Optimization of a Three-Phase Tetrahedral High Voltage Transformer used in the Power Supply of Microwave

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***Abstract*—This article deals with the optimization of a three-phase tetrahedral-type high voltage transformer, sized to supply three voltage-doubling cells and three magnetrons per phase. The optimization method used is based on an algorithm implemented in Matlab/Simulink to study the influence of transformer geometrical parameters on the electrical operation of the power supply. This study will allow to find reduced volume of transformer respecting the current constraints imposed by the magnetrons manufacturer. The choice of optimal solution is done by calculation of magnetrons powers in order to respect the nominal operation.**

***Keywords*—Optimization; tetrahedral; voltage-doubling; transformer; magnetrons**

I. Introduction

In the development study of power supplies for microwave applications, we always seek to find more powerful and optimal solutions in terms of installation space, cost of manufacture and maintenance. In this context, this work defines a method to optimize the three-phase HV transformer used in this kind of power supplies with nine magnetrons (three for each phase).

Unlike the old power supplies already developed, whether single-phase magnetron 800Watts-2450Mhz or three-phase of three magnetrons 2400Whats-2450Mhz [1-3]. This new technology of nine magnetrons is optimized compared to that previously developed [4]. It offers an identical microwave power of 7200Watts-2450MHz. So it can use less optimized power supply to size a more powerful industrial microwave.

The design of this power supply is based on a three-phase HV transformer with magnetic shunts of tetrahedral type having a shell type structure. Each phase feeds three doublers cells giving a voltage which is suitable for the operation of the three magnetrons that delivers the microwaves [5]. The magnetic shunts of the transformer ensure the stability of the current in each magnetron in order to not exceed the values recommended by the manufacturer Imax<1.2A and Iavg ≤ 300mA.

This paper is divided in two sections. In the first, we present the model and the results obtained by simulation under Matlab/Simulink. In the second section, we study the influence of each geometrical parameter of the transformer on the operation of the power supply. This study will allow us to define the optimized algorithm based on the simultaneous variation of these parameters. This leads to various solutions that respect the criteria recommended by the magnetron manufacturer. The choice of the best solution is validated by the calculation of the volume as well as the comparison of the results obtained with those of the non-optimized power supply, taking into account the operation of magnetrons in full power.

II. Modeling and Simulation of the Three-Phase High Voltage Power Supply with Three-Magnetrons per Phase

A. Description and Modeling of Power Supply

The general model of the three-phase HV power supply constitutes of a magnetic shunt transformer, doublers cells, and three magnetrons for each phase. The three-phase HV transformer is represented by three identical models of single-phase transformers coupled in star as shown in Fig. 1. Unlike conventional transformers, this special transformer contains intermediate magnetic shunts between the side columns and the central column, which allows to ensure the stabilization of the current in the magnetrons by the saturation of its magnetic circuit.

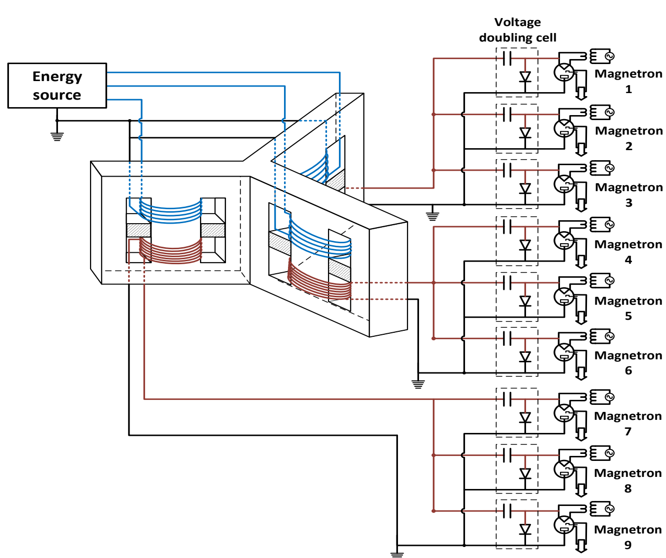


Fig 1. Three-Phase Power Supply of Three Magnetons per Phase having a Tetrahedral-Type Transformer.

