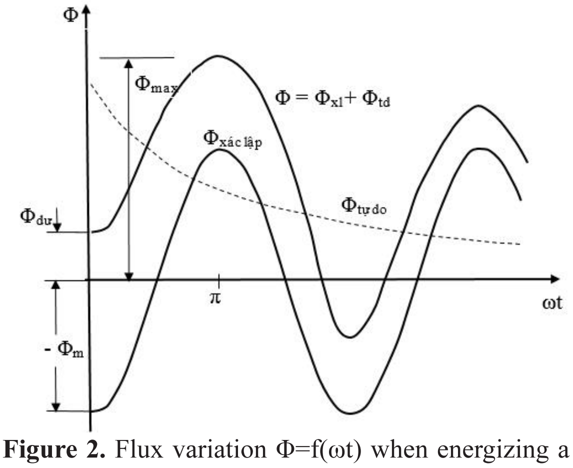


**Figure 2.** Flux variation Φ=f(ωt) when energizing a power transformer

Figure 2 shows the transformer flux according to angular frequency (ωt) based on Equation (10). As shown in Figure 2, the flux gets its maximum value when the angular frequency equals π (ωt = π), after half cycle.

When $r_1 << \omega L_1$, then:

$$e^{-(r_1/L_1)t} = e^{-(r_1\pi/\omega L_1)} \approx 1$$

The residual flux depends on the construction of the magnetic circuit which is the transformer core construction, and also depends on the type of core laminates. Magnetic circuit having obtuse or perpendicular coupling will get a small residual flux value. In contrast, the alternating construction has a high magnetic residue B = 0.6 ÷ 1.0T.

Therefore, the maximum flux value shown in Figure 2 is double compared with the normal operation value, so the transformer core is strongly saturated and the magnetization current $i_0$ during the energizing transient will be many times larger than the steady state $I_0$.[1,2]

## 2.2. Finite element method using Ansys Maxwell software

### *2.2.1. Ansys Maxwell software*

Ansys Maxwell[8] is a high performance interactive software package that uses finite element analysis to solve electrical and magnetic problems. Maxwell solves electromagnetic problems by solving Maxwell's equations in the limited space domain and implementing Electrostatic, Magnetostatic, Eddy Current and Magnetic Transient solvers.

The process of solving the problem on Ansys Maxwell is summarized in Figure 3:

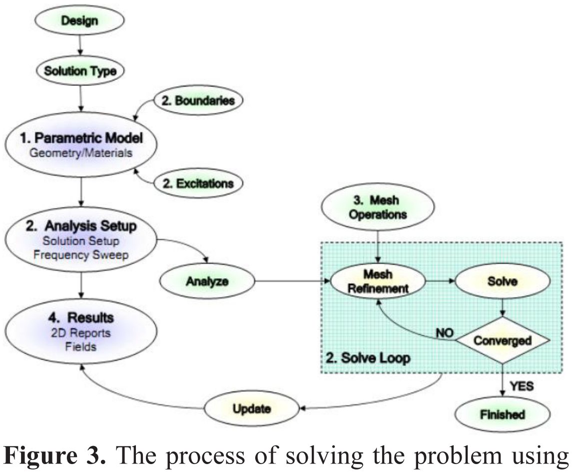


**Figure 3.** The process of solving the problem using the Finite Element method

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Ansys Maxwell is a package included in ANSYS Electronics Desktop software V19.R1; copyrighted software (license) at the computational and simulation room of the Faculty of Engineering & Technology, Quy Nhon University.

*2.2.2. Transformer using Ansys Maxwell software*

Table 1 shows the parameters of a 250 kVA power transformer from SANAKY in Ha Noi. The detailed dimension is obtained from the drawings provided by the manufacturer.

The parameters shown in Table 1 and design dimensions of the transformer will be the input data for Ansys Maxwell software.[8]

**Table 1.** Transformer parameters

| No. | Parameters | Value |
|---|---|---|
| 1 | No. of phase | 3 |
| 2 | Frequency [Hz] | 50 |
| 3 | Rated power [kVA] | 250 |
| 4 | Winding diagram | Y/Y |
| 5 | Rated voltages [kV] | 35/0.4 |
| 6 | Number of turns per phase in Primary/Secondary side [turns] | 2800/32 |
| 7 | Rated currents [A] | 4.12/361 |
| 8 | Primary/Secondary winding diameter (mm) | 0.8/1.5 |
| 9 | No load current (%) | 2 |
| 10 | Short circuit voltage $u_k$ (%) | 5.7 |

Figure 4 shows the transformer model used in Ansys Maxwell 3D.

