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AN IMPROVED POWER SUPPLY BASED ON A NEW MAGNETIC FLUX LEAKAGE TRANSFORMER FOR MICROWAVE OVENS

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ABSTRACT

This work presents a new contribution to improve the stable power supply systems, which are intended to supply magnetrons in microwave ovens. The conventional system is based on a single-phase power supply that can feed one magnetron at a time. The new system proposes a three-phase magnetic flux leakage transformer, which can supply simultaneously three magnetrons per phase. Accordingly, this work is based on a different design of the core-type five-limb transformer. The system can reduce the installation space, volume, and cabling size. This paper presents a detailed design, sizing, and implementation procedures of the new power supply, including the feasibility study of manufacturing. The modeling performed is based on the nonlinear inductances related to transformer dimensions taking into account its complex magnetic field. At last, a newly developed method describes an approach for modeling the nonlinear inductances by an analytic expression, using the Neuro-Fuzzy Network under the MATLAB-SIMULINK® code. As a result, the simulation curves are consistent with the experiments in the case of the conventional power supply used in a microwave oven. Also, the stabilization of magnetron current is insured.

Keywords: *Stable power supply, Magnetic flux leakage Transformer, Magnetron, Modelling, ANFIS-MATLAB*

1. INTRODUCTION

Currently, the industry of microwave generators uses a single-phase stable power supply based on the Microwave Oven Transformer. It is a high voltage (HV) transformer with magnetic shunts, also known as a magnetic flux leakage transformer (MFLT). In addition to ordinary transformer functions, the MFLT also has capabilities to provide constant voltage and stabilized current for the magnetron (MGT) [1-2]. The latter is a special and non-linear load. It is a high-power electron tube that requires a dual power supply circuit: a filament (cathode) power, and a stabilized anode power supply for its right operation [3]. Its role is to produce microwave energy first in radars and after in domestic and industrial microwave applications [4]. In traditional systems, each MGT requires an independent stable power supply with its own single-phase MFLT. The latter supplies a voltage-doubling cell, connected to a single MGT [5-6]. Despite its simplicity, this installation is bulky and heavy. It presents more cabling, more breakdowns, and more complex installation and maintenance. For this, other types of stable power supply have been studied [7-8], but the MFLT-based system is still widely used for its good performance, high reliability, and low cost.

In this sense, our research approach aims to simplify the actual power supply and to propose new systems able to simultaneously power a greater number of magnetrons with the same MLFT [9-10-11]. This work proposes a three-phase system with a single MFLT able to power a load of nine MGT, instead of the reel system that requires nine single-phase MFLT. The present study consists of the design sizing and validation of a new MFLT with a five-limb magnetic circuit. It is a core type transformer, which makes it easier for manufacturing and maintenance. In addition, this new design allows to save space, volume, and wiring of the total installation. Consequently, to reduce manufacturing and maintenance costs.

Few studies in the scientific literature focus on the modeling of the MFLT [1-2-5], which is the basic element of the stable power supply. In this paper, the modeling principle is different from the conventional methods used for the ordinary transformers, due to the presence of shunts and the complexity and non-linearity of the load. It is necessary to account for the stabilizing effect of the power supply and to consider the nonlinearity of the system. Our study considers that the MFLT is without iron losses. The shunts channel the leakages that exist. Thus, the leakage of air dispersion is negligible. Only the saturation phenomenon is taken into consideration. The method followed is based on the π model of the MFLT [12-13]. This model depends on the MFLT ferromagnetic material and geometric parameters. Therefore, its design and sizing will influence the modeling results.

In the first section, we start with a description of the three-phase stable power supply. Then, we present the analytical design and sizing of its new 5-limb MFLT. The latter is sized to improve the power produced while keeping the correct functioning of the nine MGTs at nominal operation. The feasibility of the design is based on the calculation of the winding space and arrangement in the transformer window. To process the validity of the MFLT design and analyze its performance, we establish, in the next section, an equivalent circuit of the power supply using the π-model of the MFLT. At last, we achieve the simulation of the nominal operation of the model with MATLAB-SIMULINK using the Neuro-Fuzzy Network (ANFIS) method [10] for the modelling of the nonlinear inductances. We use, for verification, the available experimental results of the real system. Therefore, the comparison of the simulation curves obtained with those of the experimental tests shows a good agreement. Moreover, a continuous voltage of 4000V at the output of the MFLT, and a stable current at the magnetron anode respecting the constraints set by its manufacturer, are essential for the validation of the accepted design

2. NEW STABLE POWER SUPPLY OF THREE MGTS PER PHASE

The study of the new stable power supply and its three-phase 5-limb MFLT is based on the existing power supply with the single-phase MFLT, used actually in microwave applications [14-15]. It will be the reference system for the following study.