From the different electrical and magnetic equations already developed of this transformer [4], each phase is modeled as a quadruple in π, composed of three non-linear inductances on the primary, secondary and shunts sides. These inductances have a section S, a length ℓ and a characteristic ϕ(i) which can be determined from the relation $L(i) = \frac{n_2 \phi(i)}{I}$ and also the curve B(H) of the material transformer [6][7]. The different equations that determine the current and flux (I, ϕ) for each inductor are expressed as follows:

For primary inductance L'_p:

$$\begin{cases} \phi_p = n_2 . S_1 . B \\ i'_p = \frac{H.\ell_p}{n_2} \end{cases} \quad (1)$$

For secondary inductance L_s:

$$\begin{cases} \phi_s = n_2 . S_2 . B \\ i_s = \frac{H.\ell_s}{n_2} \end{cases} \quad (2)$$

For shunt inductance L'_{sh} :

$$\begin{cases} \phi_{sh} = n_2 . S_{sh} . B \\ i'_{sh} = \frac{H.\ell_{sh}}{n_2} \end{cases} \quad (3)$$

Fig. 2 shows the different geometrical parameters of a single tetrahedral transformer phase.

- The width of the core: a = 75 mm
- The width of the magnetic circuit : b = 25 mm
- Number of stacked sheets of the shunt : n_3=18
- Number of primary windings : n_1= 224
- Number of secondary windings: n_2 =2400
- Height of shunts: h = 0.5×n_3 mm
- Primary and secondary core surface: S_1= S_2= a×b
- Surface of shunt: S_{sh} = b×h
- Thickness of the air gap: e = 0.75 mm
- ℓ_p=4.5×a (correspond to the path ABCD)
- ℓ_s=4.5×a (correspond to the path DAFE)
- ℓ_{sh}=(2.5×a -2×e) (correspond to the path AD)

Each magnetron is presented by a model describing its operation which contains a diode with dynamic resistance R = ΔU/I = 350 Ohm and a threshold voltage E = 3800V. Fig. 3 shows the general model of the power supply.

B. Simulation of the Model

The equivalent model of the three-phase HV power supply is implemented under Matlab/Simulink. The primary of the transformer is powered by a nominal voltage of 220/380V with a phase shift of 2π/3. Each non-linear inductance is modeled by Simulink blocks showing their operation. One of these blocks is used to interpolate the B(H) curve with the ANFIS neuro-fuzzy method [8-10]. Fig. 4 and 5 give the different currents/voltages curves of magnetrons, diodes, capacitors and transformer secondary obtained in a previously study [4]. These curves will be the comparison tool between the optimized and non-optimized power supplies.

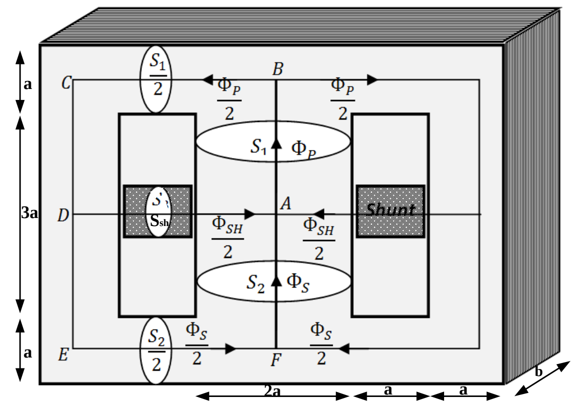


Fig 2. Geometry of a Single Tetrahedral Transformer Phase.