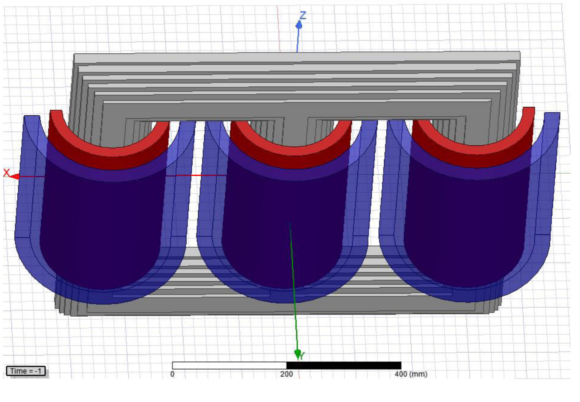


**Figure 4.** Transformer model used in Ansys Maxwell 3D

**2.3. Analysis results in transformer mode with rated load**

*2.3.1. Voltage value of high voltage (HV) and low voltage (LV) windings*

The investigated period in this analysis is up to 500 ms. However, in order to better observe the voltage and current waveforms, in Figures 5 and 6, the 0 ÷ 100 ms time axis has been chosen to be displayed.

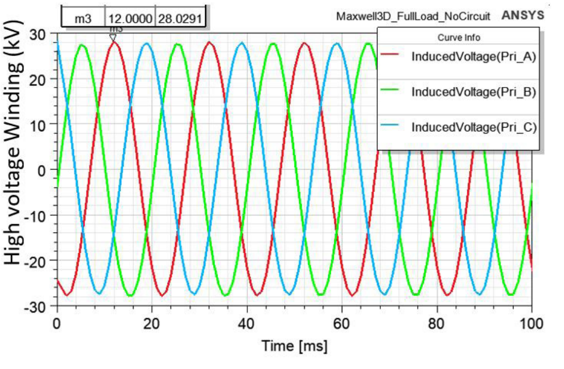


**Figure 5.** High-voltage winding voltage for a period of 100 ms

As shown in Figure 5, the rms value of the simulated phase voltage is $U_{Pri\text{-}A}$ = 19.82 kV compared with the rated voltage applied in transformer primary side $U_{Pri\text{-}A\text{-}rated}$ = 20.2 kV.

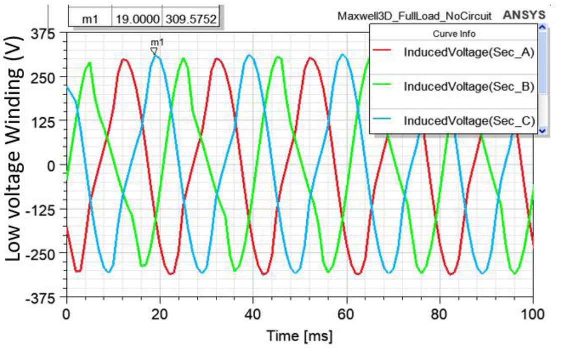


**Figure 6.** Low-voltage winding voltage for a period of 100ms

Also, in Figure 6 the rated value and simulation result of secondary side phase voltage are 219 V and 220 V, respectively. The error between phase voltages at primary and secondary side is about 2%.

*2.3.2. Flux density in transformer core*

At time t = 500 ms, when steady state is stable, the current is equal to the rated max current value $I_{HVrate}$ = 6.0 A. The results of flux density survey at the core of the transformer are shown in Figure 7.

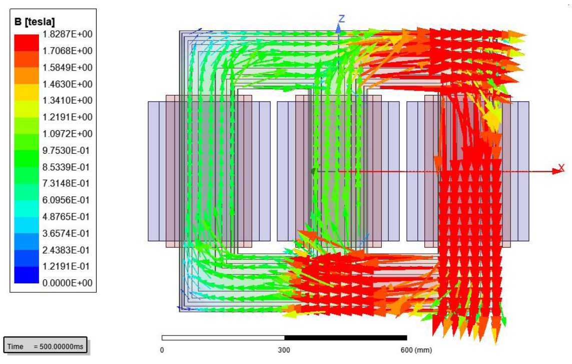


**Figure 7.** Vector distribution of the flux density at t = 500ms

As a result, at time t = 500 ms, the flux density at the transformer working average B = 1.0 T, but at the corners of the core magnetic circuit the flux density has the greatest value B = 1.8 T.

Analyzing the simulation results, we get the voltage and current values. These simulation results are compared with the calculated values in Table 2.

**Table 2.** Comparison between simulation and calculation results

| No | Parameters | Simulation result | Calculation result | Error % |
|---|---|---|---|---|
| 1 | Phase voltage of HV $U_1$ (kV) | 19.82 | 20.2 | 1.9 |
| 2 | Phase voltage of LV $U_2$ (V) | 219 | 220 | 0.4 |
| 3 | Phase current of HV $I_1$ (A) | 4.24 | 4.12 | 3.0 |
| 4 | Phase current of LV $I_2$ (A) | 364.8 | 361 | 1.0 |

**2.4. Simulation results in transformer mode closing the high-voltage winding to the grid at no-load**

*2.4.1. Current result at the time of inrush current*

In the case of transformer load at rated, the values of current, voltage, and inductance are compared with the calculation to be completely correct. Since then, this simulation model has been really accurate. Therefore, this model is simulated in the closed field to the grid at no-load of the transformer.

The results of the analysis of the current value when the transformer is connected to the grid and the low voltage side is unloaded are shown in Figure 8.