2.1 Description of the three-phase power supply

Figure 1 shows the design of the three-phase power supply for nine MGTs. its components are chosen according to the reference data. It is mainly made of three fundamental elements:

- ✓ A three-phase MFLT of 5-limb type, which will be sized in the following paragraph. In its secondary, the winding delivers a high voltage of about 2357V applied to the loads.
- ✓ Three doubling-voltage cells in parallel per phase connected to the secondary. The cell is composed of a capacitor and an HV diode. It provides a double voltage and a rectified current to power the MGT anode.
- ✓ Three magnetrons of 800W at 2450GHz per phase. Each one is linked to the cell.

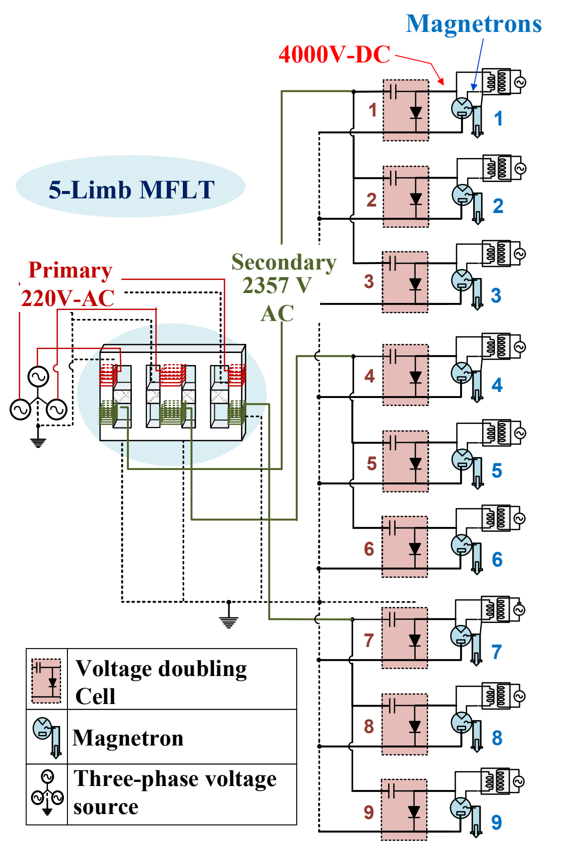

Figure 1: Design of the three-phase power supply of three MGTs per phase

The MGT requires stabilization of its power supply for its good functioning at nominal operation. Thus, the proposed system can be accepted if only it checks the current constraints imposed by the MGT manufacturer. Namely, a continuous voltage V_{DC}=4000V is recommended with an average anode current: I_m ≈300mA, without exceeding the peak current (I_{pk}<1.2A) which may damage it [16].

2.2 The MFLT design methodology

It is known that the MFLT constitutes the basic element of the MGT stable power supply system.

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Thus, designing the system consists of designing its transformer. The latter must provide, at its secondary, an electrical power sufficient to supply properly and simultaneously three identical MGT of 800W per phase in nominal operation

The design method of the 5-limb MFLT is different from the ordinary transformer design, due to the presence of the magnetic shunts. Figure2 describes the approach followed to design and validate the 5-limb MFLT for the power supply of Figure 1. It will be sized to produce a total output power of 2400W for each phase. The specifications and hypothesis of this calculation are based on the characteristics of the reference MFLT. The desired result is to obtain an MFLT design able to ensure a stabilized power supply for the proper functioning of all the MGTs. Initially, the analytical calculation will propose an MFLT feasible design verifying constraints of winding parameters. The design will be validated by simulation after modeling. The materials and dimensions of the MFLT will be adequate for possible optimization.

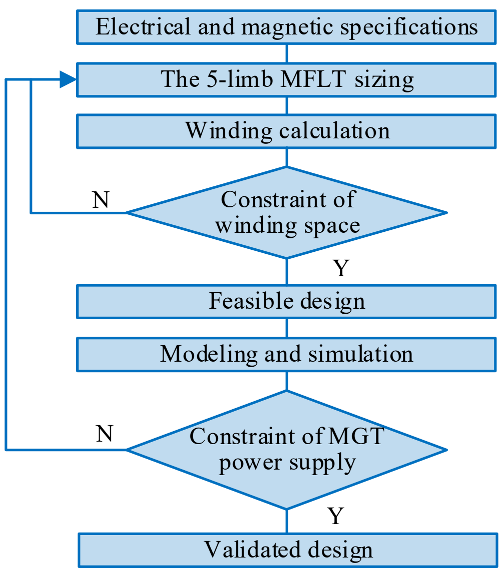

Figure 2: Methodology of the MFLT design

2.3 Design and sizing of the 5-limb MFLT

The previous works treated the stable power supplies using a three-phase MFLT of shell type, namely the tetrahedral MFLT at [9], the 3-limb MFLT at [11], and tetrahedral transformer at [10]. The present study proposes a new design of the MFLT technology in Figure 3. The obtained design is a core type MFLT with a magnetic circuit of 5-limb and 2-yokes. As is well known, core type transformers are simpler in design and permit easier assembly and insulation of the windings. The latter are accessible, so it is easy to inspect and dismantle for repair. The exposure of the windings also presents an advantage for their cooling system [17].