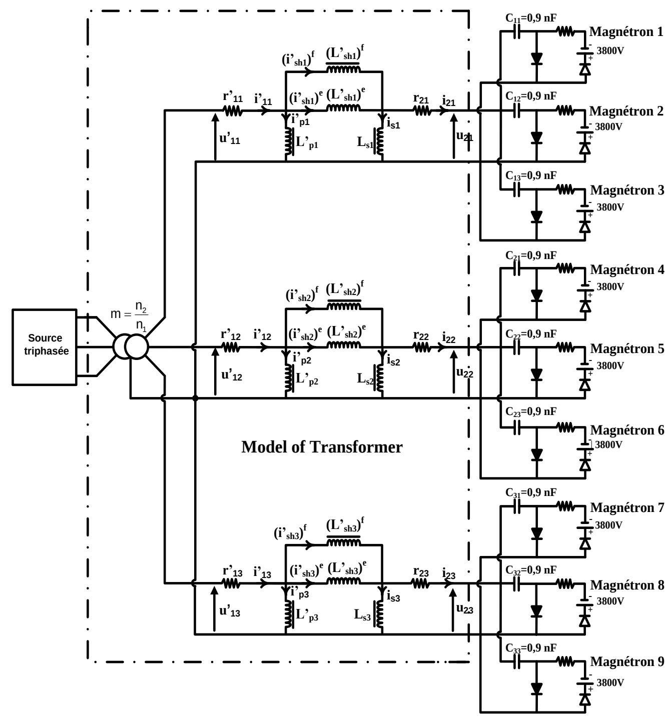
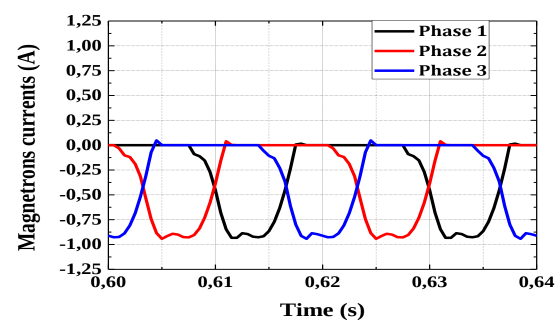


Fig 3. Electrical Diagram Equivalent of Three-phase High Voltage Power Supply for Three Magnetrons per Phase.



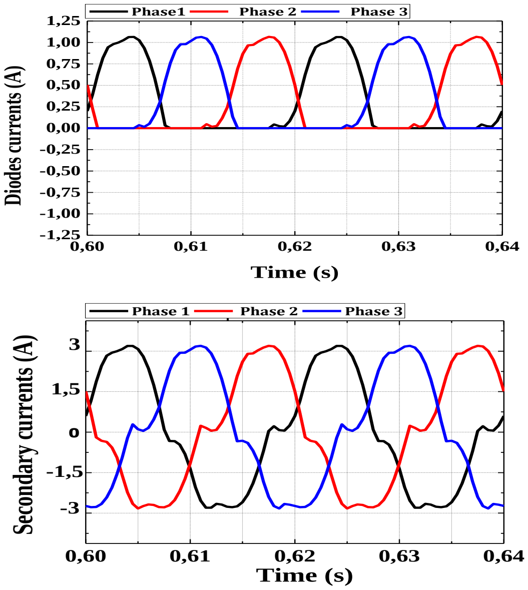


Fig 4. Result Obtained by Simulation of Magnetrons Currents, Diodes and Secondary.

