IMPROVED MODELING OF A SINGLE-PHASE HIGH VOLTAGE POWER SUPPLY FOR MICROWAVE GENERATORS FOR ONE MAGNETRON

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Abstract: *The research presented in this paper aims to develop a new original fuzzy model of single-phase HV power supply of a magnetron. The design of this system is composed of leakage flux transformer with magnetic shunts supplying a cell, which multiples the voltage and stabilizes the current and one magnetron at the output of the cell. An equivalent model of this transformer is presented taking account the characteristics of the magnetron. It is based on the development of a new diagram block of non-linear inductance, using the Adaptive Neuro-Fuzzy Inference System (ANFIS). This model was validated under MATLAB-SIMULINK software near the nominal state. The results obtained by simulation are in good agreement with experimental measurements.*

Key words: *ANFIS, fuzzy modeling, magnetron, power supply, transformer.*

NOMENCLATURE

B: Magnetic flux density

HV: High voltage

r'_1: Primary winding resistance referred to secondary.

i_1: Primary current;

U_1: Voltage of the primary winding.

r_2: Secondary winding resistance

U_2: Voltage of the secondary winding.

i'_P : Current circulating in the inductance L'_P.

L_S: Secondary inductance

$(L'_{Sh})^f$: Iron shunt inductance referred to secondary.

$(R'_{Sh})^f$: Iron reluctance

H: Magnetic field

r_1: Primary winding resistance

n_1: Number of turns in the primary coil.

i_2: Secondary current

U'_1: Primary voltage referred to secondary.

n_2: Number of turns in the secondary coil

i'_1: Primary current referred to secondary.

i'_{Sh}: Current circulating in the shunts referred to secondary.

L'_P: Primary inductance referred to secondary.

$(L'_{Sh})^e$: Shunt inductance in the air-gaps referred to secondary

R_P, R_S, RSh: Reluctance of the primary, secondary and the shunts.

1. Introduction

Figure 1 shows the classic high voltage power supply for microwave generators for magnetron 800watt-2450MHz.It is composed essentially of three parts: a single phase leakage flux transformer with magnetic shunts, a cell composed of a capacitor and a diode, which doubles the voltage and stabilizes the current and one magnetron at the output of the cell [1, 2, 3, 4, 5]. This special transformer with shunts is the most important part of this circuit. By the saturation of its magnetic circuit, it ensures the stabilization of the average anode current in the magnetron. The characteristics of the magnetron [6, 7] as well that these limit values impose a proper design of its power supply.

In this article, we present a fuzzy modeling method for modeling the non-linear inductances using the Adaptive Neuro-Fuzzy inference system (ANFIS).This approach allowed us to give a general equivalent model for an eventual HV power supply of the microwaves generators with several magnetrons for the industrial applications. This will contribute to the development of the technological innovation in the manufacturing industry of the power supply for magnetron of microwave ovens for domestic or industrial use.

The paper is organized as follows: In the first part, we remind the modeling already developed of a single-phase HV power supply for magnetron 800 Watts and 2450 MHz, which consists essentially to model its special HV transformer in order to derive a π quadruple model [8, 9] with three nonlinear inductances (primary secondary and shunt). In the second step, we will improve the old model of the transformer with magnetic shunts to another new based on the development of a new diagram block of non-linear inductance by using the Adaptive Neuro-Fuzzy inference system (ANFIS). And we propose a validation of this improved model based on the comparison between experimental and simulated currents and voltages [1, 10, 11, 12]