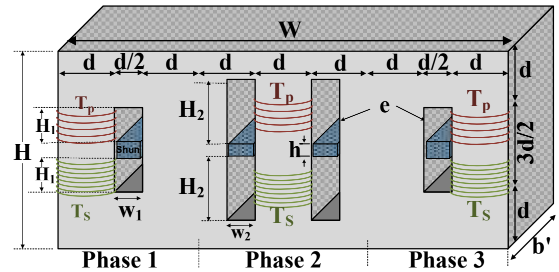

Figure 3: Design of the new 5-limb MFLT

The three primary coils (LV winding) and the three secondary coils (HV winding) are linked in a star connection. The LV winding is connected to the three-phase alternative voltage source. The HV winding delivers an HV to the three identical receivers (MGTs) in each phase.

2.3.1. Output Equation:

The 5-limb MFLT allows the double supply of the magnetron. It is composed of two coils:

- ✓ Primary winding: Generally subjected to the available voltage 220V/50Hz.
- ✓ Secondary winding: Acts as a generator delivering an HV voltage of 2350V.

The primary coil creates a variable magnetic field, its flux through the secondary coil varies in time at a frequency of "50Hz". According to Lenz's law, the fundamental relation of the transformer armature voltage is:

$$u_2 = 4{,}44 * f * T_s * B * A \qquad (1)$$

- ✓ u_2: Induced voltage (V).
- ✓ f : Frequency (Hz).
- ✓ T_s : Secondary turns Number.
- ✓ B : Magnetic induction (Tesla).
- ✓ A : Magnetic core section (m²).

Table 1: Specifications of the MFLT.

Designation	Symbol	Value
Primary rated voltage	u_1	220 V
Secondary rated voltage	u_2	2357 V
Primary rated current	i_1	21 A
Secondary rated current	i_2	1,92 A
Frequency	f	50 Hz
Primary turn number	T_p	224
Primary turn number	T_s	2400
LV wire diameter	d_p	2,6 mm
HV wire diameter	d_s	0,8 mm

Table 1 present the electrical specifications of the 5-limb MFLT. Knowing that each phase supplies three identical MGT in parallel, the good performance of these MGTs means tripling the output power of the MFLT. However, for each phase, the primary power supply voltage remains unchanged, and the distribution of the flux will always be constant. Thus, the instantaneous current supplied will triple at the output of the transformer.

2.3.2. Magnetic circuit:

The constitution of the magnetic circuit of the 5-limb MFLT repose on SF19 type blades, insulated with an air gap of 0.5mm, to reduce eddy current losses. The permeability of the material "μ" is described by the magnetization curve B(H), with "B" the flux density and "H" the magnetic field. The insertion of shunts between the primary and secondary of each phase aims to deviate an important part of the flux to regulate the anode current in the magnetron.

2.3.3. Magnetic core:

The 5-limb MFLT in Figure 3 has a rectangular core. The purpose of its sizing is to produce a power sufficient to supply all the MGTs and check at the same time the constraints of the winding layout [18-19]. The analytical calculation results in a 5-limb MFLT characterized by parameters of Table 2, based on the following hypothesis:

- ✓ The ampere-turns of the reference MFLT are tripled in the 5-limb MFLT. According to Ampère's theorem, this amounts to tripling the lengths of different parts of the reference MFLT core.
- ✓ The distribution of the flux for each phase in the 5-limb MFLT is the same of different instantaneous flux in the reference MFLT. Since the flux density is directly related to the core area, we conserve the same Areas of the reference MFLT core.

Table 2. Geometric and electric parameters of MFLT

Designation	Symbol	Value
Depth of the MFLT magnetic circuit	b'	20 mm
Width of the wound core	d	150 mm
Height of the MFLT shunts	h'	54 mm
Width of the MFLT magnetic circuit	W	1200 mm
Height of the magnetic circuit	H	525 mm
Height of free space in the MFLT window	H_f	171 mm
Width of the window	W_f	75 mm

2.3.4. Winding layout:

The objective of this calculation is to ensure that the free-space window is sufficient for the total copper windings on the primary and secondary sides. Thus, each window must be able to carry the LV and HV windings including insulation on either side of the shunt [17-20].

In this sense, we define the copper fill factor "r_{ck}" that is the ratio of the total bare conductor area "A_{ck}" to the total window area "A_f" for the primary (k = p) and the secondary (k = s) windings. It reflects the relative quantities of insulation and copper in the window.

$$r_{ck} = \frac{A_{ck}}{A_f} \tag{2}$$

With the cooper area on both sides of the shunt (cm²):

$$A_{ck} = T_k * \left(\frac{\pi * d_k}{4}\right) \tag{3}$$

And the area of the free-space window on both sides of the shunt (cm²):

$$A_f = H_f * W_f \tag{4}$$

Table 3. Winding parameters

Designation	Symbol	Value
The free-space area	A_f	128,25 cm²
Cooper area in LV winding	A_{cp}	11.87 cm²
Copper fill factor for LV winding	r_{cp}	0.1
Cooper area in HV winding	A_{cs}	12.06 cm²
copper fill factor for HV winding	r_{cs}	0.1

According to the results of windings parameters in Table 3, it is clear that the effective surface of the copper in the free-space window is considerably small in the proposed MFLT design. Thus, we can ensure the arrangement of the windings including insulation wires in the LV and HV windings. The design proposed is feasible. However, we suggest a possible optimization based on the minimizing of the volume of the MFLT designed in this study.