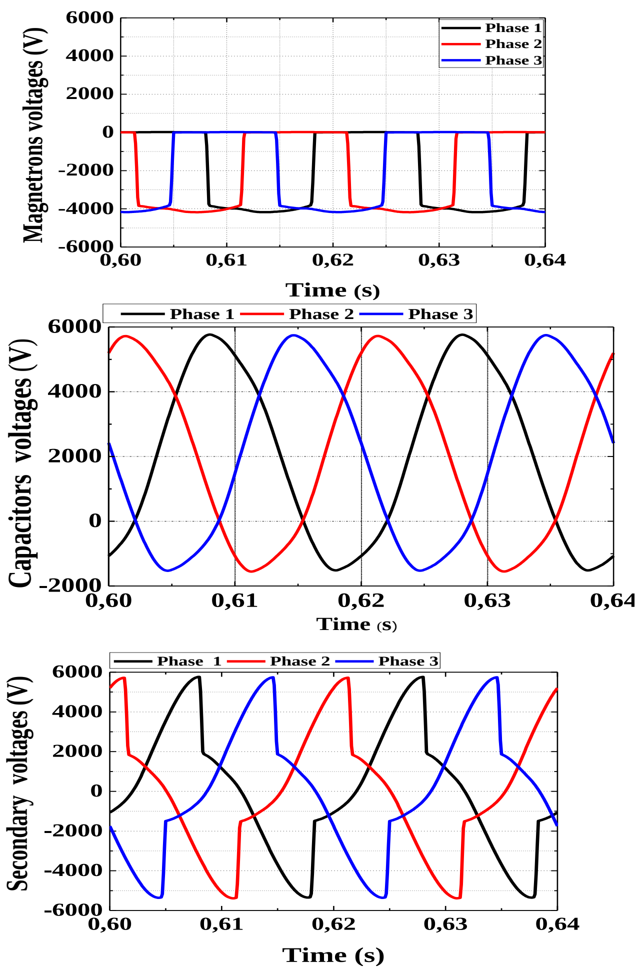


Fig 5. Result Obtained by Simulation of Magnetrons Voltages, Capacitors and Secondary.

III. Optimization of the Tetrahedral Transformer used in the Power Supply

The optimization stage is based on the model developed on Matlab/Simulink of the three-phase HV power supply with three-magnetron per phase. This model will allow us to study with respect to the reference transformer case (non-optimized transformer) the sensitivity of each geometrical parameter to the nominal operation of the power supply [11-13]. This study will give us an idea of how we can simultaneously vary all the parameters in order to meet the following criteria:

- Have the various possible optimal solutions that offer a reduced volume without risk of exceeding the limits recommended by the magnetron manufacturer.
- Among the obtained solutions, find a better optimal one that respects the full power operation of the magnetrons.

A. *Influence of each Single Transformer Parameter on the Magnetron Current*

The π quadruple model of the three-phase tetrahedral HV transformer contains non-linear inductances that depend on the geometrical parameters. Therefore, the variation of such a parameter modifies the overall operation of the equivalent circuit of the power supply. The simulation results of the model permit to plot the variation of the maximum and average magnetron current in terms of the selected transformer parameters as shown in Fig. 6 to 10. These parameters must be within the ranges specified in Table I.

TABLE I. Variation Range of the Parametrer

Name of the parameters	Rating values
a (mm)	$45 \leq a \leq 75$
n_2	$2000 \leq n_2 \leq 2800$
n_3	$10 \leq n_3 \leq 18$
e (mm)	$0{,}45 \leq e \leq 1{,}05$

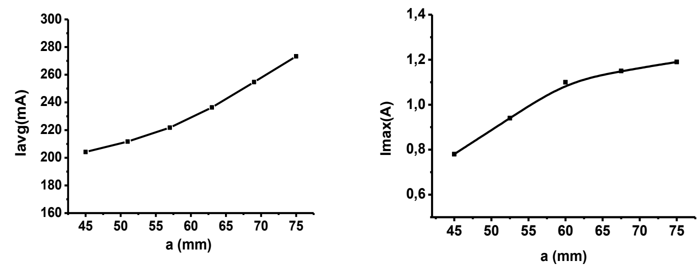


Fig 6. Magnetron Current Simulation Results as a Function of «a».

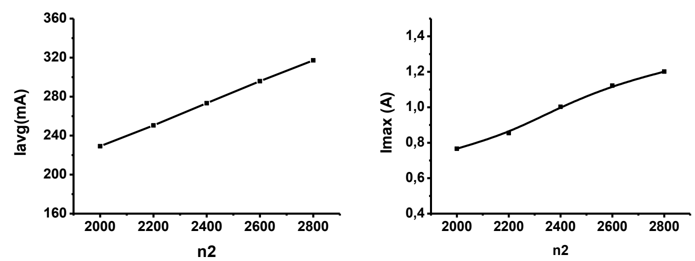


Fig 7. Magnetron Current Simulation Results as a Function of «n_2».

