Bulletin of Electrical Engineering and Informatics
Vol. 9, No. 1, February 2020, pp. 57~66
ISSN: 2302-9285, DOI: 10.11591/eei.v9i1.1679

Optimal design of a three phase magnetic flux leakage transformer for industrial microwave generators

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Article Info

Article history:

Received Jul 7, 2019
Revised Sep 26, 2019
Accepted Nov 30, 2019

Keywords:

Magnetron
Microwave
Modeling
Optimization
Power supply

ABSTRACT

This paper aims to get an optimal high voltage magnetic flux leakage transformer design of a three-phase shell type. Optimal design of transformer requires determination of design variables to optimize a particular objective and satisfying a set of constraints. The objective function is to minimize the total mass and reduce the volume of the transformer. This function depends on inputs, which are divided into optimization variables. Each optimization variable varies within a certain interval thus defining a global search space. It is within this space that we seek the optimal solution. The constraints: maximum and average current of magnetron anode are part of the problem in order to limit the overall search space. The results obtained indicate that the method has provided a global optimum. The computation time and cost of active material are much reduced compared with the conventional design results.

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1. INTRODUCTION

Optimization presents the way to find out the best possible optimum design, and at the same time satisfies all limitations or restraints imposed on its performance. Several techniques have progressed through centuries to deal with the optimal solution. Some of them are traditionally based on mathematical formulation and others are non-traditional based on soft-computing techniques.

As far back as the beginning of the 20th century, early research in transformer design attempted to reduce much of this judgment in favor of mathematical relationships [1, 2]. The manufacturers started to research optimization methods [3, 4]. They sought to reduce much of this judgment with analytical formulas using a computer was a pioneer by [2, 5]. Later [6-9] suggested a method for getting an optimized design of distribution transformer. Several other techniques were also used [10-13].

Looking for the optimal solution requires many iterations. It is difficult to accelerate the same through simple calculations using a calculator. To get an optimal solution option must be made to a digital computer. It can perform calculations at an extremely high condition and it has got a large amount of memory. In fact, it is the advantage of the computer, which has revolutionized the field of optimization.

The magnetic flux leakage transformer (MFLT) is the most important and costly components used in power supply systems. A good transformer design satisfies certain functions and requirements, such as powering many magnetrons by keeping the same transformer with respecting the constraint imposed without damaging them. We can satisfy these requirements with various designs [14, 15]. The aim of this study is to find the most economical choice and arrive at an optimum design respecting the limitations imposed by the constraint functions. As a result is to reduce the volume, ensure better utilization of material, it saves space, and reduce loss, consequently get the lowest cost unit. In the case of the MFLT, we considered several aspects of the transformer design such as core shape, size, properties, copper wire turn, etc.

Minimization of the volume and the weight depend on inputs that are divided into optimization variables. These variables are the size of the magnetic circuit characterized by the width of outer limb (a), the number of secondary turns (n_2), the size of each gap between the two shunts and the magnetic circuit (e) and the number of stacked sheets (n_3).

2. GEOMETRY OPTIMIZATION OF THE MAGNETIC FLUX LEAKAGE TRANSFORMER

The cross section for shell type transformer is a rectangular shape as shown in Figure 1, which is a typical three-phase three-limbed core structure used for stable power supply applications. The core is made by stacking varnished laminations of silicon steel SF_{19}. Either copper is used as conductor material. The primary and secondary windings are wound in the center of the core columns. Different from the ordinary transformer, the flux leakage flowing in the magnetic shunts could not be ignored [14, 16]. There are two vertical shunts for each phase composed of silicon steel sheets in the center. The importance of steel sheets is to provide a magnetic flux path, which laminated along the direction to reduce the iron loss. The air gaps, one at each end of the shunts, provide for different flux densities in the primary and secondary portions of the center leg.

Figure 2 presents the equivalent model quadruple in π of three-limb three-phase power supply treated and developed in previous papers [16]. Where u_{1j} and u_{2j} are the voltages at the transformers terminals. n_1, i'_{1j}, r'_{1j}, L'_{pj} and n_2, i_{2j}, r_{2j}, L_{sj} are the number of turns, the currents through the coil, the resistances and the leakage inductances of the primary and the secondary windings, respectively. L'_{shj}, i'_{sh}, i'_{pj} and i_{sj} are leakage inductances of the shunt, the currents through the shunt, primary and secondary inductance, respectively. Subscript j denotes the phase.

