



Design of Magnetic Sheet for a Three-Phase Transformer with D-Yn Connection in FEMM

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December 5, 2023

Design of magnetic sheet for a Three-Phase Transformer with D-yn connection in FEMM

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Resumen—En la actualidad, el planteamiento de fenómenos electromagnéticos por medio de simuladores desde el desarrollo de su teoría, ha sido la base para el diseño de numerosas máquinas y sistemas mejorando el método de producción y construcción de estos sistemas electromecánicos, frente al antiguo método de prototipo por la observación de modelos a escala ya desarrollados. En este documento se presenta el diseño de una chapa magnética para un transformador trifásico con una conexión Dy-n aprovechando las herramientas de simulación disponibles en FEMM (Finite Element Method Magnetics), con el fin de comprender fenómenos como los enlaces de flujo, corrientes de los arrollamientos, curvas de saturación de materiales y corrientes de excitación, que son aspectos muy importantes para la comprensión del funcionamiento de los transformadores.

Abstract—Currently, the approach of electromagnetic phenomena by means of simulators since the development of their theory, has been the basis for the design of numerous machines and systems improving the method of production and construction of these electromechanical systems, compared to the old prototype method by observing scale models already developed. This paper presents the design of a magnetic sheet for a three-phase transformer with a Dy-n connection, taking advantage of the simulation tools available in FEMM (Finite Element Method Magnetics), in order to understand phenomena such as flow links, the windings, material saturation curves and excitation currents, that are very important aspects for understanding the operation of the transformers.

Índice de Términos—Calibre, Chapa Magnética, Corriente Nominal, Densidad de Flujo, Inducción Máxima, Transformador Trifásico.

Index Terms—Gauge, Magnetic sheet, Nominal Current, Flux Density, Maximum Induction, Three-Phase Transformer.

I. INTRODUCTION

The design of three-phase transformers has been an important activity since the existence of electrical energy. The aim is to make a distribution in the most optimal way possible, with the least number of losses. This is achieved by raising the voltage, for which transformers exist. Currently, the engineering programs developed in recent years are very useful to simplify the work necessary to achieve the desired results on the first attempt. The first part presents the theoretical basis used for the design of the sheets, the different calculations necessary and the principles on which the operation of the transformers is based. The use of the FEMM program is of vital importance to obtain accurate results regarding the operation of a real three-phase transformer in operation.

The main objective is to design the magnetic plate for a three-

phase transformer following a series of calculations established in logical order to obtain the parameters of the equivalent circuit of the transformer designed using FEMM and verify through it that the established conditions are met.

II. SPECIFICATIONS

The initial design specifications are shown in table 1, however, the dimensions of the transformer will be established as the results of the calculation carried out are obtained.

TABLE I
DESIGN SPECIFICATIONS

Parameters	Units	Magnitude
Number of turns	turns	To define
Intensity through the wire	Amp	1.4
Relative permeability of iron	-	2500
Primary/secondary voltage	Volts	3000/230
Apparent power	VA	3000

III. CALCULATIONS

A. Specific Voltage

In the proposed exercise, the aim is to design a three-phase transformer with the previously assigned specifications. To carry out the different calculations and be able to define the parameters of a three-phase transformer, the formulas available in [1] have been used. In addition, it was decided to design an armored transformer for permanent service.

It begins by calculating the specific voltage which is given by the following equation:

$$V_e = A * \sqrt{P_a} \quad (1)$$

According to (1), A it is a coefficient that is given in tables for the usual types of transformers and is given in maximum value and minimum value for ring core and armored core, P_a it is the apparent power of the transformer in VA.

The following table [2] shows the different values of A according to the type of transformer.

