A novel cost-effective power supply model for industrial appliances based on triangular magnetic shunt transformer design

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ABSTRACT

This paper presents a new design of a magnetic shunt transformer for use in industrial microwave generators. The proposed transformer has a triangular shape and offers several advantages over existing transformer designs, including reduced volume and maintenance costs. We provide a detailed analysis of the transformer's dimensions and an equivalent model of the three-phase high voltage power supply system. The results of this study have significant implications for the field of industrial microwave generator design and could lead to the development of more efficient and cost-effective systems. The resulting model is comprised of saturable inductors capable of accounting for the non-linear phenomena of saturation. The power supply is simulated using MATLAB/Simulink with a neuro-fuzzy ANFIS approach. The results are compared to experimental validations of a single-phase reference power supply for a magnetron, validating the proposed power supply. Additionally, the simulation results demonstrate the effectiveness of the proposed design, which outperforms existing transformers in terms of volume, energy efficiency and maintenance costs.

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1. INTRODUCTION

The use of microwave radiation to heat-treat products emerged in the 1950s and 1960s with the first technological developments resulting from the work of Percy Spencer and Raytheon [1]. Nowadays, the microwave has proven its necessity in several fields of application, in particular it is used in most domestic heating and in a large number of industrial processes. The main objective is to reduce heat treatment time compared to conventional treatment, which means greater process flexibility while reducing overall energy consumption.

The magnetron is used as a source of microwave energy by transforming the kinetic energy of electrons into electromagnetic energy [2]–[5]. This magnetron requires high-performance power supplies to provide the energy needed to generate microwaves with satisfactory efficiency. There are several types of power supplies to ensure the aforementioned function. However, most of the existing power supplies present problems in terms of power utilization [6]. Consequently, the voltage doubler power supply is the most used by the majority of manufacturers of microwave applications, in particular household ovens. The advantage of using this type of power supply is to limit the need for operating power. This power supply uses a single-phase high voltage (HV) transformer with magnetic shunts, sized to operate only a single magnetron with a useful power of 800 Watts and a frequency of 2450 MHz [7].

In this sense, for an industrial application requiring several magnetrons, the current power supply requires a transformer for each magnetron, which leads as a problem, an installation cumbersomeness, more wiring, more breakdowns and additional costs due to construction, installation and maintenance. However, few studies in the scientific literature relate to the sizing, modeling and simulation of said power supplies in order to improve their performance. It is therefore essential to develop a new generation of power supplies, as well as new structures of the constituent transformers, optimized in terms of size, volume and mass. This will considerably reduce the cost of production and maintenance of this power supply, while respecting the criteria imposed by the manufacturer's magnetrons.

In this respect, this article is part of the research axis relating to the development of HV magnetron power supplies for microwave generators. Specifically, it is to develop a new generation of three-phase transformers with more advantages over existing technologies, namely the tetrahedral, 5-column, 7-column and 3-column transformer [8]–[10]. The new geometry of the magnetic circuit sized for the new transformer is triangular in shape. The sizing study is carried out taking as reference the geometric parameters of single-phase two-shunts transformer used in industry. The geometric shape found makes it possible to supply the magnetons in the correct operation.

The article is organized as follows: after a presentation of the power supply studied in section 2, a sizing study is carried out in section 3 to validate the new proposed triangular transformer geometry. The modeling and simulation of the presence of power supply are described in section 4, we present the electrical model found with the results obtained under MATLAB/Simulink using the neuro-fuzzy adaptive neuro-fuzzy inference system (ANFIS) approach for the modeling of nonlinear inductors in the model. In section 5, the results obtained by simulation are compared with those obtained experimentally for the single-phase power supply used as a reference, in addition to a comparative study, which allowed us to cite the advantages of the new design compared to the old technologies. Finally, section 6 presents the conclusion of this article.

2. PRESENTATION OF THE STUDIED POWER SUPPLY

This three-phase HV power supply developed for a microwave generator constitutes a new geometry of the shunt transformer having a triangular shape. This form is recognized in the industrial world, for classic three-phase transformers, for its excellent performances such as the good energy efficiency (low iron loss when empty), the best voltage quality and the reduction of magnetic interference fields and harmonics [11]–[14].

The dimensioned three-phase transformer is supplied by mains voltage from its primary windings connected to a balanced three-phase low voltage (LV) source of 220 V. It delivers at the output of its secondary windings a three-phase HV of 2300 V to supply a voltage doubling cell and a magneton at each phase. The transformer further includes a secondary winding distinguished from the magnetron heater filament [15]. Figure 1 presents a synoptic diagram of the new power supply studied.