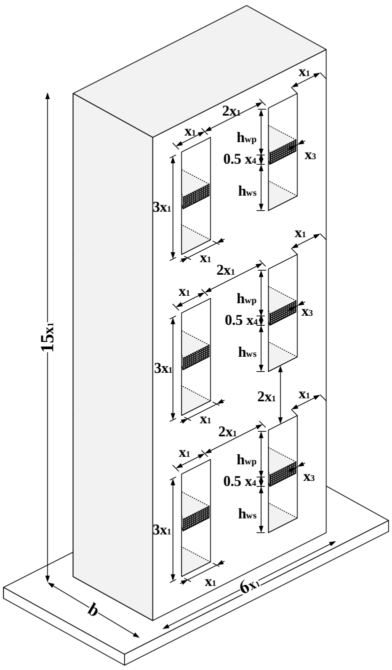

Figure 1. Investigated shapes of three-phase magnetic flux leakage transformer (Geometry and dimensions)

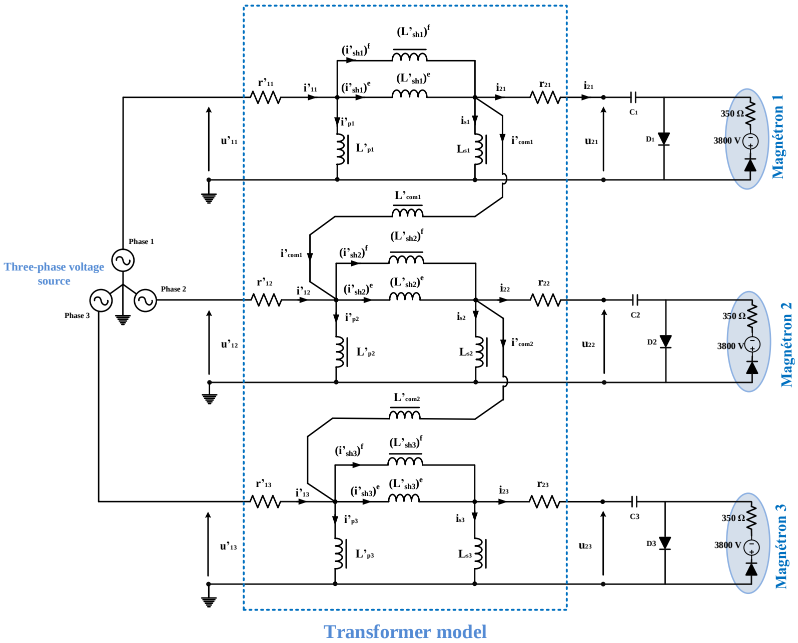

Figure 2. The equivalent electrical model of the three-phase transformer power supply one magnetron per phase [17, 18]

The obtained equivalent model nonlinear characteristics were implemented in MATLAB Simulink to simulate the transformer response of current and voltage waveforms recorded during simulation tests [16-18]. The results confirm that the reference model is available [14, 15, 17, 18] and can use it in order to get more results that are satisfying. This is the objective in the following sections. The basic design variables in this optimization method are: $X = \{x_1, x_2, x_3, x_4\}$, where x_1 is the width of the uncoiled core a, x_2 is the number of turns at the secondary n_2, x_3 is the size of each gap e and x_4 is the number of stacked plates n_3.

3. MFLT DESIGN OPTIMIZATION PROBLEM

The aim of transformer design optimization is usually to optimize an objective function, which is subjected to several constraints. Among the various objective functions, the frequently used objective functions are the minimization of volume, total mass, main material cost, space, congestion and maximization of transformer nominal power. Under parameter constraints, the problem is expressed as follows:

Minimize (or maximize) $f(X)$
$X_j^l < X < X_j^u$, i=1…n

Where X presents the vector of transformer parameter, $f(x)$ is the objective function to be minimized or maximized, X_j^l and X_j^u are lower and upper bound of j-th parameter X_j.

3.1. Optimizing techniques

This subsection proposes a new optimization approach [7, 10, 19] for this special HV magnetic flux leakage transformer. The objective function is to minimize the total mass of copper and core material, by minimizing at the same time all geometric parameters of the transformer. Searching for the optimum design using an appropriate mathematical technique. The process of optimization initiates by choosing the optimization variables and specifying the design constraints. The chosen variables are to be defined and their bounds determined. Then the objective function is to be formulated.