TABLE 2
COEFFICIENT FOR USUAL TYPES OF TRANSFORMERS

Transformer type	Maximum value	Minimum value
Ring core, intermittent service	0.022	0.014
Ring core, constant service	0.030	0.020
Armored core, intermittent service	0.026	0.025
Armored core, constant service	0.045	0.033

Since an armored core has been selected, a value of 0.025 (minimum value in tables) has been used for the constant A. Therefore:

$$V_e = 0.025 * \sqrt{3000} = 1.37V$$

B. Spires Number

The number of turns was calculated using (2), which relates the nominal voltage and the specific voltage.

$$N = E/V_e \quad (2)$$

Number of turns in the primary:

$$N_1 = E_1/V_e = 3000/1.37 \approx 2190 \text{ turns}$$

Number of turns in the secondary:

$$N_2 = E_2/\sqrt{3} * V_e = 230/1.37 \approx 97$$

The number of turns used for the primary will be 2190 turns, while for the secondary it will be 97, considering in the case of the primary, that the voltage values in a star connection are different for phase and line, the conversion must be carried out using the factor $\sqrt{3}$.

C. Current

The line current to circulate through the windings is given by the following equation:

$$I = P_a/\sqrt{3} * E \quad (3)$$

In the case of the primary, it is necessary to use the factor $\sqrt{3}$ to obtain the phase current, since in a delta connection, the line and phase current are different.

$$I_1 = \left(\frac{3000}{\sqrt{3} * 3000} \right) = 0.577A \leftarrow \text{line current}$$

$$I_1 = \left(\frac{0.577}{\sqrt{3}} \right) = 0.333A \leftarrow \text{phase current}$$

$$I_2 = \left(\frac{3000}{\sqrt{3} * 230} \right) = 7.53A$$

D. Caliber selection

Based on the currents obtained, the gauge [3] is selected.

TABLE 3
CONDUCTOR SIZES ACCORDING TO CURRENT

AWG number	Diameter in mm	Section in mm ²	Current in Amperes
12	2,053	3.31	9.3
26	0.4049	0.13	0.361

- Primary selected gauge: 26AWG
- Selected gauge for secondary: 12AWG

E. Core Area

The calculation of the area of the core is done by means of the equation:

$$S = V_e * (1 \times 10^8) / (4.44 * f * B) \quad (4)$$

Where B is the maximum induction in Gauss, this maximum induction, in transformers can take values that depend on the type of service [2], figures of 10,000 to 13,000 are usually used for intermittent service and values of 13,000 to 15,000 for constant service, in this case, a value of 15,000 Gauss (1.5 T) was taken since the aim is to design a transformer with constant service.

Therefore:

$$S = 1.37 * (1 \times 10^8) / (4.44 * 60 * 15000) = 34.28cm^2$$

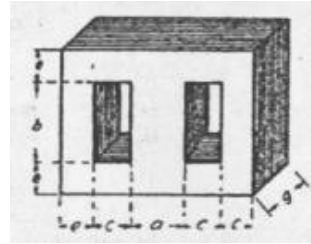


Illustration1. Dimensions of a three-phase armored core

To size the rest of the transformer, the equations established by [2] are used.

$$c = \sqrt{N * I / 75 * K_c * \delta} \quad (5)$$

In (5) the current density is represented by δ , While K_c is the fullness factor of copper

A value of $\frac{1A}{mm^2}$ has been taken for the current density and a value of 0.4 for the copper form factor based on the graph available in [4]. By calculating the value established by (5) we have

$$c = \sqrt{97 * 7.53 / 75 * 0.4 * 1} = 4.93cm$$

While the height of the column or window is 3 times the value of c:

$$b = 3 * c \quad (6)$$

$$b = 3 * 4.93 = 14.79cm$$

The core can have a square section, in which case its side is the root of the section, therefore, its value will be:

$$a = \sqrt{34.28cm^2} = 5.85 cm$$

F. Sheet selection

TABLE 4
SHEET METAL MODELS - PRODIN FERRITE

Model	Central R.	Abroad	Window
EI 80/80	16	80x80	16x48
EI 100/100	20	100x100	20x60
EI 125/125	25	125x125	25x75
EI 150/150	30	150x150	30x90
EI 170/170	3.4	170x170	34x102
EI 190/190	38	190x190	38x114
EI 200/200	40	200x200	40x120
EI 220/220	44	220x220	44x132
EI 250/250	50	250x250	50x150
EI 280/280	56	280x280	56x168
EI 300/300	60	300x300	60x180
EI 350/350	70	350x350	70x210
EI 400/400	80	400x400	80x240

Due to the measurements found previously, it is concluded that an EI 250/250 sheet should be used, since the measurements are very approximate to those obtained in the previous calculations, being 50mm wide and 150mm high for the window.