3. MODELING OF THE STABLE POWER SUPPLY FOR THREE MAGNETRONS PER PHASE

The modeling of the stable power supply in Figure 1 is different from the method used for ordinary 5-limb transformers as [21]. It is based on the π-model of its MFLT, and it depends on the external circuits (the loads), namely the MGT. Indeed, the modeling of the MFLT designed above requires an equivalent model that reflects the behavior of the whole system. It is therefore necessary to find a formulation that allows the simultaneous resolution of the electric and magnetic equations of the system. We admit that the MFLT is without iron losses. The shunts channel the leakages that exist. Thus, the leakage of air dispersion is negligible. Only the saturation phenomenon is taken into consideration

3.1. Electrical and magnetic study

In the proposed study, we follow the modeling steps below for each phase of the three-phase 5-limb MFLT, basing on the reference MFLT of [12-13-22]. For the primary (k=p), secondary (k=s), shunts (k=Sh), and common parts of the MLFT, we define the following electrical and magnetic parameters for a phase "j":

- ✓ u_{1j}, i_{1j}, r_{1j}: Voltage, current and resistance of the primary circuit.
- ✓ u_{2j}, i_{2j}, r_{2j}: Voltage, current and resistance of the secondary circuit.
- ✓ i'_{kj} : current through the inductance "L'_{kj}" of the part "k" of the circuit, which length "ℓ_k", section "A_k", and covered by the flux "ϕ_{kj}".
- ✓ $i^{c\prime}_{kij}$: Current through the inductance "$L^{c\prime}_{kij}$" of the iron part common between phase "n" and phase "o" which lengths "ℓ^c_k", section "A^c_k", and covered by the flux "ϕ^c_{kij}".

3.1.1 Electrical equations:

We apply ohm's law to the primary and secondary windings of each phase "n={1,2,3}". Therefore, we obtain the equations describing the electrical operation of the transformer refer to the secondary:

$$\begin{cases} u'_{1j} = r'_{1j}.i'_{1j} + \dfrac{d}{dt}\left(L'_{pj} + i'_{pj}\right) \\ u_{2j} = -r'_{2j}.i'_{2j} + \dfrac{d}{dt}\left(L_{sj} + i_{sj}\right) \end{cases} \tag{5}$$

Knowing that: $$T_s . \phi_k = L'_k . i'_{kj} \tag{6}$$

And: $$i'_{kj} = \frac{R_k.\phi_k}{T_s} \tag{7}$$

With: $$R_k = \frac{\ell_k}{\mu.A_k}$$

3.1.2 Magnetic equations:

We use the flux distribution of the MFLT circuit in Figure 4 to process the magnetic state of the transformer. After mathematical development of the magnetic equations obtained by application of the law HOPKINSON's law to the different contours of the magnetic circuit, we can write:

$$i_{21} = i_{s1} - i'_{sh1} - i^c_{s12} \tag{8}$$

$$i'_{12} = i'_{p2} + i'_{sh2} - i^{c\prime}_{p12} + i^{c\prime}_{p23} \tag{9}$$

$$i_{22} = - i_{s2} + i'_{sh2} + i^c_{s12} + i^c_{s23} \tag{10}$$

$$i'_{13} = i'_{p3} + i'_{sh3} + i^{c\prime}_{p23} \tag{11}$$

$$i_{23} = - i_{s3} + i'_{sh3} + i^c_{s23} \tag{12}$$

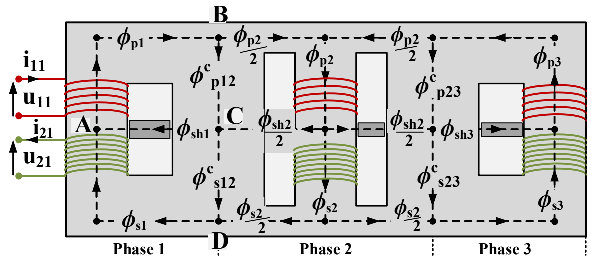

Figure 4: The flux distribution of the 5-limb MFLT

On the other hand, the derived time of equations the law of flux conservation for each phase "n", is written in the general formula:

$$\frac{d}{dt}(L'_{pj} . i'_{pj}) = \frac{d}{dt}(L_{sj} . i_{sj}) + \frac{d}{dt}(L'_{shj} . i'_{shj}) \tag{13}$$

In addition to the following equation concerning the common parts between two successive phases: i,j={1,2,3}:

$$\frac{d}{dt}(L^{c\prime}_{kij} . i^{c\prime}_{kij}) = \frac{d}{dt}(L'_{ki} . i'_{ki}) - \frac{d}{dt}(L'_{kj} . i'_{kj}) \tag{14}$$

The magnetic shunts contain a ferromagnetic part and an air gap. Therefore, the shunt inductance of each phase "L'_{shj}" is equivalent to two inductances in parallel: the nonlinear inductance "L'^{f}_{shj}" and the constant inductance "L'^{e}_{shj}", traversed by the currents "i'^{f}_{shj}" and "i'^{e}_{shj}".