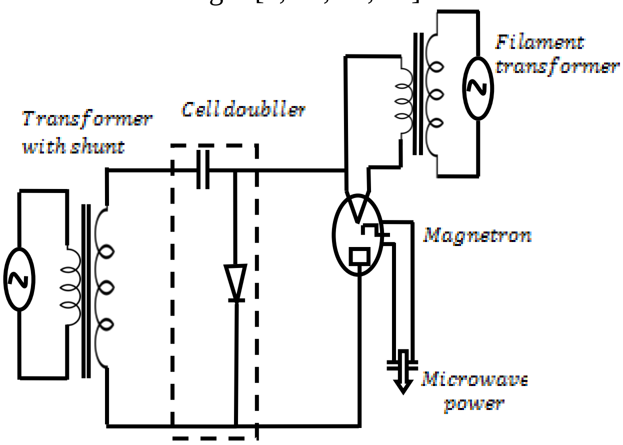

Fig. 1. Current power supply for a magnetron (Amperex type)

2. Modeling of single phase power supply for magnetron

2.1. study of the transformer with magnetic shunts

Figure 2 shows the geometry of the transformer currently used in the industrials applications using the traditional HV supply of one magnetron. Unlike conventional transformer [13, 14, 15, 16], this transformer has magnetic shunts which are used to divert an important part of flux circulating between the primary and secondary windings [1, 17]. Taking into account the size of the residual air-gaps and saturation state of materials, the magnetic fluxes in the air can be considered negligible compared to the flux through the shunts. In the proposed study, we consider the transformer without iron losses (hysteresis loss and eddy current). Only the phenomenon of saturation is taken into account. The geometrical dimensions of the transformer are shown in fig 14 (see appendix).

2.2. Electrical and magnetic equations

By the application of Ohm's generalized law to the primary windings (receiver convention) and secondary ones (generator convention) and the Hopkinson's law, we obtain the following complete electric and magnetic equations governing the operating of the transformer.

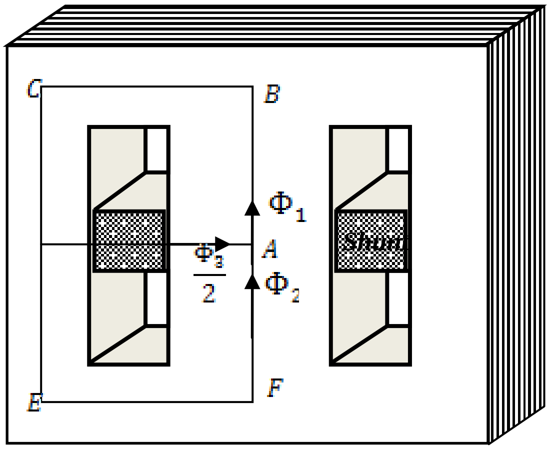

Fig. 2. Section of cuirassed transformer with shunts.

$$U_1 = n_1 \frac{d\Phi_1}{dt} + r_1 i_1 \quad (1)$$

$$U_2 = n_2 \frac{d\Phi_2}{dt} - r_2 i_2 \quad (2)$$

$$R_P \Phi_1 + R_{SH} \frac{\Phi_3}{2} = n_1 i_1 \quad (3)$$

$$R_S \Phi_2 - R_{SH} \frac{\Phi_3}{2} = -n_2 i_2 \quad (4)$$

$$R_P \Phi_1 + R_S \Phi_2 = n_1 i_1 - n_2 i_2 \quad (5)$$

$$\Phi_1 = \Phi_2 + \Phi_3 \quad (6)$$

By transforming the equations (1) to (6), we obtain the following equations (7) to (12) gouverning the operation of the π quadruple model representative of the transformer refered to secondary (For more details see [1, 8]).

$$U'_1 = r'_1 \, i'_1 + \frac{d(L'_P . i'_p)}{dt} \quad (7)$$

$$U_2 = -r_2 i_2 + \frac{d(L_S . i_S)}{dt} \quad (8)$$

$$n_2 \frac{d\Phi_1}{dt} = \frac{d(L_S . i_S)}{dt} + \frac{d(L'_{SH} . i'_{SH})}{dt} \quad (9)$$

$$i'_1 = i'_p + i'_{SH} \quad (10)$$

$$i'_{SH} = i_S + i_2 \quad (11)$$

$$n_2 \Phi_{SH} = (L'_{SH})^f . (i'_{SH})^f + (L'_{SH})^e . (i'_{SH})^e \quad (12)$$

The previous equations respond to the equivalent digram of the transformer. Thus we obtain a π model of this transformer composed of three nonlinear inductances referred to secondary, L'_p on the primary side, L_s on the secondary side and L'_{Sh} on the shunts side (Fig. 3).