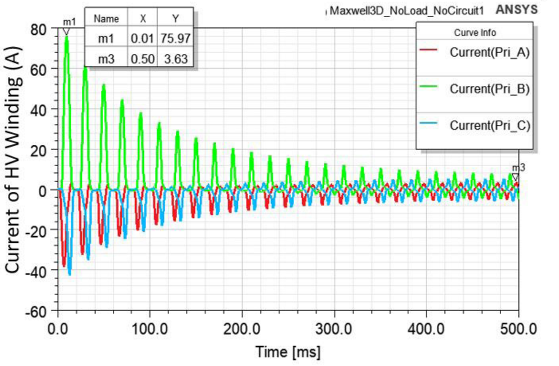


**Figure 8.** Current of the high-voltage winding no load for a period of 500 ms.

Figure 8 shows three phase currents at the HV winding when connecting the transformer to power grid. The current waveforms are similar to the previous case with the maximum point of the inrush current is $I_{inrush\ current}$ =75.97 A at the period t = 10 ms. In addition, a higher capacity leads to a higher transient time constant which means the current damping is slower and gets its steady state value of no-load $I_{0HV}$ = 2.5 A after t = 500 ms.

In the currents on phase A, B, C, the reason for the current on the high-voltage winding of phase B to reach the greatest value is because at the point t = 10 ms, phase B voltage is zero.

Compared with the high-voltage current in the rated mode $I_{HVrate}$ = 6.0 A, the transformer of the inrush current is 12.6 times higher.

*2.4.2. Flux density in transformer core at the time of inrush current*

Flux density in the transformer core is calculated at t = 10 ms when the primary side current has the maximum magnitude $I_{inrush\ current}$ =75.97 A.

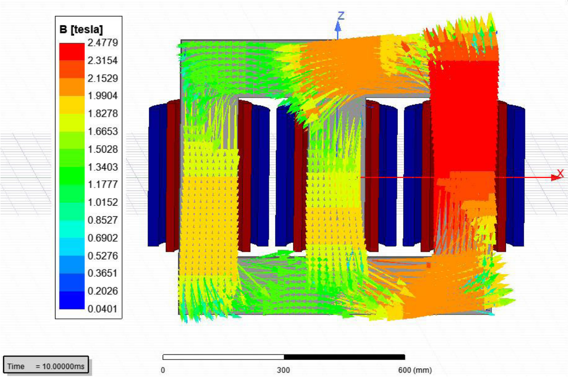


**Figure 9.** Vector distribution of the flux density at t = 10ms

As shown in Figure 9, at t = 10 ms, the transformer core is highly saturated with the flux density up to 2.48 T. Then, the working magnetic density of steel core B = 1.8 T, showing that the steel core reaches very strong magnetic saturation.

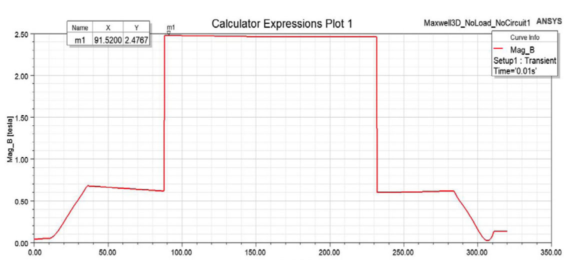


**Figure 10.** Distance distribution of the flux density magnitude inside transformer core at t = 10 ms.

In Figure 10, we see the results of surveying the magnetic flux density at the core of phase B reaching the maximum B = 2.48 T at time t = 10 ms.

The simulation results of current value, magnetic flux density are summarized in Table 3.

**Table 3.** The simulation results

| Power (kVA) | Rated primary side current $I_{HV\text{-}rated}$ (A) | Maximum inrush current $I_{inrush\text{-}max}$ (A) | Maximum flux density $B_{max}$ (T) | Proportion of the inrush current to the rated primary current (times) |
|---|---|---|---|---|
| 250 | 6.0 | 75.97 | 2.48 | 12.6 |

## 3. CONCLUSION

Through the process of analysis, calculation and simulation, the following results have been achieved:

The Ansys Maxwell software has been applied to simulate the energizing duration of the transformers with capacity of 250 kVA under no load condition.

In the case of transformer load at rated, the values of current, voltage, and inductance are compared with the calculation to be completely correct. Since then, this simulation model has been really accurate. Therefore, this model is simulated in the closed field to the grid at no-load of the transformer.

The current waveforms are similar to the previous case with the maximum point of the inrush current is $I_{inrush\ current}$ =75.97 A at the period t = 10 ms. Compared with the high-voltage current in the rated mode $I_{HVrate}$ = 6.0 A, the transformer of the inrush current is 12.6 times higher and the steel core is saturated with the flux density is B = 2.48 T

After damping gradually in transient period, about 500 ms, the steady-state value of the inrush current is equal to the rated no-load current of the transformer. In addition, the steel core is also saturation free and the flux density returns to the normal operating value from 1.2 T to 1.8 T.

The electromagnetic simulation results of currents, voltages and flux density have given a clear visualization of the extreme (maximum and/or minimum) values of the above quantities. Furthermore, it helps engineers and manufacturers to design, calculate, operate, and choose the appropriate plan/scenario in case a transformer is connected to power grid.

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