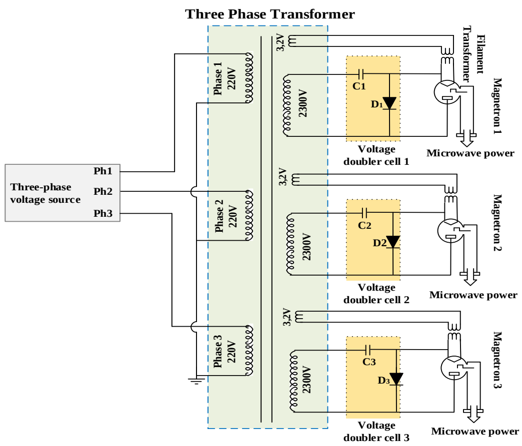

Figure 1. Diagram of the three-phase HV power supply studied

The sized magnetic shunt transformer is characterized, in addition to its ordinary function as a voltage booster, by the stabilization of the electric current supplying the magnetron, while respecting the manufacturer's optimal constraints (I_{avg}=300 mA, I_{min}=1.2 A). This transformer also has the ability to provide a constant voltage, good protection against overloads, excellent shock resistance and an acceptable power factor [6].

3. SIZING STRATEGIES FOR THE NOVEL TRANSFORMER

3.1. Method

The sizing study of a new triangular HV three-phase transformer with magnetic shunt for microwave power supplies aims to find a structure capable of powering the magnetrons under nominal conditions. To do this, we take as a reference the different geometric parameters of the single-phase transformer with two magnetic shunts currently used in the microwave industry indicated in [8]. The proposed design of the new triangular-shaped three-phase HV transformer is based on the single-phase HV transformer of a single magnetic shunt equivalent to the reference transformer presented in [7]. The sizing of the design proposed in this article is done by grouping three single-phase transformers of a single equivalent shunt in triangular shape while keeping the same nominal power supplied to the magnetrons.

From the various geometric parameters of the reference single-phase transformer, the sizing study is started first by calculating the various possibilities of the parameters of the magnetic circuit of the equivalent transformer presents a new transformer phase. These parameters can be found by respecting the following conditions; i) keep the same number of primary and secondary winding turns, ii) maintain the same magnetic properties, which implies keeping the same magnetic field density B using the same type of material also respecting the lengths of the primary closed loops ℓ_p, secondary ℓ_s set shunts ℓ_{sh}, between the two transformers, and iii) a similar distribution of the primary fluxes ϕ_p, secondary ϕ_s and lateral shunts ϕ_{sh} which amounts to keeping the same sections S for the two primary and secondary parts.

For the magnetic shunt part, flux conservation is obtained if the equivalent shunt section S'_{sh} is twice that of one of the two shunts S_{sh} of the reference transformer with:

$$2.\phi_{sh} = 2.B.S_{sh} = \phi'_{sh} = B.S'_{sh}$$

$$2.S_{sh} = S'_{sh} \quad (1)$$

The various possible configurations for the transformer equivalent to a single magnetic shunt have been treated on the basis of the predefined constraints. Among the constraints which must also be validated the sufficient location of the primary and secondary windings. To do this, it is necessary to check for each combination of the parameters found that the air surface available for the "S_{air}" winding is greater than the surface occupied by the primary and secondary windings" S_{occu-w}". In this sense, we define the copper filling factor "k_f" which is the ratio between "S_{occu-w}" and "S_{air}". In the transformer design standard, this factor must be between an interval of 0.7 and 0.4 whatever the type of conductors [16]. Once this condition has been treated, we pass to the equivalent transformer coupling in triangular form with a check to have a good configuration. Figure 2 shows the sizing strategy followed for the new transformer.

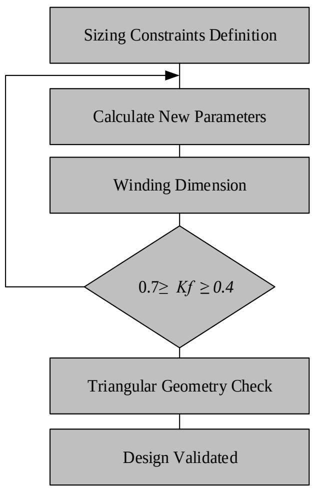

Figure 2. Sizing strategy for the new transformer

3.2. Geometry analysis of the new transformer design

The application of the sizing study made it possible to choose a geometric configuration of the HV transformer with magnetic shunt which will constitute the new triangular three-phase HV transformer shown in front view in Figure 3(a) and in top view in Figure 3(b). The new shape is designed by bringing together three single-phase magnetic shunt transformers chosen in a triangular shape. The coils are placed on the non-common cores of each phase of the transformer, we have a primary winding of n_1 turns and a secondary winding of n_2 turns. The three shunts are inserted between each of the two non-common cores between the three phases. They serve to deflect a significant part of the flux which regulates the current in the magnetrons. Each phase has a single shunt of size h, each composed of nsh plates and an air gap of overall thickness e. The dimensions and values of sections S_{air}, S_{occu-b} given by (2) and (3) are presented in Table 1.