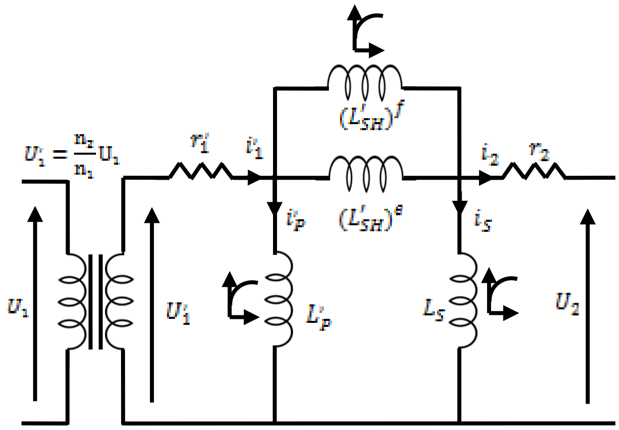

Fig. 3. Quadruple model of transformer with shunts

The advantage of the quadruple model is in its equivalent single-phase scheme referred to the secondary which seems more convenient to study the operation of this transformer using code MATLAB-SIMULINK. The three nonlinear inductance of the quadruple model are function of the reluctances of the magnetic circuit portion which it represents, which can be determined from the geometrical dimensions of the transformer and the magnetization curve B(H) of the material used by the relations.

3. ANFIS modeling of nonlinear inductance

The magnetization curve is the most fundamental physical properties of the feromagnetic material. This curve is complicated by the nonlinear relation between the magnetic field H and the magnetic induction B due to saturation. In the literature [18, 19], numeros mathematical methods have been reported te represent the magnetization curve characteristic, such as fourier serie approximation or rational function approximation. In order to model the magnetization curve B(H) of the ferromagnetic material used for fabrication of the transformer, we present a fuzzy modeling method of this curve, using the Adaptive Neuro-Fuzzy inference system (ANFIS). This leads to develop a new model of nonlinear inductance from the curve of magnetization B(H).

3.1 ANFIS structure

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is an intelligent neuro-Fuzzy technique, which was originally proposed by Jang in 1993 [20]. It is used for the modeling and control of fuzzy and uncertain systems, by using the input/output data pairs of the system under consideration. Figure 4 shows the basic architecture of ANFIS with two inputs and one output. A detailed description of the ANFIS technique can be found in [20] and [21].

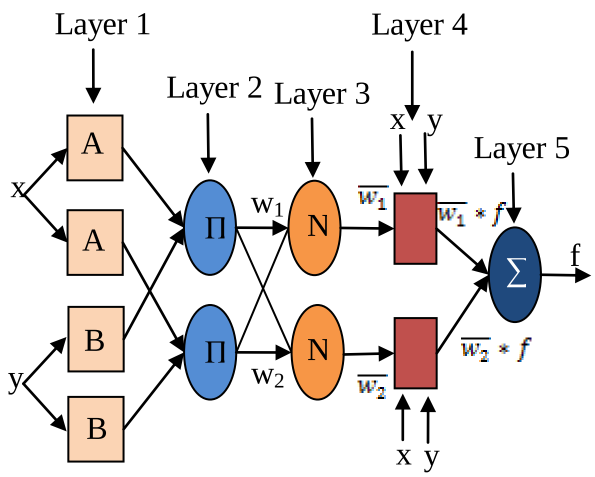

Fig. 4. General structure of ANFIS [20]

In this paper, an ANFIS model with one input and one output based on Neural Network and Fuzzy Logic has been developed to model the nonlinear inductance from the curve of magnetization B(H).