The principle of optimization technique proposed is to perform a set of simulations. We use essentially the reference case [14] of the equivalent model to study the sensitivity of the magnetron current, due to variations of one or more geometric parameters. Figure 3 shows the results of variables variation of the average and maximum current value at the nominal mode. We study the influence of each parameter by varying only one; the other parameters remained unchanged and identical at those specified in the reference case. It concludes that the variation of these parameters changes the electrical functioning of the high voltage power supply. In each simulation, we observe the waveforms of different electrical parameters of the circuit HV especially those giving the shape of the current magnetrons.

3.2. The objective function formulation

Each optimization design variables vary within a boundary condition. In order to frame the objective function in terms of the design variables, only solutions that verify the constraints defined. This problem can be defined by a triplet (X, D, C) where:

- $X = \{x_1, x_2, x_3, x_4\}$ is the set of variables of the problem, where x_1 represents the width of the unworn core (a), x_2 indicates the number of turns at the secondary (n_2), x_3 is the size of each gap (e) and x_4 corresponds to the number of stacked sheets (n_3)
- The fields of definition: $D = \{D_1, D_2, D_3, D_4\}$ is the set of domains of the variables, for all $k \in [1; 4]$ we have $x_k \in D_k$, thus $D_{x_1} = [15{:}2.5{:}25]$, $D_{x_2} = [2050{:}200{:}2450]$, $D_{x_3} = [0.45{:}0.25{:}1.05]$ and $D_{x_4} = [10{:}2{:}18]$.

Each of these variables is assumed to be continuous. The following constraints $C = \{C_1, C_2, C_3\}$ are imposed on the design problem:

- $I = f_1(x_1, x_2, x_3, x_4)$
- $I_m = I_{min} = f_2(I)$
- $I_y = I_{aveg} = f_3(I)$
- $Vol = f_4(x_1, x_2, x_4)$
- $C_1 : I_{i_s}^{min} \leq I_m \leq I_{i_s}^{max}$
- $C_2 : I_{y_s}^{min} \leq I_y \leq I_{y_s}^{max}$
- $C_3 : C_1, C_2$ and $min(Vol)$

With:
- The function f_1 is provided by Simulink of the magnetron current (A) for the equivalent global model.
- The function f_2 calculates the minimum value of the magnetron current in the interval [0.6, 0.64 (s)].
- The function f_3 calculates the average value of the magnetron current in the interval [0.6, 0.64 (s)].
- C_1: Constraint on the minimum current (A) which guarantees the operation of the magnetron at full power and whose values should belong to the interval [I_m^{min} I_m^{max}]=[- 1.2 -0.80].
- C_2: Constraint on the average current (mA) which guarantees the operation of the magnetron at full power and whose values should belong to the interval [I_y^{min} I_y^{max}]=[- 300 -200].
- C_3: Compound constraint which imposes the satisfaction of C_1 and C_2 and which seeks the states or the state having the minimal volume.