With: $$i'_{shj} = i'^{f}_{shj} + i'^{e}_{shj} \tag{15}$$

3.2. Equivalent π-model

The system of equations (5), and (8) to (15) allows to obtain the equivalent diagram of the 5-limb MLFT in Figure 5, proposed for powering nine microwave generators. This diagram expresses the behavior of the entire power supply system. It is based on the π-model of the 5-limb MFLT. To the secondary of each phase, we connect the three similar loads: a doubling voltage cell linked to a magnetron. To schematize the magnetron, we study its Volt-Ampere characteristic. It is equalized with a small dynamic resistor connected with a diode and a cut-off continuous voltage V_{DC}=4000V in series [2-16]

For each phase "j", the MFLT model is composed of three nonlinear inductances: the primary inductance "L'_{pj}", the secondary inductance: "L_{sj}", the inductance of shunts side: "L'_{shj}", in addition to the common inductances between phases "i" and "j" : "$L^{c'}_{kij}$"

3.3. Modeling of the nonlinear inductance

The advantage of the model in Figure 5 is the simplicity of its equivalent diagram whose key element is the non-linear inductances. The analytical expressions of (6) and (7) describe the laws of nonlinear variation (flux-current) of each nonlinear inductance [22]. With:

$$\phi_k = B * A_k \qquad (16)$$

$$i_k = \frac{H.\ell_k}{T_s} \qquad (17)$$

The modeling principle is clear. The inductance characteristic of (16) and (17) is based on the geometric parameters of the MFLT, as well as the magnetization curve of the ferromagnetic material SF19. The B-H curve makes the model complicated due to its non-linear relationship. Therefore, modeling the system requires an efficient method for fitting the B-H curve.

4. VALIDATION OF THE PROPOSED POWER SUPPLY

4.1. The simulation

To validate the three-phase power supply, we simulate with Matlab the global model of Figure 5 basing on the π-model of the 5-limb MFLT. In our survey, it is necessary to account for the stabilizing effect of the power supply, and to consider the non-linearity of the system. However, Matlab-Simulink does not contain a block for nonlinear inductances. For this, we create a block that accepts data related to non-linear inductances and reflects the "flux-current" relationship of (16) and (17) using the ANFIS method for the fitting of the magnetization curve B(H). We replace each non-linear inductance with its equivalent block in Figure 6.

The block in Figure 6 representing the nonlinear inductance model reflects the characteristic giving the total flux "$T_s.\phi_k(i_k)$". It contains:

- ✓ A voltage measurement block: to extract voltage at the terminals of the inductance.
- ✓ An integrator block: The voltage extracted is integrated to obtain the flux "ϕ_k".
- ✓ A division block: the induction B is obtained by division of the flux by " $T_s.A_k$ ".

A controller block: The induction B is the input of the fuzzy logic controller block that implements the ANFIS fuzzy inference system (FIS). This integrated system combines the advantages of the two techniques, fuzzy logic, and neural networks. It adjusts the different parameters of the membership functions associated with the different input "B" and output variables "H" of the diagnostic system (FIS) by the learning process in order to obtain the best results during the diagnosis of the faults studied. A previous work presents the details of this method for the modeling of nonlinear inductances in [23].