The ANFIS model for nonlinear inductance was developed in the following steps:

Step 1: define the collection of input and output data used for training of ANFIS. Step 2: find fuzzy partition of input space by ANFIS; Step 3: training and testing the input/output data via the neutral network.

Figure 5 shows the flow chart process for modeling the nonlinear inductance by ANFIS. The findings are analyzed and discussed in the following chapter.

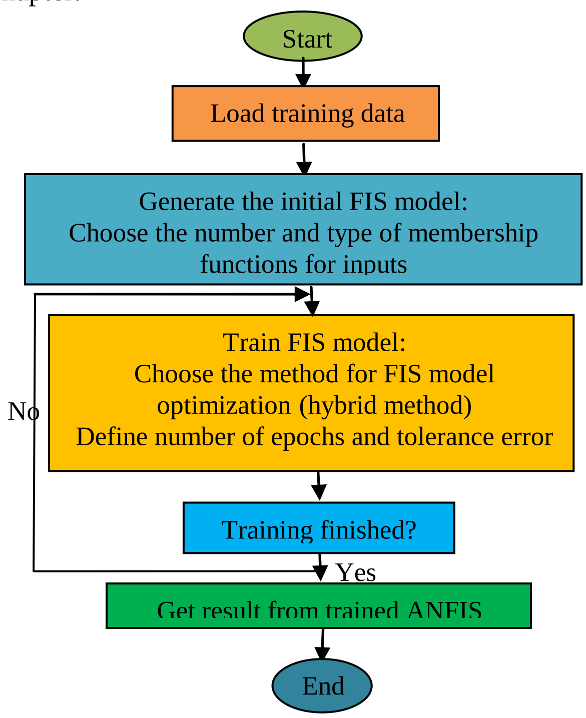

Fig. 5. ANFIS training process

MATLAB Fuzzy Logic Toolbox from MathWorks was selected as the development tool to test the proposed model.

3.2 Definition of input/output data

ANFIS modeling process starts by obtaining a data set (input-output data pairs) .The data set is a set of measurement data H_n and B_n (n=1,2,3…..n=100) of this special transformer. The data arranged as column vectors, and the output data (H data) in the last column. The Data used in training of ANFIS are given in Table I:

TABLE I: data used for training ANFIS

B(T)	H(AM)	B(T)	H(AM)
-2.3125	-72000	0.1515	50
-2.3	-70000	0.303	100
-2.285	-68000	0.455	150
-2.27	-66000	0.606	200
-2.25	-64000	0.758	250
-2.235	-62000	0.91	300
-2.22	-60000	1.1	400
-2.2	-58000	1.25	600
-2.19	-56000	1.325	800
-2.175	-54000	1.39	1000
-2.1575	-52000	1.425	1200
-2.1425	-50000	1.475	1500
-2.1275	-48000	1.52	2000
-2.1125	-46000	1.55	2400
-2.1	-44000	1.57	3000
-2.0875	-42000	1.5925	4000
-2.0575	-40000	1.665	6000
-2.05	-38000	1.7225	8000
-2.035	-36000	1.7625	10000
-2.015	-34000	1.7975	12000
-2.005	-32000	1.825	14000
-1.9875	-30000	1.85	16000
-1.97	-28000	1.875	18000
-1.955	-26000	1.8975	20000
-1.9375	-24000	1.9175	22000
-1.9175	-22000	1.9375	24000
-1.8975	-20000	1.955	26000
-1.875	-18000	1.97	28000
-1.85	-16000	1.9875	30000
-1.825	-14000	2.005	32000
-1.7975	-12000	2.015	34000
-1.7625	-10000	2.035	36000
-1.7225	-8000	2.05	38000
-1.665	-6000	2.0575	40000
-1.5925	-4000	2.0875	42000
-1.57	-3000	2.1	44000
-1.55	-2400	2.1125	46000
-1.52	-2000	2.1275	48000
-1.475	-1500	2.1425	50000
-1.425	-1200	2.1575	52000
-1.39	-1000	2.175	54000
-1.325	-800	2.19	56000
-1.25	-600	2.2	58000
-1.1	-400	2.22	60000
-0.91	-300	2.235	62000
-0.758	-250	2.25	64000
-0.606	-200	2.27	66000
-0.455	-150	2.285	68000
-0.303	-100	2.3	70000
-0.1515	-50	2.3125	72000