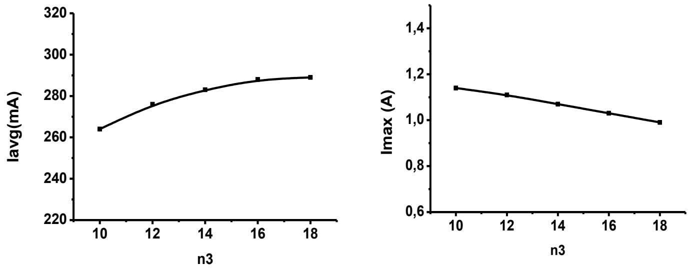


Fig 8. Magnetron Current Simulation Results as a Function of «n3».

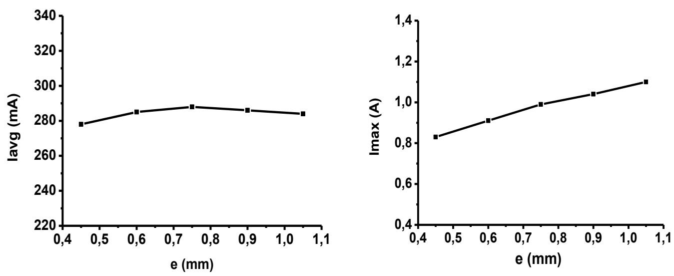


Fig 9. Magnetron Current Simulation Results as a Function of «e».

From Fig. 6 to10, we can see that the maximum current and the average magnetron current decreases when the three parameters (a, n_2,e) decrease. On the other hand, for the case of the n_3 parameter, we notice that the increase in the number of plates constituting each shunt causes a decrease in the maximum value of the current in the magnetrons. We also note that the variation of n_3 does not exceed the acceptable limits of the magnetron current mean value.

These observations make us think of reducing the magnetic circuit volume of the transformer, without risk of damaging the magnetron tubes.

B. *Optimization Algorithm*

The analysis of the results obtained previously confirms the magnetron current sensitivity with respect to the variation of each geometrical parameter of the transformer. These results prompted us to define an algorithm to study the influence of more than one geometrical parameter on the electrical operation of the power supply. We seek to simultaneously minimize all the parameters (a, n_2, n_3, e) thus the total volume of the tetrahedral transformer. The different optimal solutions found allow us to make a better choice between the transformer volume and the average power output by the magnetron.

The algorithm is used to minimize an objective function, which is the volume of the transformer in (cm^3) while respecting the operating conditions of the three phase magnetron power supply. The objective volume function is defined in the following form:

$$V_{transformer} = V_{core} + V_{copper} \tag{4}$$

From Fig. 2, V_{core} can be calculated as follows:

$$V_{core} = 3 \times [(\text{Total volume of the magnetic circuit}) + (\text{Volume of the stack of shunts}) - (\text{Total volume of the winding window})]$$

$$V_{core} = 3 \times [(6a \times 5a \times b) + (2 \times (a \times b \times h)) - (2 \times a \times b \times (3 \times a))] \tag{5}$$

The volume of the copper is defined by :

$$V_{copper} = 3 \times \left\{ S \left[E_{coil/colum} \left[\sum_{i=0}^{E_{coil/colum}} (b + a + 4d * i) \right] + (N_{coil/colum} - E_{coil/colum})(b + a + 4d(i+1)) \right] \right\} \tag{6}$$

- d : presents the diameter of the copper cable on the primary or secondary side
- $N_{coll/colum}$: presents the number of turns per column
- $E(N_{coll/colum})$:presents the entire part of $N_{coll/colum}$
- $N_{coll/colum} - E(N_{coll/colum})$: presents the fractional part of $N_{coll/colum}$

By using the different intervals of variation of the geometrical parameters defined previously. The vector X used in our algorithm (Fig. 10) will take all the possible combinations between the different parameters X = [x_1, x_2, x_3, x_4] = [a, n_2, n_3, e]. Table II gives the step and the variation margin of each combined and defined parameter in the vector X.