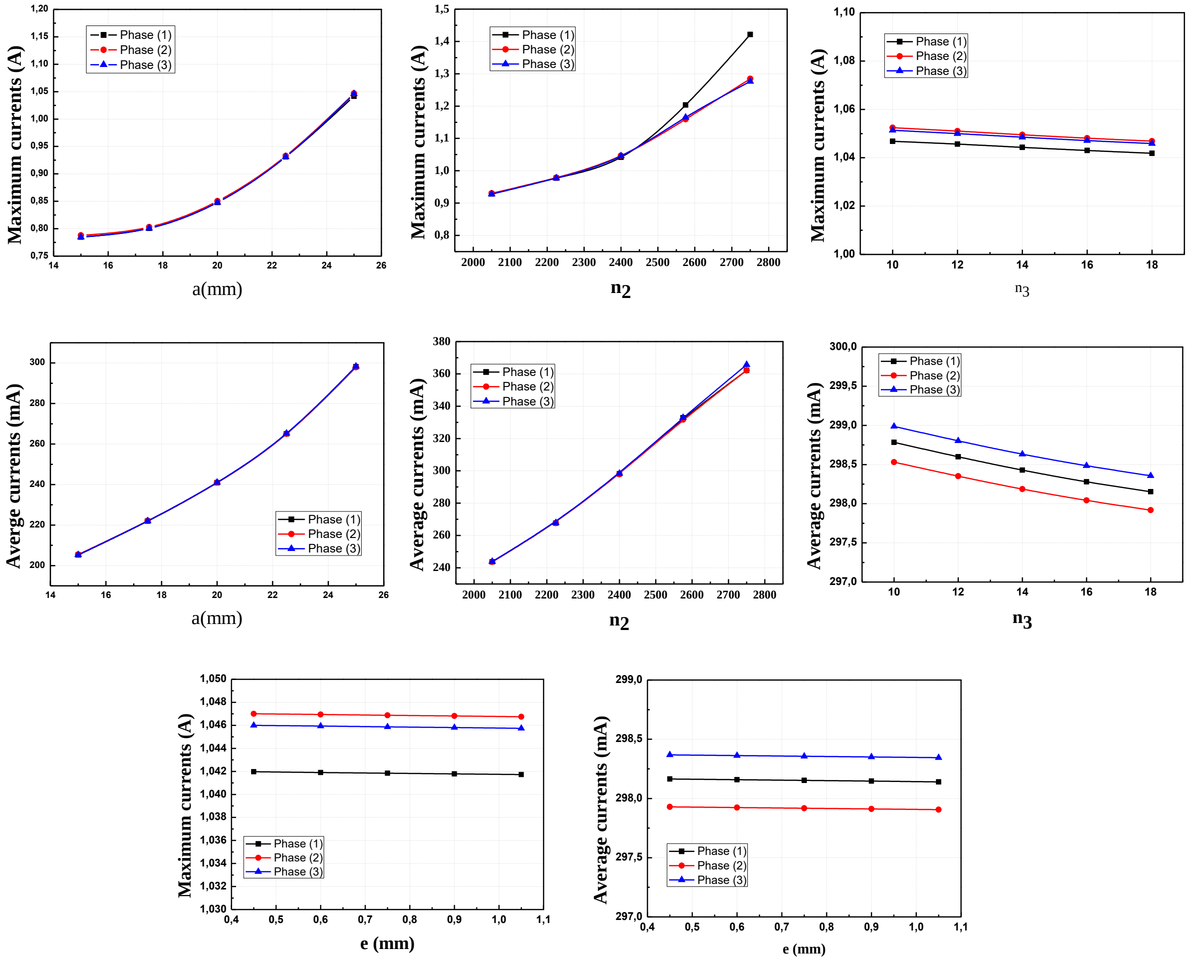

Figure 3. Influence of study design variables on the behavior of magnetron load maximum and average currents

The function f_4 calculates the volume total (cm^3) of the transformer composed of the copper and tank core volume as shown in the (1).

$$V_{Tot} = V_{cu} + V_{Fe} \tag{1}$$

Transformer tank volume can be obtained as defined with the following formula

$$V_{Fe} = (A \cdot C + 6 \cdot h \cdot (F - e) - 6 \cdot E \cdot F) \cdot B \tag{2}$$

The (2) can be rewritten in terms of design variables (x_1, x_2, and x_4) as following

$$V_{Fe} = [72x_1^2 + 3 \cdot x_3 \cdot (x_1 - 2x_4)] \cdot 60 \quad (3)$$

The volume of copper wire in a transformer depends upon the mean winding length L_m of primary and secondary windings, the total number of turns and cross-sectional area. It is given by

$$V_{Cu} = L_{pj} \cdot S_{pj} + L_{sj} \cdot S_{sj} \quad (4)$$

Calculating the length of primary and secondary turns for each phase

$$L_{pj} = L_{mj} \cdot n_1 \text{ and } L_{sj} = L_{mj} \cdot n_2$$

Calculating the mean length per turn (L_{mj}) for both primary and secondary coils

$$L_{mj} = 2 \cdot B + 2 \cdot D + 4 \cdot F \quad (5)$$

The volume total of copper wire in a transformer

$$V_{cu} = L_{mj} \cdot (n_1 \cdot S_{pj} + n_2 \cdot S_{sj}) \quad (6)$$

The (6) could write also according to x_1 and x_2

$$V_{cu} = 3 \cdot (120 + 8x_1)(424.8 + 0.20x_2) \quad (7)$$

Finally, from the (3) and. (7), we get the volume total (cm^3) of the transformer:

$$f_4(x_1, x_2, x_4) = [72x_1^2 + 3 \cdot x_3 \cdot (x_1 - 2x_4)] \cdot 60 + 3 \cdot (120 + 8x_1)(424.8 + 0.20x_2) \quad (8)$$

Calculating the total weight of copper in the transformer, m_{cu}

$$m_{cu} = \rho_{cu} \cdot V_{cu} \quad (9)$$

$$m_{cu} = 3 \cdot \rho_{cu} \cdot (120 + 8x_1)(424.8 + 0.20x_2) \quad (10)$$

Calculating the weight of the iron core in the transformer

$$m_{Fe} = \rho_{Fe} \cdot [72x_1^2 + 3 \cdot x_3 \cdot (x_1 - 2x_4)] \cdot 60 \quad (11)$$