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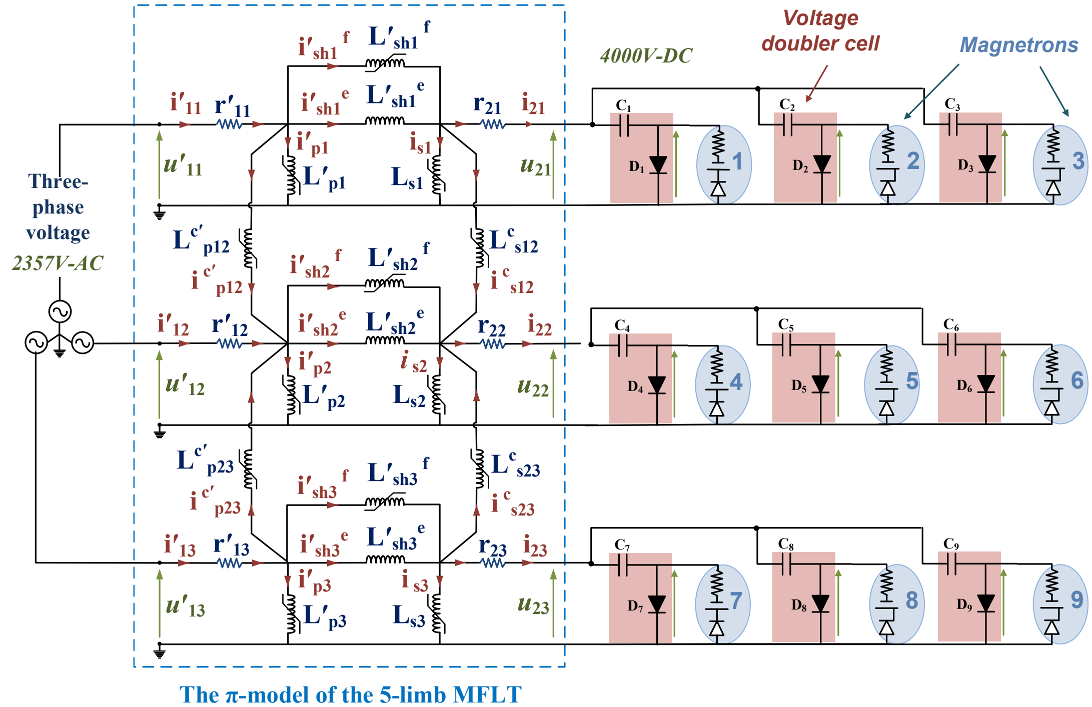


Figure 5: Model Of The Stable Power Supply

✓ The multiplication block: The magnetic field H obtained is multiplied by " ℓ_k/T_s " to find the output current " i_k" of the inductance

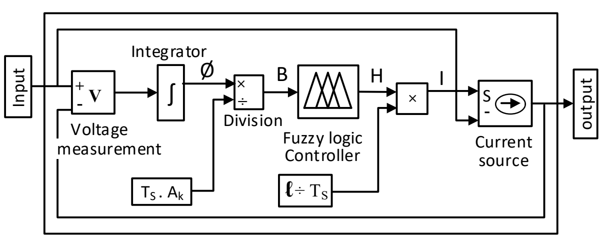
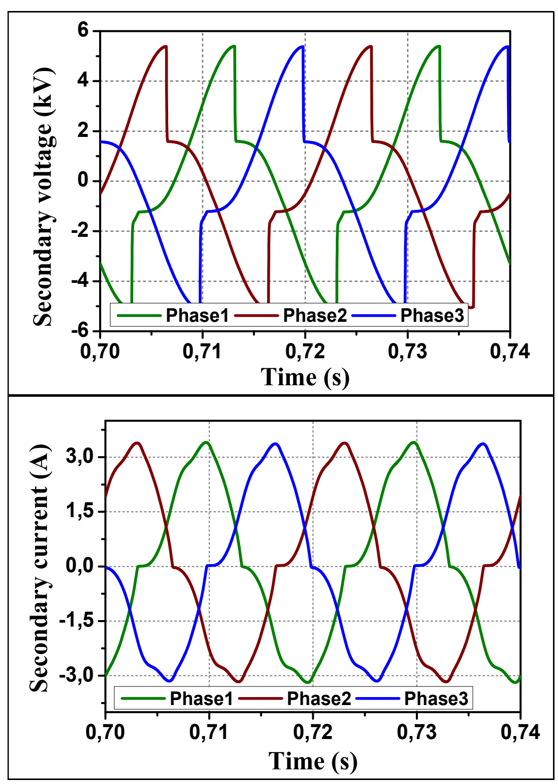
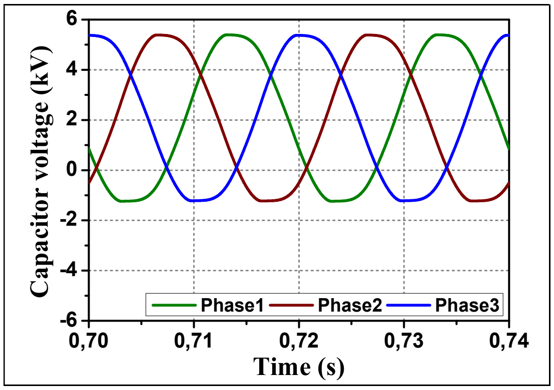