TABLE II. STEP AND VARIATION MARGIN OF EACH PARAMETER

Name of the parameters	Start	Step	End
a(mm)	45	5	75
n_2	2000	100	2800
n_3	10	2	18
e(mm)	0,45	0,15	1,05

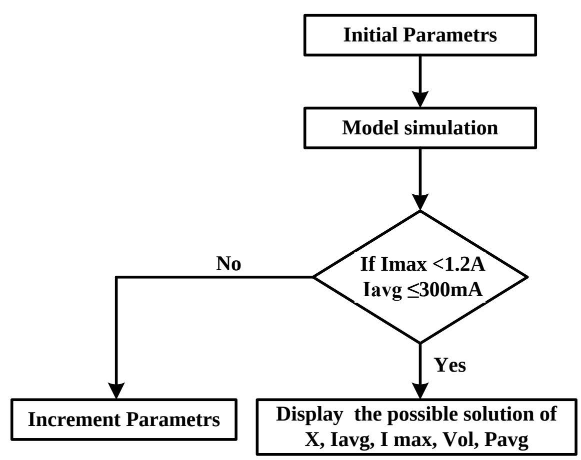


Fig 10. Different Steps of Optimization Algorithm.

TABLE III. BEST SOLUTION OBTAINED BY THE OPTIMIZATION ALGORITHM

	a (mm)	n_2	n_3	e (mm)	Imax (A)	Iavg (mA)	Volume (cm^3)	Pavg (w)
ref	75	2400	18	0,75	0,95	271,17	9988,36	1100,47
S_1	75	2400	18	0,45	0,95	271,17	9989,01	1100,47
S_2	65	2600	10	0,75	0,91	264,34	7788,87	1074,60
S_3	70	2400	10	0,75	0,90	259,73	8834,97	1054,61
S_4	70	2400	16	1,05	0,84	256,53	8859,06	1036,58
S_5	55	2800	14	0,45	0,79	244,85	5925,99	983,47

At each X iteration, we perform a model simulation on Simulink using the "sim" function in Matlab. The results obtained from each simulation will be checked in order to take the one that respects the operating constraints of the power supply. By displaying to each solution found the values of vector X, the max and average current as well as the average power of the magnetron.

After simulating the model with the different combinations of the geometrical parameters, Table III presents the five best solutions selected that meet the current imposed by the manufacturer also that it allows to operate the magnetrons in nominal power.

From Table III, we find that solution S_2 presents the best compromise between the volume of the transformer and the operation of the magnetron (Pavg = 1074,6W, Imax= 0.91(A) and Iavg =264,34 mA, Volume= 7788,87cm^2). For the solution S_5, it has a minimum volume, but it does not allow nominal operation at full power of the magnetrons.

We simulate the model under Matlab/Simulink with the new geometrical parameters of the transformation optimization solution. The waveforms of the voltages and currents obtained (Fig. 11 and 12) are almost identical to those obtained in the case of reference, while respecting the operating constraints of the magnetrons. So we can say that 22 % of the power supply volume is optimized without having a large magnetron power lost after optimization.

Transformer optimization rate (τ).

$$\tau = \frac{\text{Vref}-\text{Vopt}}{\text{Vref}} = \frac{9988{,}36-7788{,}87}{9988{,}36} = 0{,}22 \quad (7)$$

Magnetron power lost after optimization (P_{lost}).

$$P_{lost} = P_{mref} - P_{mopt} = 1100{,}47 - 1074{,}60 = 25{,}87W \quad (8)$$

P_{mref} : Average magnetron power given by the reference transformer.

P_{mopt} : Average magnetron power given by the optimized transformer.