The total weight is taken as the objective function, which is influenced by the design variables X and constraints. The function f is written like the following:

$$m_{Fe} + m_{cu} = \rho_{Fe} V_{Fe} + \rho_{Cu} V_{Cu} \quad (12)$$

The optimizing function has been computed and the expression is given below

$$f(X) = \rho_{Fe} \cdot [72x_1^2 + 3x_3 \cdot (x_1 - 2x_4)] \cdot 60 + \rho_{Cu} \cdot [3 \cdot (120 + 8x_1)(424.8 + 0.20x_2)] \quad (13)$$

Where $\rho_{Cu} = 8940$ is the mass density of copper in [Kg/m^3] and $\rho_{Fe} = 7650$ is the mass density of core material in [Kg/m^3].

3.3. Procedure for optimization

In order to get an optimal solution, the first step needs to formulate the problem, choose the design variables, define the constraints and precise the objective function. Minimum (or Maximum) bounds are imposed on the design variables. This subsection describes the method for the optimal design of a three-phase shell-type distribution MFLT using the method of sequential programming (SQP) [20-25].

The use of this method is successful in optimization of dimensioning and shape optimization. This algorithm is powerful and effective in the nonlinear programming, attempts to resolve the program directly instead of transforming it into a sequence problem of minimization without constraints, which makes this algorithm differs compared to other methods (method of optimization without constraints). The advantage of the SQP method is that it can be manipulated in MATLAB by using the function "fmincon" in the toolbox of MATLAB. This algorithm minimizes a given objective function respecting the constraints determined by the user, where the objective function, defined the total volume of the transformer with shunts, is in the following form. The algorithm can be explained in the form of pseudo-code as follows:

Algorithm:

a. Read transformer data, independent variables, constrain and define of domains of the variables.
b. Set the loop conditions for each variable for all $x_k \in D_k$.
c. Check constraint (C_3) which imposes the constraints of (C_1) and (C_2) and which seeks the states or the state having the minimal volume.
d. Accept or reject each point, check if the C_3 is verifier and go to next step. Otherwise, go to **step (b)**.
e. Formulate of the objective function and calculate the initial volume.

Once this analysis is completed, the decision is making the ability of the computer to get the best solution with respecting the constraints imposed in order to obtain the lower volume and mass.
Performance characteristics obtained from the simulation test has been listed in Table 1.

Table 1. Comparison of results obtained using the conventional design of three-phase transformer performances

Solution		S_{data}	S_1	S_2	S_3	S_4
Design variables X [a n_2 n_3 e]	x_1	25	22.5	20	17.5	15
	x_2	2400	2400	2750	2050	2400
	x_3	18	18	10	18	18
	x_4	0.75	0.9	0.9	0.45	0.75
I_{max} (A)	Phase 1	1.0418	0.932	0.931	0.829	0.785
	Phase 2	1.0469	0.933	0.932	0.833	0.785
	Phase 3	1,0459	0.931	0.931	0.829	0.788
I_{mean} (mA)	Phase 1	298,1	265.1	280.1	201.3	205.2
	Phase 2	297,9	265.1	280.0	201.5	205.4
	Phase 3	298,3	265.3	280.3	201.5	205.3
P_{mean} (W)	Phase 1	1240,9	1092.9	1157.6	820.4	835.5
	Phase 2	1239,9	1092.8	1157.4	821.3	836.2
	Phase 3	1241,8	1093.6	1158.4	820.7	835.8
Volume (cm^3)	V_{cu}	868.6	814.3	818.8	651.1	651.4
	V_{Fe}	2776.1	2254	1760.7	1376.7	1015.7
	V_{Tot}	3644.7	3068.3	2027.9	2027.9	1667.2
Mass (Kg)	m_{cu}	7.76	7.26	7.32	5.82	5.81
	m_{Fe}	21.24	17.24	13.47	10.53	7.78
	f(x)	29	24.5	20.79	16.35	16.59

It is supposed that we have a calculation for a three-phase 1650VA transformer. The input voltage source is 50Hz, 220 V sinusoidal AC voltage with a ±10% regulating range. The secondary voltage is 2230V. The transformer has 3 phases, 3 limbs; the silicon steel used for the iron core material is SF_{19}. A voltage doubler capacitor C=0.9µF and high voltage rectifier diode D_1. The main program, objective function calculation, and optimization algorithm were coded in MATLAB 2014a, including the implementation of the equivalent electrical model of the three-phase transformer power supply.