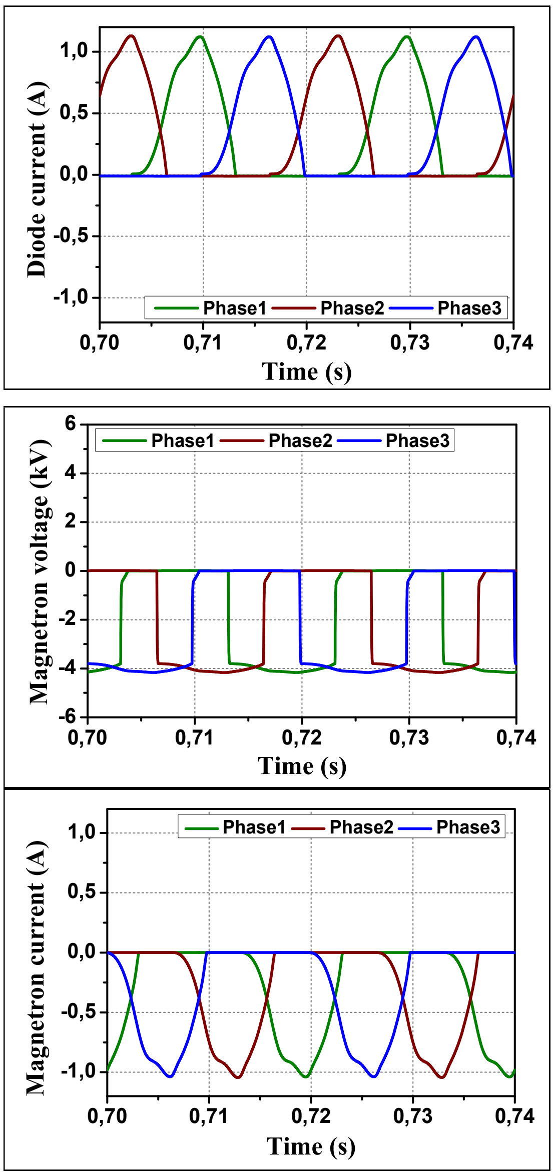
Figure 6: Equivalent Model Of A Non-Linear Inductance Under MATLAB-Simulink

At last, we present the different electrical signals of voltages in figure 7(a) and current in figure 7(b), for each phase in the simulation model. In order the check the agreement with the reference system and the compliance with the constraints of MGT supply.





a)- Voltages



b)- Currents

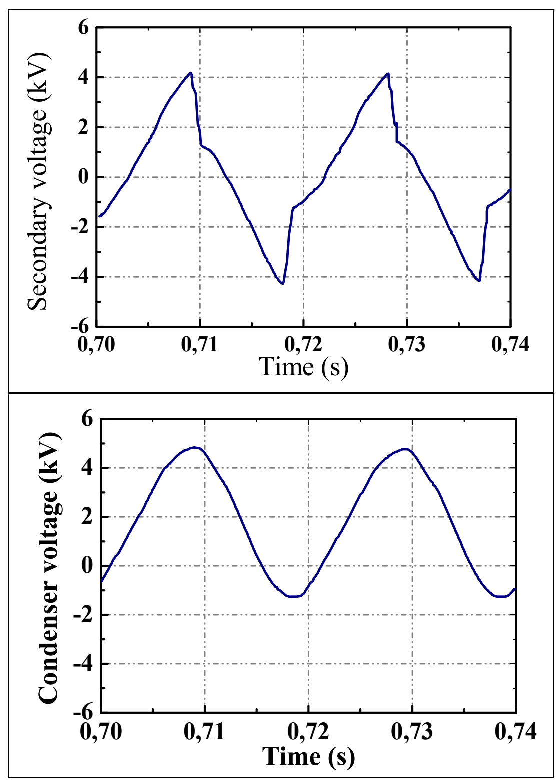
Figure 7: Simulation Waveforms

4.2. Experimental test

To understand the real operation of the stable power supply of the MGT, and to visualize the different instantaneous voltages and currents, we use the results of the experimental tests in [13] . This test was performed by members of “Modeling systems and information techniques team” in the department of electrical engineering of the higher School of Technology in Agadir (Morocco). It was done with the reference stable power supply for an MGT in nominal operation. This system is composed of:

- ✓ A single-phase MFLT with the nominal characteristics: "$u_1 = 220V$", "$u_2 = 2375V$", and "$f = 50Hz$". In no-load operation: "$T_p = 224$", "$T_s = 2400$", "$r'_1 = 100\Omega$" and "$r_2 = 65\Omega$".
- ✓ A voltage doubling cell, composed of a capacitor "C=0,9F" and a HV rectifier diode
- ✓ A magnetron designed to operate at: "$V_{DC} = 4000V$, $I_a = 350mA$ and $R = 350\Omega$"

The experiment allows recording the characteristics of different voltages in figure 8(a) and currents in figure 8(b) of the reference stable power supply. The curves will be used for comparison with the simulation results, and thus for verification and validation of the MFLT feasible design