From this the depth of the core is calculated with the measurements provided by Prodin Ferrite:

$$d = 34.28cm^2 / 5cm = 6.86cm$$

The thickness of the EI 250/250 sheet is 0.5mm, from this the number of sheets is calculated.

$$Number\ of\ sheets = 68.6mm / 0.5mm = 137\ sheets$$

IV. MATERIAL TO USE

M-22 transformer steel will be used. Specifications for this material are provided by the FEMM program. The BH curve for this material is the following:

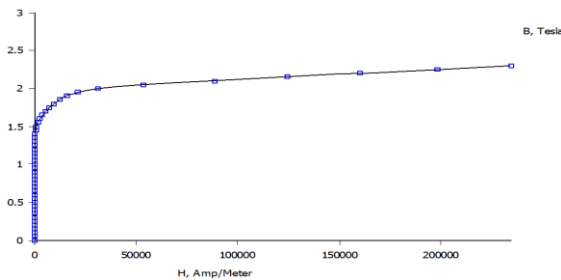


Illustration3. BH curve steel M-22

V. FINAL SPECIFICATIONS

- The following gauges will be used for the windings
 - Primary: 26 AWG

- Secondary: 12 AWG
- Rated current
 - Primary: 0.333 A
 - Secondary: 7.53
- The number of turns for the windings will be
 - Primary: 2190
 - Secondary: 97
- The sheet to be used according to Prodin Ferrite specifications is EI 250/250
- The number of plates that will be used is 137

VI. FEMM SIMULATION

A. Initial test

With $I_{excitation} = (0.07)(0.333) = 0.02331 A$ for the high voltage winding "B" and the two remaining windings A and C with:

$$I = -I_{excitation} / 2 = -0.011655 A$$

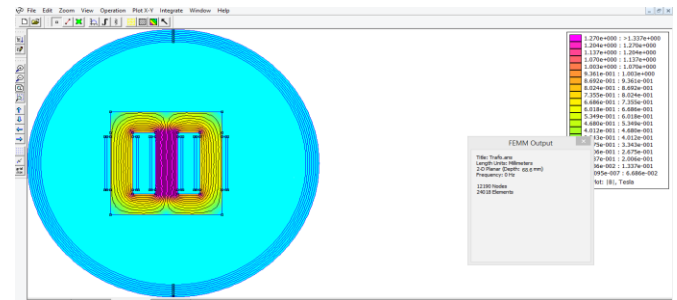


Ilustración 2. Simulación inicial en FEMM

When performing the simulation in FEMM, the magnetic induction with the previous data is 0.8 T, this is achieved with a high excitation current in each winding. The excitation current is only a percentage of the nominal, generally 3% to 6-7% when applying that consideration an induction of 1.33T is obtained, which is a value less than 1.5 T (15,000 Gauss) so it is necessary to make changes to the transformer measurements to obtain an induction of 1.5 T.

We start again from the equation $E = 4.44NBS$ where the magnetic induction and the emf $E \approx U_{1.62}$ remain constant, so only the number of turns of each winding and the area of the core can be varied.