3.3 Find fuzzy partition of input space by ANFIS

Before starting the FIS training, we generate the initial FIS model by defining the number and type of membership functions for input. Two partitioning techniques are used by ANFIS to generate the initial FIS model [22, 23, 24]:

- Grid partition: Generates a single-output Sugeno-type FIS by using grid partitioning on the data.
- Subtractive clustering: generates an initial model for ANFIS training by first applying subtractive clustering on the data.

In this study, we have choosing the grid partition method to define the fuzzy partition of input data. The ANFIS provides 8 types of membership function, including the triangular membership function, the Gaussian membership function, etc. Gaussian function was found suitable for the present study as it is more accumulate with modeling behavior. The membership functions for input, which are learned by ANFIS method, are shown in Figure. 6.

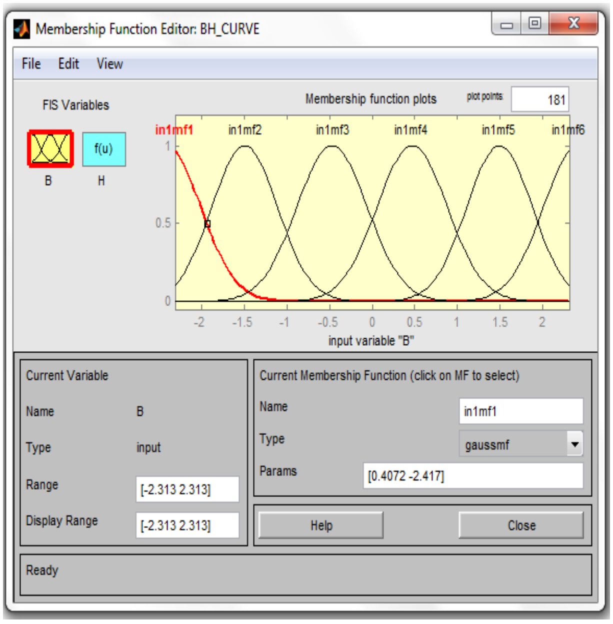

Fig. 6. The membership functions of input data (B)

3.4 Training and testing the input/output data via the neutral network

After loading the training data and generating the initial FIS structure, we can start training the FIS. ANFIS provides two learning algorithms, including back propagation or hybrid algorithm. In this study the input/output data is trained through hybrid algorithm by using 300epochs with 0.005 error tolerances. Figure 7 show the training error curve.