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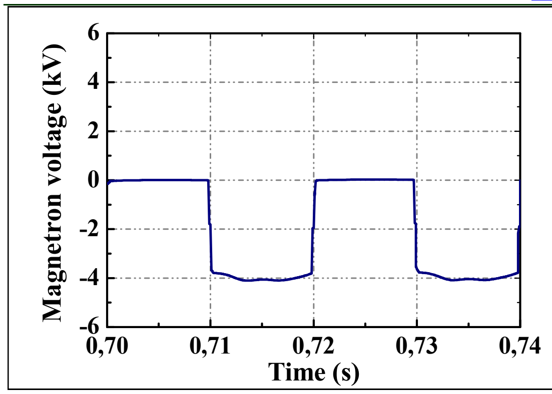
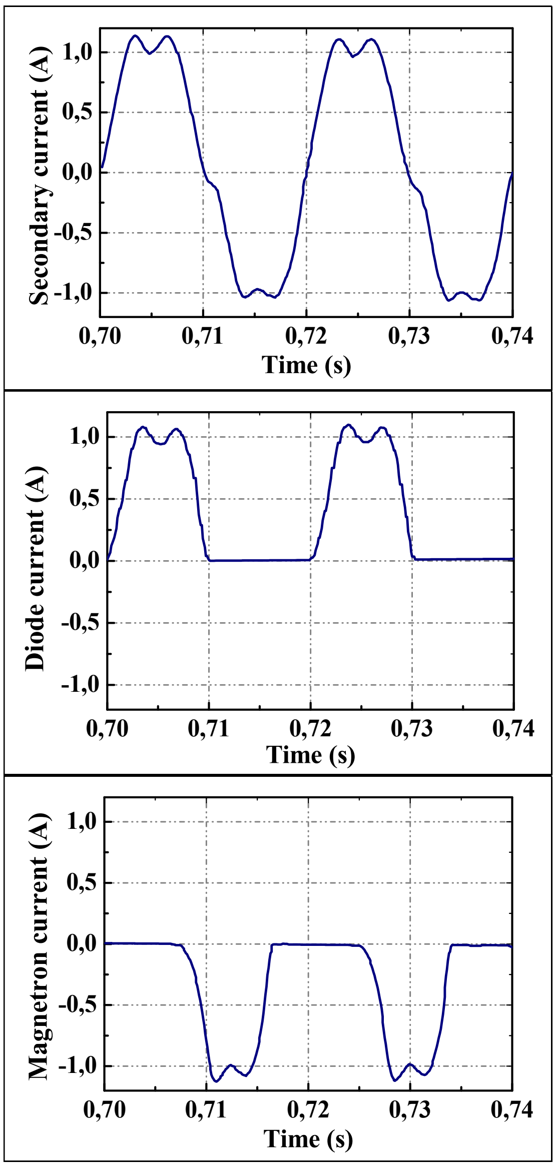


a)- Voltages



b)- Currents

Figure 8: Experimental waveforms

4.3. Results and discussion

First, we notice that the electrical signals in Figure 7 obtained by simulation for the three phases represent variable and periodic quantities. They are phase-shifted between them with $2.\pi/3$. The phase shift confirms the absence of interaction between magnetrons.

Generally, the comparison of each phase of the different simulation signals with the experimental curves allows us to note the following points:

- ✓ Each phase of the currents and voltages curves of the simulation has practically the same form compared with experimental signals.
- ✓ The secondary voltage shows an alternate signal with the same value as the experimental one after the transformation of the primary voltage.
- ✓ The secondary current is tripled compared with the experimental one. Because the studied system supplies a triple load of 3 MGTs par phase.
- ✓ Each capacitor voltage is the double of secondary voltage, as in the experimental result, thanks to the charge and discharge of the capacitor every half period.
- ✓ The current flowing in each diode is rectified to obtain a direct current (DC) at the output of the cell, like the experimental one.
- ✓ After the circuit cell, we obtain a DC voltage at each MGT terminal of about 4000V equal to desired cut-off voltage "V_{DC}".
- ✓ The current flowing each MGT is a DC with a calculated average value of "I_m = 289mA", which can be considered valid.

From the above, we can conclude that different simulation signals are following the experimental waveforms. In addition, the magnetron supply respects the constraints recommended by the manufacturer for its good operation. The new 5-limb MFLT design, which has not been studied or realized until now, is validated. Thus, the power supply system is successfully validated.

Eventually, these results allowed to develop a new three-phase HV power supply for a total of nine magnetrons 800 Watts to 2450 MHz, instead of the current voluminous and bulky system of nine single-phase MFLT, for industrial microwave generators.

5. CONCLUSION

In this paper, we have proposed a new stable power supply of three magnetrons per phase

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for an industrial microwave. We have successfully designed and sized the special 5-limb MFLT of core type, to supply simultaneously nine MGT. Then, we have modeled the entire system, using the π-model of the MFLT describing its saturation characteristics. The power supply model was simulated in non-linear mode with the Matlab-Simulink in order to study its performance at nominal operation and to validate the transformer designed. The modeling of the nonlinear inductances of the MFLT was performed by the ANFIS method for the fitting of the magnetization curve. The results confirmed that there were no interactions between magnetrons, and the comparison between numerical and experimental curves showed a significant agreement, with the respect of the magnetron supply constraints required to its good functioning.

This system can simplify the installation and reduce the cost of industrial microwave power supplies. Firstly, the space and the wiring are reduced by designing a single power supply system for nine magnetrons. In addition, the new core-type MFLT ensures easier manufacturing and maintenance and a less complex cooling system. For industrial applications, the satisfactory results obtained in this study, encourage the realization of this new generation of the stable power supply for microwave generators

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