To balance the operation, the number of turns of both the primary and secondary will be multiplied by 2.5, as well as the section will be divided by 2.5 which makes a balance, without altering equations, the following is obtained:

$$N_1 = 2.5 * 4190 = 5,475$$

$$N_2 = 2.5 * 97 = 242.5 \approx 243$$

$$S = 34.28cm^2 / 2.5 = 13.712cm^2$$

Now, the calculations made previously are carried out again, but with the values that have just been calculated:

$$c = \sqrt{243 * 7.53 / 75 * 0.4 * 1} = 7.80 cm$$

$$b = 3 * c = 3 * (7.80 cm) = 23.429 cm$$

Due to the measurements found previously, it is concluded that an EI 400/400 sheet should be used since the measurements are very approximate to those obtained in the previous calculations. From the above, the depth of the core is calculated:

$$d = 13.712 \text{ cm}^2 / 8 \text{ cm} = 1.714 \text{ cm} = 17.14 \text{ mm}$$

The thickness of the EI 400/400 sheet is 0.5 mm, from this we calculate the number of sheets.

$$\text{Number of sheets} = 17.14 \text{ mm} / 0.5 \text{ mm} = 34 \text{ sheets}$$

B. Corrections to final specifications

1. The following gauges will be used for the windings:
 - a. Primary: 26AWG
 - b. Secondary: 12AWG
2. Rated Current:
 - a. Primary: 0.333A
 - b. Secondary: 7.53A
3. The number of turns for the windings will be:
 - a. Primary: 5475
 - b. Secondary: 243
4. The sheet to be used according to specifications will be Prodin Ferrite EI 400/400
5. The number of plates that will be used is 34.

C. Simulation with corrections on the discharge side.

With $I_{excitation} = (0.07)(0.333) = 0.02331 \text{ A}$ and the remaining two windings A and C with $I = -I_{excitation} / 2 = -0.011655$ and the low side windings at zero.

The high windings have been excited with a current $I_0 = 7\% I_1$ current and the low windings have been left at zero (vacuum test).

As can be seen, a magnetic induction of 1.42T is already obtained, it has been decided to establish the measurements calculated after this simulation.

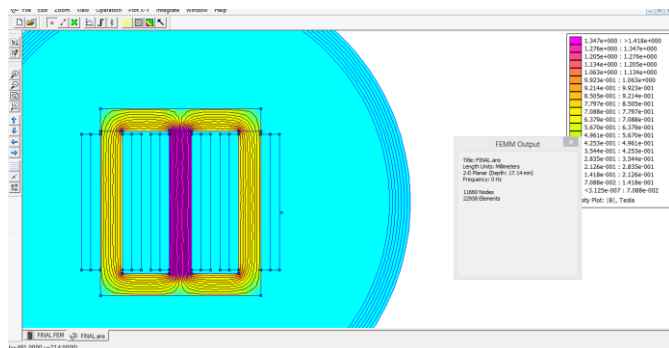


Illustration4. Simulation after making corrections

VII. OBTAINING THE PARAMETERS OF THE EQUIVALENT CIRCUIT

A. High side

The nominal current value of the primary is excited with 7%, and the other circuits created in FEMM [5] are left with a zero current value. When simulated, an information table is obtained as shown below. proceeds to verify the same data for the windings that constitute the high side (A and C) and the procedure is followed.

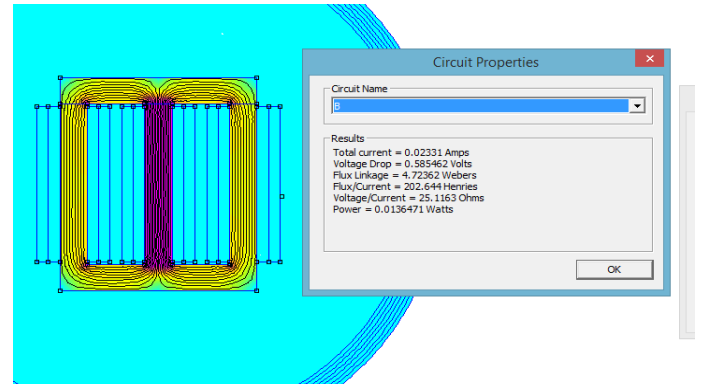


Illustration5. Central column arousal (high)