3.4. Dimensions of shell type transformer

During this work, we have taken the manufacturers' data as a reference. The following geometrical dimensions of the shell type, both optimized and reference transformer have been shown in Figures 4 and 5. Core design includes the window height, window width, and the outer and central limbs. The winding design includes the area of cross section and number of turns. The geometry design and dimension details of the optimal transformer are given below. The transformer has been obtained by precisely considering he resulted dimensions calculated from the practice described in sections above. Measurements of he dimensions obtained from the calculations have been enlisted in Table 2.

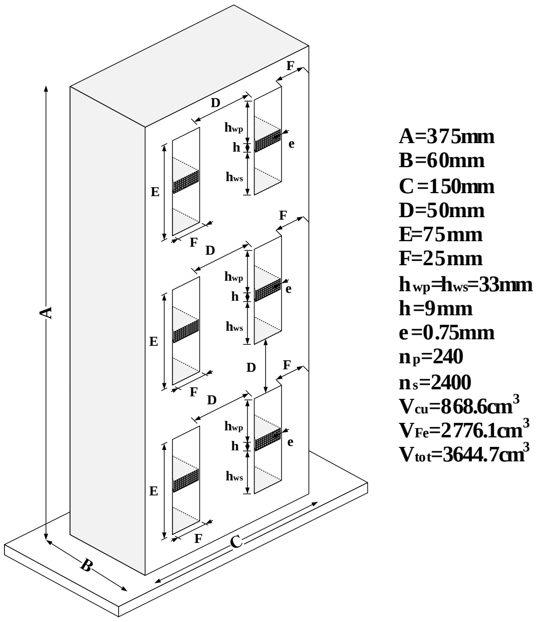

Figure 4. Dimensions of shell type magnetic shunt flux leakage transformer reference case

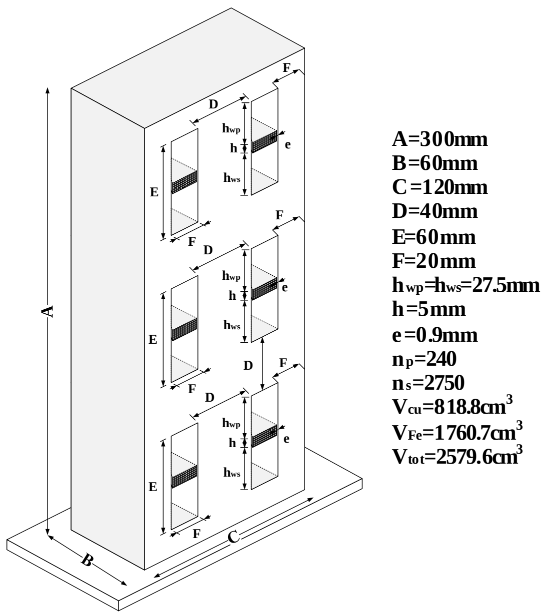

Figure 5. Dimensions of shell type magnetic flux leakage transformer optimized case

Table 2. Comparison with a manufacturer's data and optimized transformer

Dimensions		Resulted Measurements: Manufacturers' data	Resulted Measurements: Optimal Design
Core Design	Width of outer limb (D/2)	2.5 cm	2 cm
	Depth of core (B)	6 cm	6 cm
	Width of central limb (D)	5 cm	4 cm
	Central limb cross section (2ab)	30 cm^2	24 cm^2
Window Design	Height of window (E)	7.5 cm	6 cm
	Width of window F)	2.5 cm	2 cm
	Area of window (Aw)	18.75 cm^2	12 cm^2
Overall Frame Design	Overall Width (A)	15 cm	12 cm
	Overall Height (C)	37.5 cm	30 cm
Windings Design	Cross section primary (Sp)	1.77 mm^2	1.77 mm^2
	Cross section secondary (Ss)	0.20 mm^2	0.20 mm^2
	Diameter primary (φ_p)	1.5 mm	1.5 mm
	Diameter secondary (φ_s)	0.5 mm	0.5 mm
	Secondary Resistance (Rs)	65Ω	64.68 Ω
	Primary Resistance (Rp)	100 Ω	89.3 Ω
	Primary Wire Length (Lp)	71.68 m	62.72 m
	Secondary Wire Length (Ls)	768 m	770 m
	Mean Wire Length (L_m)	320 mm	280 mm
	No. of primary turns (n_p)	224	224
	No. of secondary turns (n_s)	2400	2750
Shunt Design	Height of shunt (h)	9 mm	5 mm
	No. of stacked sheets (n_3)	18	10

4. COMPUTATIONAL RESULTS AND DISCUSSION

Simulations have been conducted in order to verify the proposed optimal transformer model. The work started with study the influence of various geometrical parameters of the transformer. Then we observe their influence on the magnetron currents. The proposed algorithm is selected to study. The high voltage transformer response of the solution chosen is listed during the simulation. Therefore, Statistical results and design variable values for the best solutions can be highlighted in Table 1.