$$S_{air} = \frac{G\times E - (d\times E)}{2} \quad (2)$$

$$S_{occu-wi} = n_i \times \pi \times \left(\frac{d_k}{2}\right)^2 \quad (3)$$

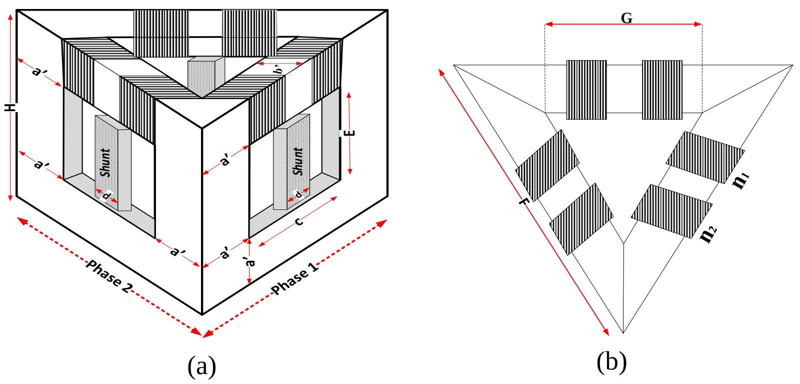

Figure 3. The geometric shape of new magnetic shunt transformer: (a) front view and (b) top view

Table 1. Geometric parameters of new transformer

Parameters	Symbols	Values
Width of the wound core	a'	54.8 mm
Depth of the magnetic circuit	b'	54.8 mm
Width of the window	C	138.5 mm
Height of the transformer shunts	d	10 mm
Height of free space in the transformer window	E	25 mm
Width of the transformer magnetic circuit	F	248.9 mm
Triangle side formed the free space	G	76.11
Height of the transformer magnetic circuit	H	139.4 mm
Primary windings	n_1	244
Secondary windings	n_2	2400
Number of stacked sheets of the shunt	n_{sh}	20
LV wire diameter	d_p	1.5 mm
HV wire diameter	d_s	0.5 mm
Air surface available for winding	S_{air}	826.4 mm^2
Surfaces occupied by the primary winding	$S_{occu-wp}$	431.2 mm^2
Surfaces occupied by the secondary winding	$S_{occu-ws}$	471.2 mm^2
The fill factor of the copper primary winding	K_{fp}	0.521
The fill factor of the copper secondary winding	K_{fs}	0.57

4. MODELLING AND SIMULATION APPROACH

The validation of transformer operation in the power supply consists of establishing an electrical model of the studied transformer based on the dimensions already defined. Transformer modeling will allow us to check the proper functioning of the entire power supply model. In the proposed modeling study, we consider a three-phase transformer without losses (hysteresis and eddy current losses) in the iron, we assume that the leakage present is only channeled in the shunt, dispersion leaks into the air being negligible. As the triangular shaped dimensioned transformer is made up of three same phases, so we take phase 1 as an example. The definition of the electric and magnetic equations made it possible to find the equivalent model of a transformer which is in the form of a quadrupole in π brought back to the secondary. In the modulization processed, the nomenclature of each physical quantity G_{ij} used is noted as follows (i=1 for the primary phase, i=2 for the secondary, j number of the phase).

4.1. Electrical equations

The Kirchhoff's voltage law applies to electrical circuits and is often used to solve complex circuits. For a three-phase circuit, the Kirchhoff's voltage equations can be expressed as (4) and (5) for each phase at the primary and secondary levels:

$$u_{1j} = r_{1j}i_{1j} + n_1\frac{d\Phi_{1j}}{dt} \tag{4}$$

$$u_{2j} = -r_{2j}i_{2j} + n_2\frac{d\Phi_{2j}}{dt} \tag{5}$$

4.2. Magnetic equations

The magnetic modeling of a transformer is mainly carried out based on the distribution of fluxes of the magnetic circuit shown in Figure 4(a) to find the reluctance circuit (R). The application of Hopkinton's law to the different closed loops of phase 1 of the circuit of the transformer reluctance presented in Figure 4(b) makes it possible to write the magnetic equations. The dimensions of the magnetic circuit are identified by the letters A, B, C, D, E, F which are relative to the average line of the magnetic flux of the different portions of the magnetic circuit.