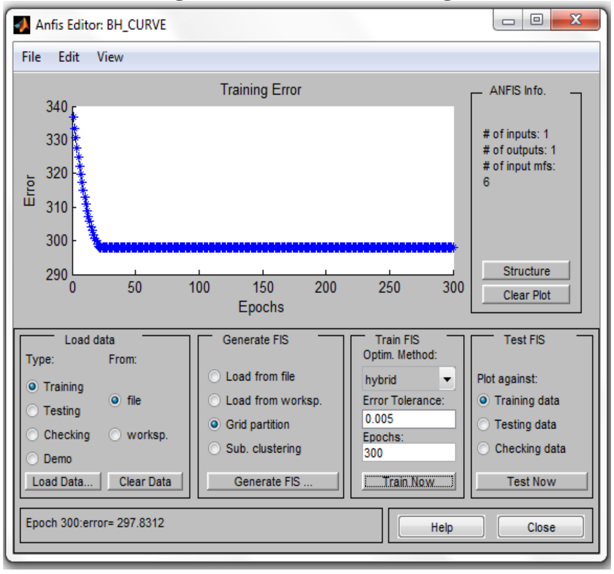

Fig. 7. Training error vs. epochs for ANFIS

Once the ANFIS is trained, we can test the system against different sets of data values to check the functionality of the proposed system. The followings figures presents the results obtained by trained ANFIS. The structure of ANFIS controller in continuous/discrete are used 6 rules, the structure is shown in Figure 8.The ANFIS generated surface is shown in Fig.ure 9. It is 2-dimensional plot between B and H.

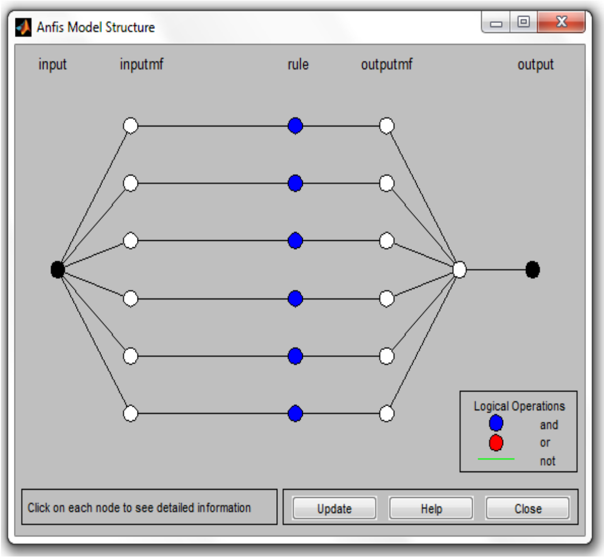

Fig. 8. ANFIS model structure

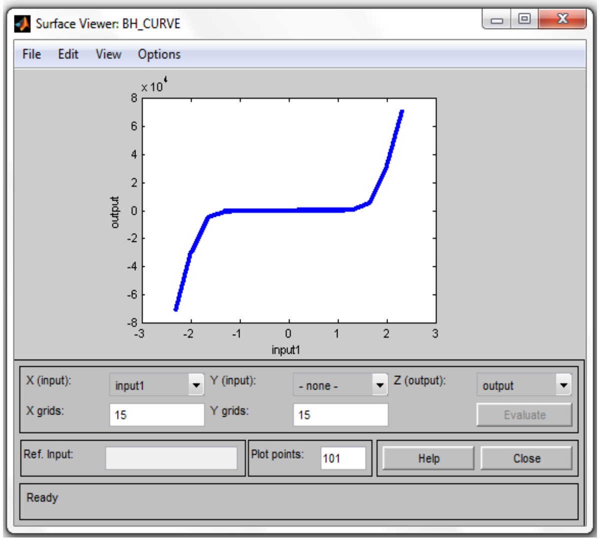

Fig. 9. surface viewer

After trainig and testing the Fis model,we can take it directly into Simulink and test them out in a simulation environment. A Simulink block diagram for nonlineair inductance is shown in the following figure. It contains a Simulink block called the Fuzzy Logic Controller block wich implements a fuzzy inference system (FIS) in Simulink, an integrator to derive the flux from the voltage and a source of current imposed. This diagram is valid for any nonlinear inductance