1) Center column B

Flow link:

$$A = -2.36072 \text{ Wb}$$

$$B = 4.72366 \text{ Wb}$$

$$C = -2.35991 \text{ Wb}$$

$$\Phi_{mutuo} = (-2.36072) + (-2.35984) = 4.72056 \text{ Wb}$$

$$\Phi_{disp} = \Phi_B - \Phi_{mutual} = 4.72388 - 4.72126 = 0.0031 \text{ Wb}$$

$$L_{\mu B} = \frac{\Phi_{mutuo}}{i} \quad (7)$$

$$L_{\mu B} = 4.72056 / 0.02331 = 202.51 \text{ H}$$

$$X_{\mu B} = 2\pi f L_{\mu B} \quad (8)$$

$$X_{\mu B} = 2\pi(60)(202.51) = 76,344.47\Omega$$

$$L_{disp,B} = \frac{\Phi_{disp}}{i} = 0.0031 / 0.02331 = 0.1329 \text{ H}$$

$$X_{disp,B} = 2\pi f L_{disp,B} = 2\pi(60)(0.1329) = 50.102\Omega$$

$$R_{Cu,B} = 25.1163\Omega$$

2) Left column A

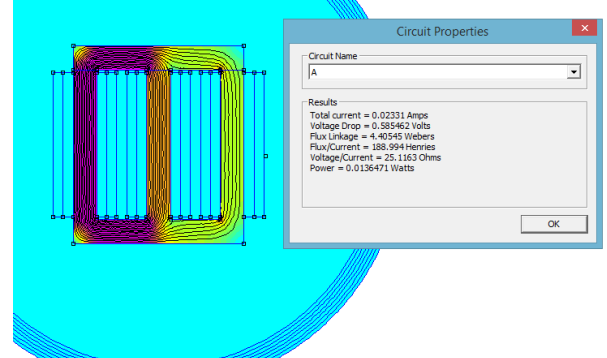


Illustration6. Left column excitement (high)

Flow link:

$$A = 4.40545 \text{ Wb}$$

$$B = -2.95666 \text{ Wb}$$

$$\begin{aligned}
C &= -1.44245 \text{ Wb} \\
\Phi_{mutual} &= (-2.95666) + (-1.44245) = 4.39911 \text{ Wb} \\
\Phi_{disp} &= \Phi_A - \Phi_{mutuo} = 4.40545 - 4.39911 = 0.00634 \text{ Wb} \\
L_{\mu A} &= \Phi_{mutuo}/i = 4.39911/0.02331 = 188.72 \text{ H} \\
X_{\mu A} &= 2\pi f L_{\mu A} = 2\pi(60)(188.72) = 71,145.76\Omega \\
L_{disp,A} &= \Phi_{disp}/i = 0.00634/0.02331 = 0.2719 \text{ H} \\
X_{disp,A} &= 2\pi f L_{disp,A} = 2\pi(60)(0.2719) = 102.50\Omega \\
R_{Cu,A} &= 25.1163\Omega
\end{aligned}$$

3) Right column C

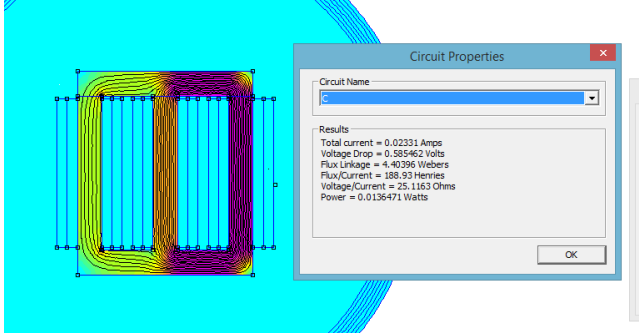


Illustration7. Right column excitement (high)