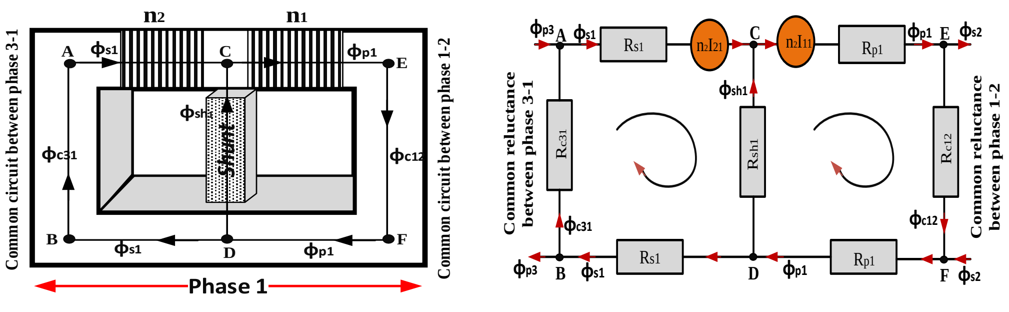

Figure 4. Magnetic representation of transformer phase 1: (a) distribution of fluxes and (b) reluctance circuit

From (6) to (11) present the different magnetic equations of phase 1.
CEFDC closed loop:

$$R_{p1}\phi_{p1} + R_{sh1}\phi_{sh1} + R_{c12}\phi_{c12} = n_1 i_{11} \tag{6}$$

ACDBA closed loop:

$$R_{s1}\phi_{s1} - R_{sh1}\phi_{sh1} - R_{c31}\phi_{c31} = -n_2 i_{21} \tag{7}$$

EABFE closed loop:

$$R_{p1}\phi_{p1} + R_{s1}\phi_{s1} + R_{c12}\phi_{c12} - R_{c31}\phi_{c31} = n_1 i_{11} - n_2 i_{21} \tag{8}$$

Conservation of flux in the first phase:

$$\phi_{p1} = \phi_{s1} + \phi_{sh1} \tag{9}$$

For the common magnetic circuits between phase 1 and the two other phases of the transformer:
Between the two phases 3 and 1 the nodes A and B:

$$\phi_{p3} = \phi_{c31} + \phi_{s1} \tag{10}$$

Between the two phases 1 and 2 the Nodes E and F:

$$\phi_{p1} = \phi_{c12} + \phi_{s2} \tag{11}$$

The study of the operation of the sized transformer in the power supply consists in finding a simple and practical model. In the modeling study we have chosen to present the equivalent model of the transformer in the form of a quadrupole in π brought back to the secondary. Such a model makes it possible to characterize each part of the magnetic circuit which cannot be seen in another type of model such as a T model [17]. By multiplying (4) and (6) by the transformer ratio n_2/n_1 and by reformulating each quantity R.ϕ and ϕ we obtain the following set of equations after development:

$$u'_{11} = r'_{11} i'_{11} + L'_{p1} \frac{d}{dt}(i'_{p1}) \tag{12}$$

$$u_{s1} = -r_{21} i_{21} + L_{s1} \frac{di_{s1}}{dt} \tag{13}$$

$$L'_{p1} \frac{d}{dt}(i'_{p1}) = L_{s1} \frac{di_{s1}}{dt} + L'_{sh1} \frac{d}{dt}(i'_{sh1}) \tag{14}$$

$$i'_{p1} + i'_{sh1} + i'_{c12} = i'_{11} \tag{15}$$

$$i'_{sh1} + i'_{c31} - i_{s1} = i_{21} \tag{16}$$

$$L'_{p3} \frac{d}{dt}(i'_{p3}) = L'_{c31} \frac{d}{dt}(i'_{c31}) + L_{s1} \frac{di_{s1}}{dt} \tag{17}$$

$$L'_{p1} \frac{d}{dt}(i'_{p1}) = L'_{c12} \frac{d}{dt}(i'_{c12}) + L_{s2} \frac{di_{s2}}{dt} \tag{18}$$

With the formula for the magnetic inductance L and the electric current i:

$$L = \frac{n_2^2}{R} = \frac{n_2^2}{\frac{\ell}{\mu.S}} \qquad \text{and} \qquad i = \frac{n_2.\phi(i)}{L}$$

The equations found correspond to the equivalent model brought back to the secondary of phase 1 of the new transformer in Figure 5.