The algorithm takes into account many variations in design variables. These variations allow the investigation of a candidate solution. For each one of the candidate solutions, it is verified whether the constraints are satisfied, and if they are satisfied, the volume and mass is calculated and the solution is considered as acceptable. Finally, among the acceptable solutions, the solution S_2 with the minimum manufacturing cost is selected, which presents the optimum transformer. S_2 allows the best compromise between the total volume of the transformer and the operation of the magnetron. As a result, the objective function calculations would be reduced by 28.3%. Another 6.71% reduction is obtained for lost energy units. Based on these values of variables. The solution S_4 presents a minimum volume, but it does not allow the functioning of the magnetron in full power during its operating life.

Using the decision variables of the solution S_2, We simulated under MATLAB Simulink the electrical behavior of the HV optimum transformer for a magnetron [25]. The waveforms corresponding to this solution are shown in Figure 6. The waveforms obtained shows that these results are in perfect accordance with those obtained by the reference case, and respect the criteria recommended by the manufacturer for each phase (I_{max}<1.2 A and $I_{mean} \leq 300$ mA.) Each magnetron into a phase that operates at rated speed (220V and 50Hz in the primary side), the electrical signals in the diode, the capacitor, the magnetron, and the secondary side have the same shape as those of a conventional single-phase power supply for one magnetron. These signals are periodic but not sinusoidal and they are phase shifted 120°.