Flow link:

$$\begin{aligned}
A &= -1.44168 \text{ Wb} \\
B &= -2.95591 \text{ Wb} \\
C &= 4.40396 \text{ Wb} \\
\Phi_{mutual} &= (-1.44168) + (-2.95591) = 4.39759 \text{ Wb} \\
\Phi_{disp} &= \Phi_C - \Phi_{mutuo} = 4.40396 - 4.39759 = 0.00637 \text{ Wb} \\
L_{\mu C} &= \frac{\Phi_{mutual}}{i} = \frac{4.39759}{0.02331} = 188.65 \text{ H} \\
X_{\mu C} &= 2\pi f L_{\mu C} = 2\pi(60)(188.65) = 71,119.37 \Omega \\
L_{disp,C} &= \frac{\Phi_{disp}}{i} = \frac{0.00637}{0.02331} = 0.2732 \text{ H} \\
X_{disp,C} &= 2\pi f L_{disp,C} = 2\pi(60)(0.2732) = 102.99\Omega \\
R_{Cu,C} &= 25.1163\Omega
\end{aligned}$$

To obtain the value of X_{μ} of the parallel branch of the equivalent circuit, an average of $X_{\mu A}$, $X_{\mu B}$ y $X_{\mu C}$

$$X_{\mu} = 72,869.87\Omega$$

To obtain the resistance of the parallel branch, the volume of the core is calculated

$$V = 0.000785402 \text{ m}^3$$

It is also necessary to know the density of pure iron.

$$\begin{aligned}
\rho &= 7,879 \text{ Kg/m}^3 \\
m &= (7,879)(0.000785402) = 6.18111374 \text{ Kg}
\end{aligned}$$

According to the tables of magnetic characteristics of the grain-oriented sheet considering the highest losses, in this case there are 8 W for each Kg, therefore:

$$P_{fe} = \left(8 \frac{\text{W}}{\text{Kg}}\right) (6.18111374 \text{ Kg}) = 49.44890992 \text{ W}$$

Using the formula:

$$P_{Fe} = 3V_{\phi} I_{Fe} \text{Cos}\phi \quad (9)$$

It is known that $\text{Cos}\phi = \text{Cos}(0) = 1$ since I_{fe} pulses in phase with the voltage.

Solving I_{fe} we obtain:

$$I_{Fe} = \frac{P_{Fe}}{3V_{\phi}} = \frac{49.44890992}{3(3000)} = 5.49 \text{ mA}$$

It's known that:

$$I_{Fe} = V_{\phi} / R_{Fe} \quad (10)$$

The resistance value of the parallel branch is obtained

$$R_{Fe} = 546.018 \text{ k}\Omega$$

To obtain X_1 from the series branch of the primary side, we need an average of $X_{dis,A}$, $X_{dis,B}$ y $X_{dis,C}$

$$X_1 = 85.19\Omega$$

For the resistance R_1 of the series branch of the primary it will not be necessary to make an average since it is the same in all 3 cases, therefore

$$R_1 = 25.1163\Omega$$

B. Low side

With $I_{excitation} = (0.07)(7.53) = 0.5271 \text{ A}$ for the low voltage winding "b" and the remaining two windings a and c with $I = -\frac{I_{excitacion}}{2} = -0.26355 \text{ A}$ and the high side windings at zero.

The nominal current value of the secondary is excited with 7%, and the other circuits created in FEMM are left with a zero current value. When simulated, an information table is obtained as shown below. We proceed to verify the same data for the windings that constitute the low side (a and c) and the procedure is followed.

1) Center column b

$$R_b = 0.0433854 \Omega$$

Flow link:

$$\begin{aligned}
b &= 0.209682 \text{ Wb} \\
a &= -0.104792 \text{ Wb} \\
c &= -0.104711 \text{ Wb} \\
\Phi_{mutual} &= (-0.104792) + (-0.104711) = -0.209503 \text{ Wb}
\end{aligned}$$

$$\begin{aligned}
\Phi_{disp} &= \Phi_b - \Phi_{mutuo} = 0.209682 - 0.209503 \\
&= 0.000179 \text{ Wb}
\end{aligned}$$

$$X_{disp} = 2\pi f \left(\frac{\Phi_{disp}}{i}\right) = 2\pi(60) \left(\frac{0.000179}{0.5271}\right) = 0.1280 \Omega$$