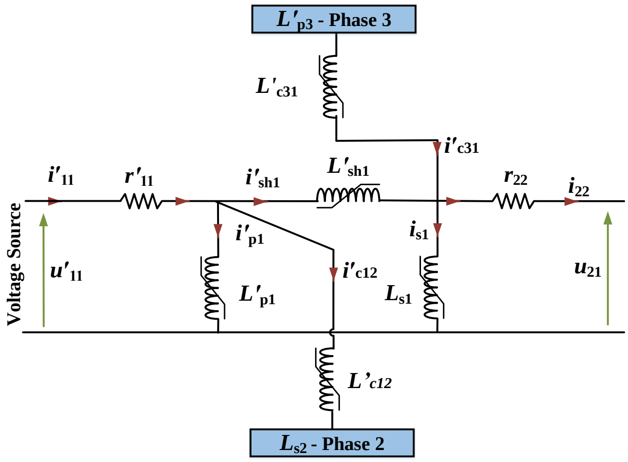

Figure 5. Equivalent electrical model of phase 1 of the new transformer

4.3. Modelling of nonlinear inductors

The nonlinear inductances of the developed model of the first phase of the new transformer presented in Figure 5 are a function of the reluctance of the portion of the magnetic circuit that it represents, on which is wound n_2 turns traversed by a current i. To be able to translate the real behaviour of each inductor in a nonlinear regime, we present each inductive element by its characteristic giving the total flux $n_2\boldsymbol{\phi}$(i) as a function of the current i.

$$\text{L (i)} \begin{cases} n_2.\phi = n_2.B.S \\ i = \frac{\ell}{n_2}.H \end{cases} \tag{19}$$

Figure 6 shows the equivalent diagram of a modelled nonlinear inductance. The B(H) block present in the nonlinear inductance model implements a neuro-fuzzy method ANFIS and is employed to adjust the B(H) curve of the ferromagnetic material used for the manufacture of the transformer [18]–[20]. This system combines the advantages of two technologies, fuzzy logic (LF) and neural network (RN). It adjusts, by learning, the various parameters of the membership functions associated with the various input and output variables B(H) of the diagnostic system (FIS) in order to obtain the best results in the diagnosis of the fault studied [21]–[24].

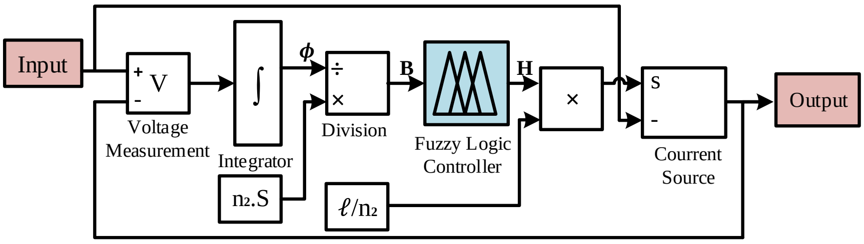

Figure 6. Equivalent model of a nonlinear inductor

The model of phase 1 of the transformer with each of its non-linear inductances makes it possible to find the equivalent electrical model of the new triangular-shaped three-phase HV transformer in the power supply. The portion of magnetic shunt is composed of two parts (iron and air gap) therefore it is modelled in the form of two inductances in parallel: the nonlinear ferromagnetic part and the constant air gap. Figure 7 shows the overall pattern of the entire new power supply.