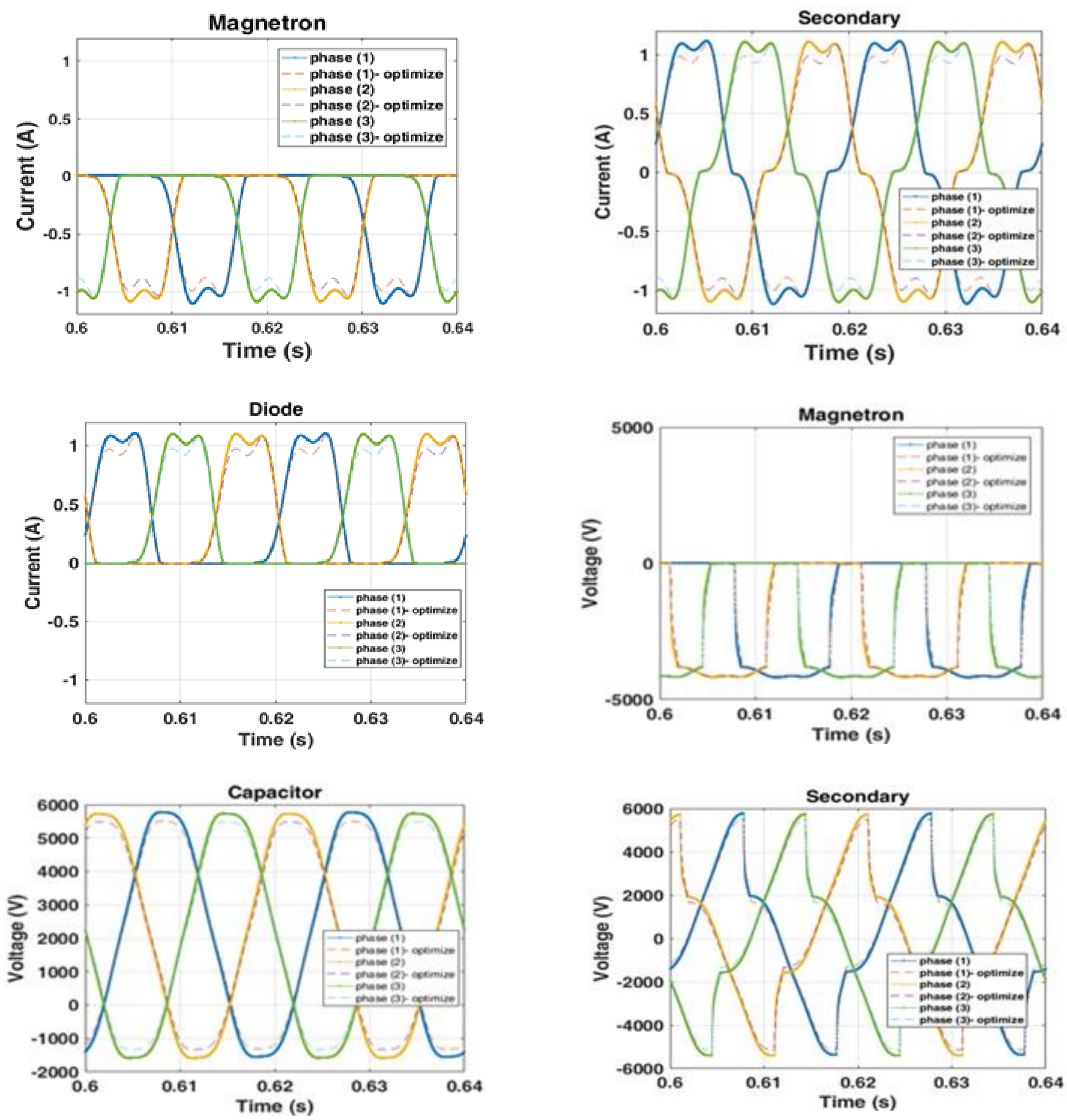

Figure 6. Simulation curves voltages and currents of the optimized transformer compared with the Manufacturers' data transformer

It is noted that the maximum allowable value of the amplitude of each magnetron’s current in the optimized transformer does not exceed the acceptable limit (<1.2A), which complies with the constraints imposed by the manufacturer. It ensures the correct functioning of the magnetron with a reasonable average current of 300mA without exceeding the recommended peak current. Given the above, the current stabilization process in each magnetron is completely ensured, which completely protects this microwave tube.

The magnetron currents regulating the process in each phase of this optimal solution was verified. While observing the stability of the current's variations in each magnetron with respect to the variations of the primary voltage of ±10% around the nominal voltage of 220 Volts. Figure 7 shows the waveforms of each magnetron's current corresponding to the respective values of 200V and 240V on the primary voltage.

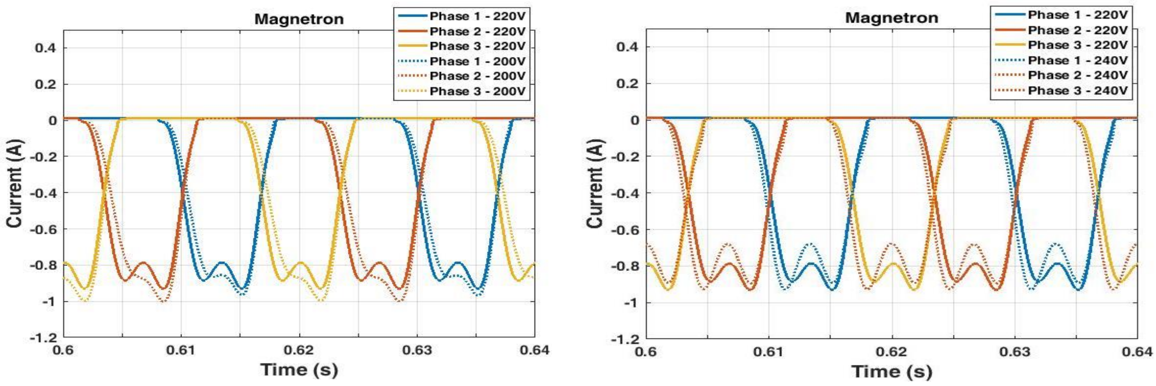

Figure 7. The voltage and current of magnetron anode for each phase with different voltage source values

5. CONCLUSION

In this paper, the detailed technique of a transformer optimization model of three-phase, shell-type transformers are presented, which can make a competitive solution. The attempt of this paper is to optimize the volume of this transformer and establish that this technique is capable of giving more solution. Thus is a viable tool for obtaining the optimal design of the three-phase transformer. Based on the value of the design variables found out by the algorithm, the dimensions of new optimized transformer selected and the performance variables have been calculated. For the validation of the model, simulation results are compared with published measurements. Although the paper is written for three-phase transformers, the developed model is suitable for the simulation of any other configuration of three-phase magnetic flux leakage transformer with several magnetrons by phase.

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