Since the equivalent circuit must be referred to the primary, it refers X_{disp} to the primary because it is in the secondary

$$m = \frac{3000}{230} = 13.04$$

$$X'_{disp} = X_{disp} * m^2 = (0.1280)(13.04)^2 = \mathbf{21.78\Omega}$$

2) Left column a

$$R_a = 0.0433854 \Omega$$

Flow link:

$$a = 0.19567 \text{ Wb}$$

$$b = -0.131258 \text{ Wb}$$

$$c = -0.0640659 \text{ Wb}$$

$$\phi_{mutuo} = (-0.131258) + (-0.0640659) = 0.195323 \text{ Wb}$$

$$\begin{aligned} \phi_{disp} &= \phi_a - \phi_{mutuo} = 0.19567 - 0.195323 \\ &= 0.000347 \text{ Wb} \end{aligned}$$

$$X_{disp} = 2\pi f \left(\frac{\phi_{disp}}{i} \right) = 2\pi(60) \left(\frac{0.0003291}{0.5271} \right) = 0.2481 \Omega$$

$$m = \frac{3000}{230} = 13.04$$

$$X'_{disp} = X_{disp} * m^2 = (0.2481)(13.04)^2 = 42.21 \Omega$$

3) Right column c

$$R_c = 0.0433854 \Omega$$

Flow link:

$$c = 0.195603 \text{ Wb}$$

$$a = -0.064032 \text{ Wb}$$

$$b = -0.131223 \text{ Wb}$$

$$\phi_{mutuo} = (-0.064032) + (-0.131223) = 0.195255 \text{ Wb}$$

$$\begin{aligned} \phi_{disp} &= \phi_c - \phi_{mutuo} = 0.195603 - 0.195255 \\ &= 0.000348 \text{ Wb} \end{aligned}$$

$$X_{disp} = 2\pi f \left(\frac{\phi_{disp}}{i} \right) = 2\pi(60) \left(\frac{0.000348}{0.5271} \right) = 0.2488 \Omega$$

$$m = \frac{3000}{230} = 13.04$$

$$X'_{disp} = X_{disp} * m^2 = (0.2488)(13.04)^2 = 42.33 \Omega$$

Since $R_a = R_b = R_c = 0.0433854 \Omega$ we refer it to the primary to obtain the equivalent circuit referred to the primary.

$$R'_2 = R_m^2 = (0.0433854)(13.04)^2 = 7.38\Omega$$

An average of the X'_{disp} values is obtained to obtain X'_2
 $X'_2 = 35.44\Omega$

VIII. EQUIVALENT CIRCUIT

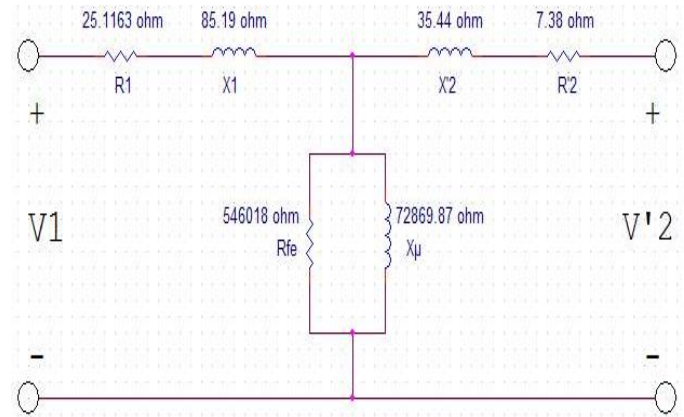


Illustration8. Equivalent circuit of three-phase transformer

IX. CONCLUSION

It can be concluded that the theoretical foundations are very useful for the design of transformers. The main objective was achieved, which was to design a 3000V/230V AC transformer with an amperage of 0.333A as nominal current on the high voltage side and an apparent power of 3000VA. Furthermore, it can be concluded that the simulation tools, in this case FEMM, allowed us to corroborate that the conditions established for the machine in design are met, however, their most important utility is the contribution of data to obtain the necessary parameters for the equivalent circuit of the transformer.

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