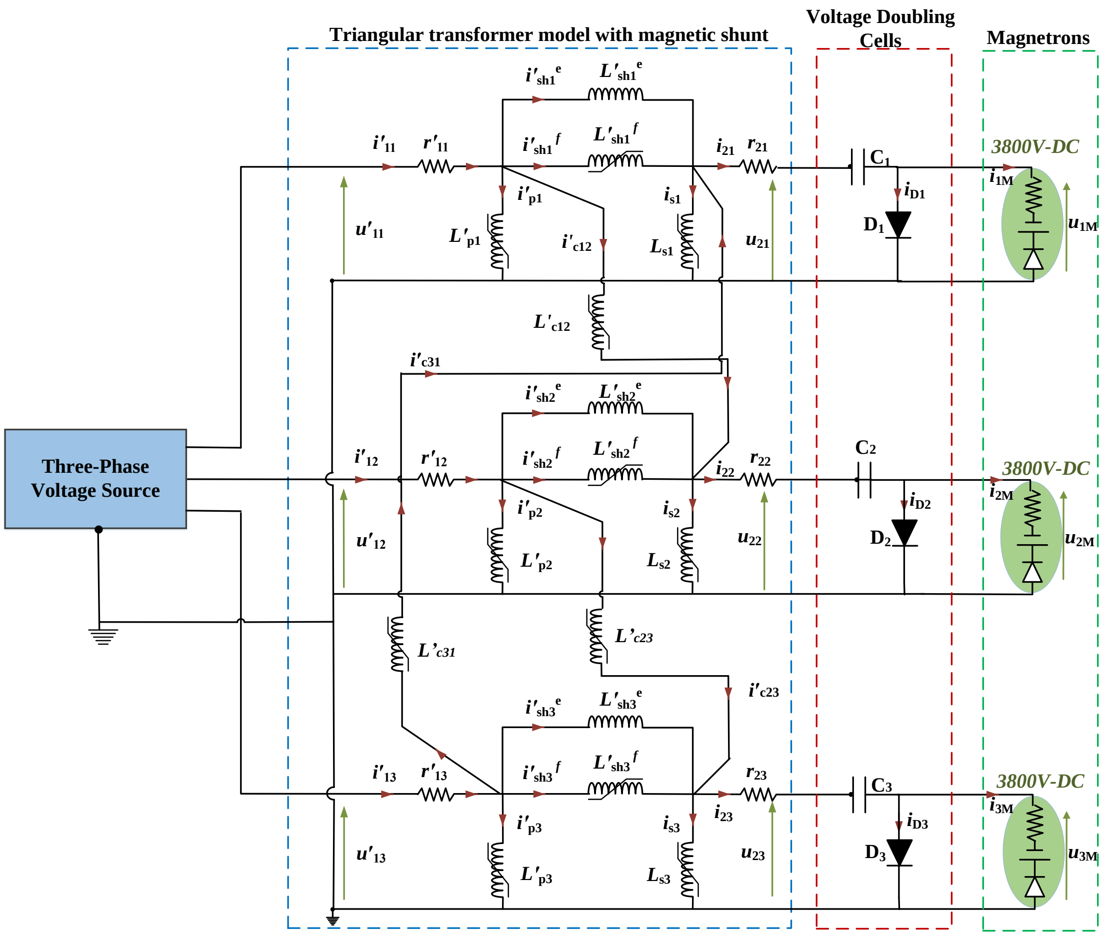

Figure 7. Electrical model of the new three-phase HV power supply with triangular-shaped transformer

4.4. Simulation of the proposed power supply

By using MATLAB/Simulink with the neuro-fuzzy ANFIS approach for the modeling of nonlinear inductors, we simulate the electrical behavior of the three-phase HV power supply of a magnetron per phase in Figure 7 composed of the following elements:

- A triangular three-phase HV transformer of nominal characteristics: f=50 Hz, U_1=220 V, U_2=2300 V and (resistance of primary brought to secondary r_{1i}=100 Ω, secondary resistance r_{2i}=65 Ω).
- A voltage doubling cell for each phase having a capacitor C_i=0.9 µF with a high voltage diode Di.
- One magnetron per phase characterized by a DC generator E=3800 V with a resistance R=350 Ω.

The different parameters observed by simulation for each phase present in Figure 8 are:

- Voltages and currents at the secondary terminals of the transformer,
- Voltages in the capacitors (C_1, C_2, C_3),
- Currents in the diodes (D_1, D_2, D_3),
- Voltages and currents at the terminals of each magnetron (1, 2 and 3).