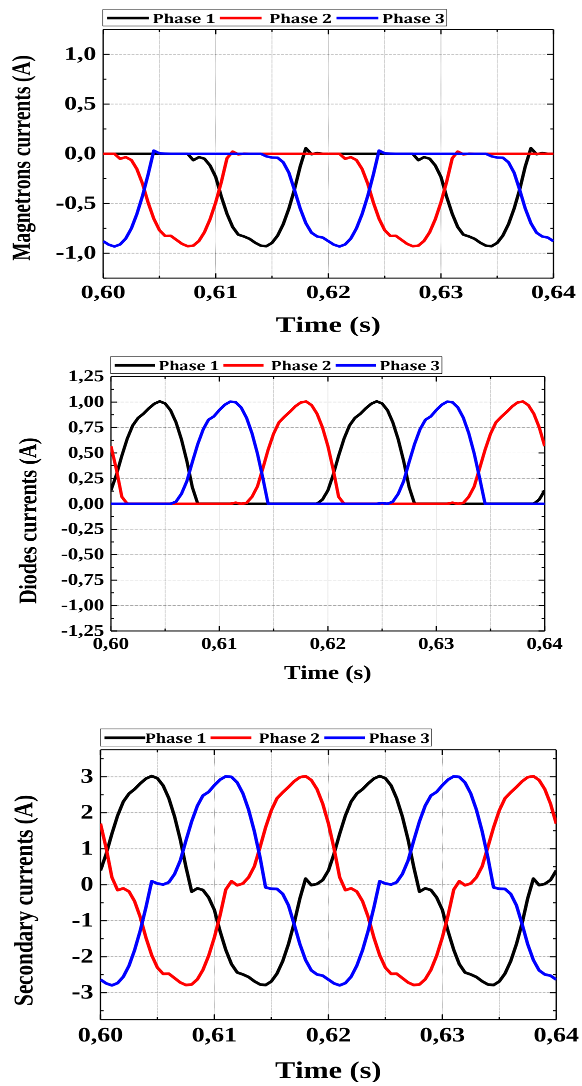


Fig 11. Results Obtained by Simulation of the Model Optimized. Currents of Magnetrons, Diodes and Secondary.

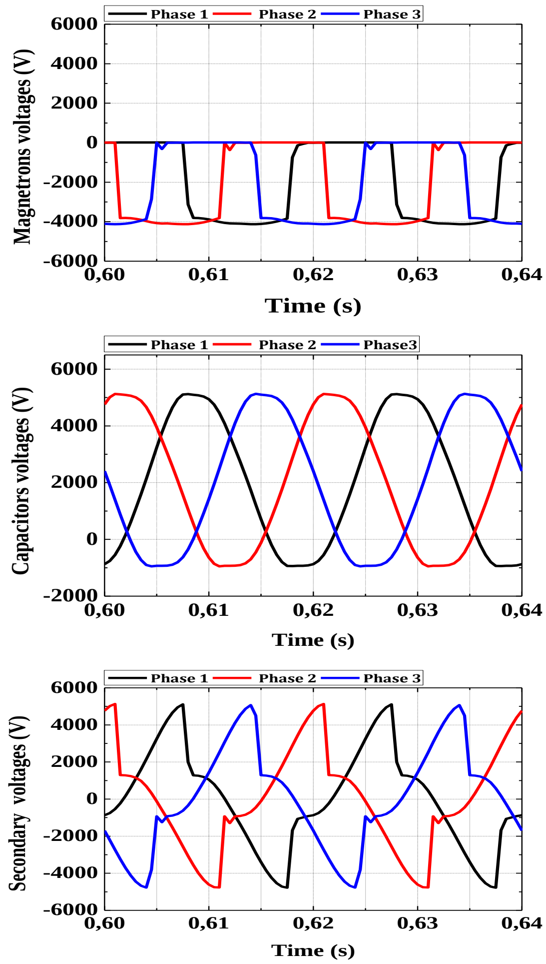


Fig 12. Results obtained by Simulation of the Model Optimized. Voltages of Magnetrons, Capacitors and Secondary.

IV. Conclusion

In this work, we have succeeded after a study of optimization, to define a proper algorithm that aims to find an optimal solution of the three-phase tetrahedral type HV transformer used to feed three magnetrons per phase. This study allowed us to reduce the volume, the congestion as well as the cost. The optimized solution obtained is compared to that of reference; it gave a transformer that meets the operating criteria of the entire power supply.

As a perspective, this work can be used as a reference to optimize another type of transformer employed for microwave application at N = 1,2,3 magnetrons per phase while seeking to do a thermal study on the optimized transformer.

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