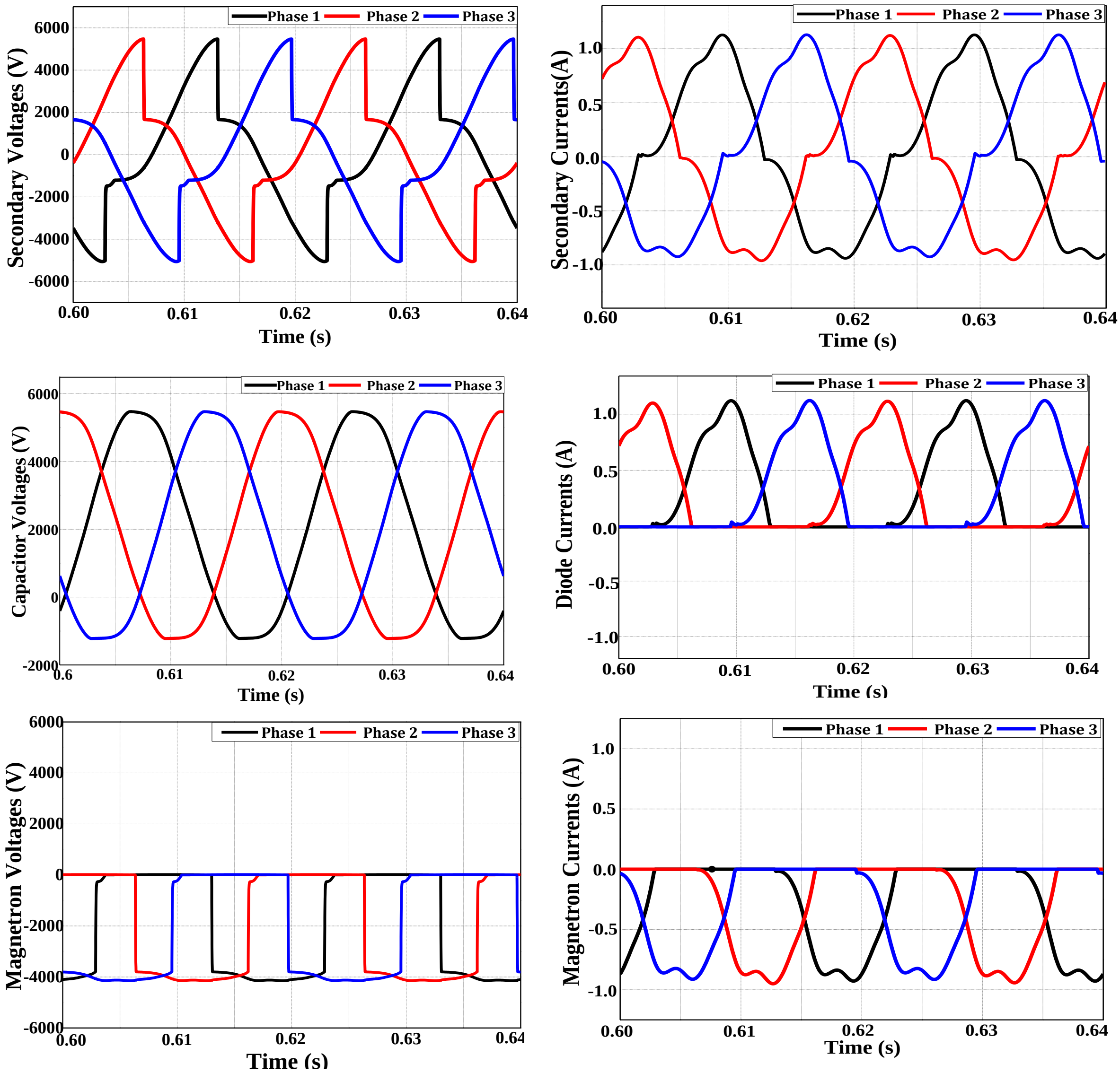

Figure 8. Voltages and currents waveforms obtained by simulation using MATLAB/Simulink

5. RESULTS AND DISCUSSION

The results found in this simulation are compared with the results of the experimental validations already treated for a reference single-phase power supply of a single magnetron presented in Figure 9. The signals of the voltages and currents of each phase found have the same form as those of a conventional power supply.

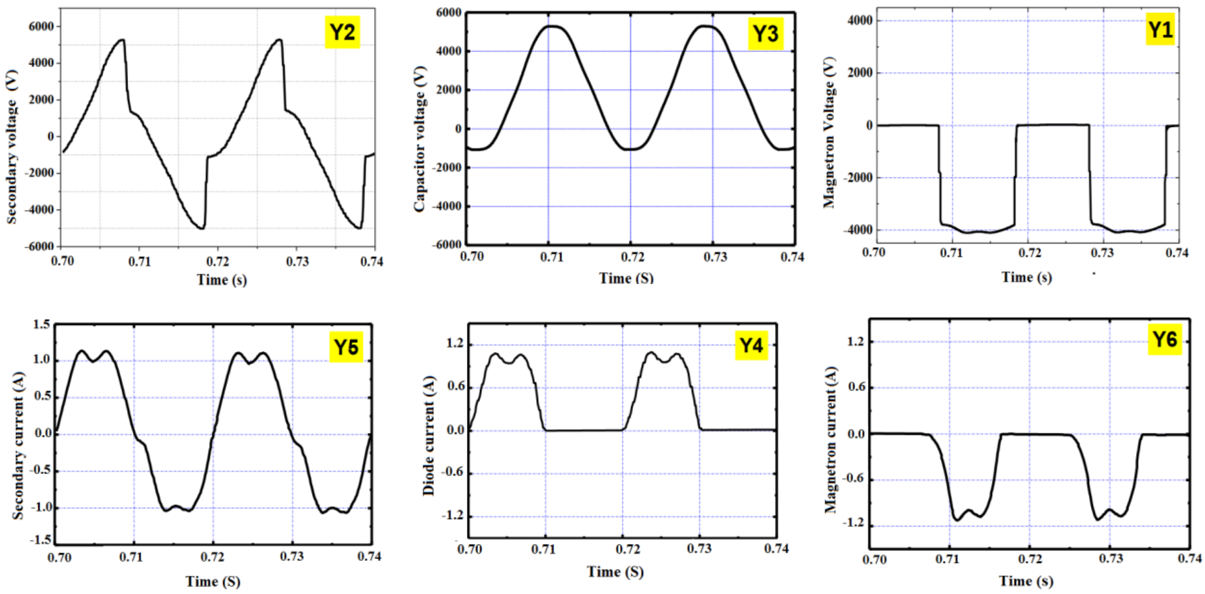

Figure 9. Voltages and currents waveforms obtained by experimental test of reference single-phase power supply

Indeed, the signals of the secondary currents and voltages of each phase keep the alternating form. The phase shift between them is 2π/3 and this confirms the absence of interaction between the three magnetrons. The currents are rectified from each diode (D_1, D_2 and D_3) and the voltage shapes found in each capacitor (C_1, C_2 and C_3) show the proper functioning of the voltage doubler cells. The maximum value of the current amplitude of each magnetron remains below 1.2 A limit imposed by the manufacturer with an average current of 296 mA. The supply voltage of the magnetrons (1, 2 and 3) is 4000 V which confirms their correct operation at full power.

This new power supply will complete the studies developed on magnetron power supplies using different types of three-phase transformer. Thus, the idea of this paragraph is to make a comparative study between the different technologies studied to date, including the one presented in this article. We will therefore list the different advantages of this new power supply. The comparison will be performed in terms of volume, maintenance, cost and energy performance.

5.1. Volume assessment of dimensioned high voltage transformer

The volume of the microwave generator power supply and its magnetic shunting transformer has always presented a disadvantage during installation. Thus, among the various possible transformer technologies, we are looking for the one that has the advantage of being less bulky. In this sense, we proceed to the volume calculation of the dimensioned HV transformer. Table 2 compares the result of the calculation of the volume of the triangular transformer carried out and those of the other different transformers proposed and validated in the literature.

Table 2. Different volumes of transformers developed

Transformer technology	Volume (cm^3)
Tétraédrique	4105.19
7 colonnes	3644.7
3 colonnes	3711
5 colonnes	4054.89
Triangulaire	3591.2

From these results, it is clear that the new triangular-shaped magnetic circuit transformer is less bulky in comparison with other technologies. It therefore has a reduced volume configuration which makes it possible to minimize the volume of the entire installation and to avoid the clutter of wiring and electrical equipment.

5.2. Cost of installation and maintenance

A reduced volume of the electrical transformer leads to a reduced amount of material used and a less cluttered and less bulky installation. The results obtained make it possible to deduce that the new triangular technology transformer can be designed at a lower cost. Thus, this last technology has the advantage of a minimal production cost compared to the other technologies studied. Having an electrical transformer of reduced volume also makes it possible to minimize the bulk of the wiring and other elements of the electrical installation. This reduction indirectly influences the maintenance of the installation by reducing failures caused during the operation of the power supply. We can thus conclude that the triangular technology of the three-phase transformer can offer the advantage of less complicated maintenance with a reduced cost compared to other types of transformers.

5.3. Energy performance

The triangular three-phase HV transformer technology, for ordinary transformers, is recognized in the industrial world by its energy performance. Several magneto-thermic studies have been initiated on classic triangular-shaped transformers showing various advantages such as: low no-load loss, reduced EMC magnetic stray fields and improved harmonic behavior [25]–[27]. These advantages can be addressed in future studies for the delta transformer with magnetic shunts.

6. CONCLUSION

The article presents a novel three-phase high voltage power supply for microwave generators, utilizing a triangular transformer. The study includes the design of the transformer and the modeling of the entire power supply, with simulations conducted using MATLAB/Simulink to validate its operation at nominal state. Additionally, a comparative study is conducted to evaluate the new technology in relation to existing three-phase transformers. Moving forward, a thermal study and optimization of the new transformer's configuration can be considered to validate its thermal behavior and reduce its geometry. This would further improve the design and performance of the power supply.

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