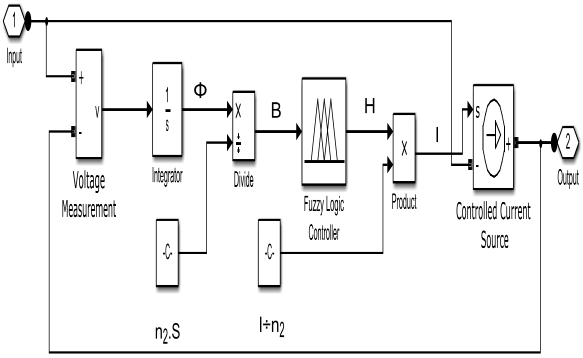

Fig. 10. Implementation of nonlinear inductance under MATLAB-SIMULINK

4. Simulation results and discussion

4.1. Simulation results

The simulation of case study is achieved by using MATLAB Ver. 2014a using the sim power system (SPS) toolbox and discrete step solver of 1e-5. To validate this model we have integrate the π quadruple model of the transformer in the overall circuit of the HV power supply (Fig. 11), where we represented the tube microwave by the equivalent diagram deduced from its electric characteristic [6, 7] which is formally similar to that of a diode of dynamic resistance neighbor of 350 Ohms and threshold voltage E of about 3800 Volts.

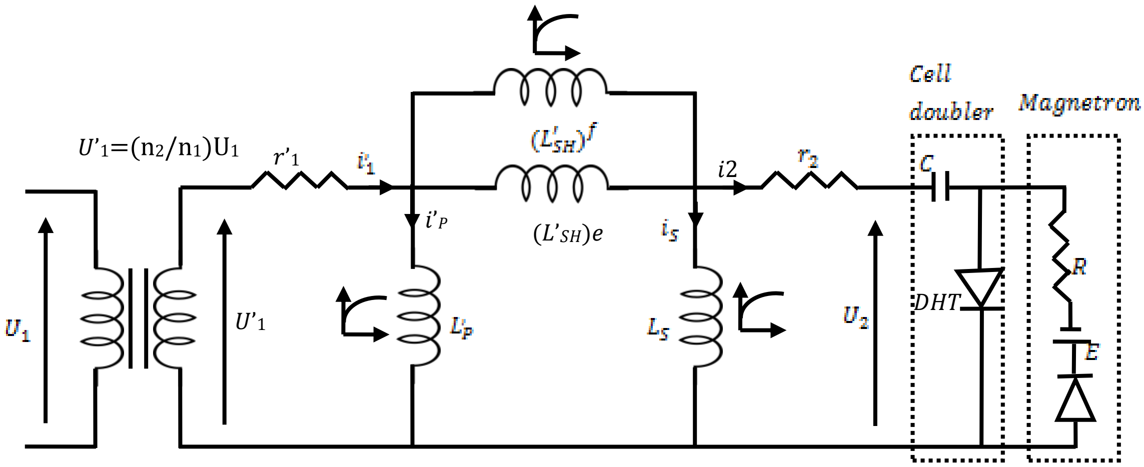

Fig. 11. Global Model of the Power Supply for one Magnetron.

We validate this new model by replaced the three nonlinear inductances L'_P, L_S and L'_{SH} (primary, secondary and shunt) by its new equivalent block (Fig. 10) and by carrying out tests on generator microwaves composed of the following elements:

- High voltage transformer with magnetic shunts possesses the nominal characteristics : f=50 Hz, S=1650 VA, U_1=220V, and vacuum U_2=2330V;
- Primary resistance referred to secondary r'_1=100 Ω, secondary resistance r_2=65 Ω;
- Number of turns in primary n_1=224, number of turns in secondary n_2 = 2400;
- A capacitor C = 0.9 µF and a high-voltage diode DHT;
- A magnetron designed to function under a voltage approximately 4000 V. To obtain its nominal power, it needs an average current I_{mean}=300 mA, but without exceeding the peak current which might destroy it (I_{peak} < 1, 2 A).

We superimpose in Figure 12 the simulation results of this new modeling obtained by MATLAB SIMULINK code with those obtained in practice (Fig. 13) under the same conditions (U=220 V, f=50Hz).

4.2. Experimental setup and results

The Figure 10 shows the experimental setup for measuring of the characteristics current and voltage of the high voltage power supply for magnetron in nominal operation. This test was performed in the department of electrical engineering of higher School of Technology in Agadir (Marocco).

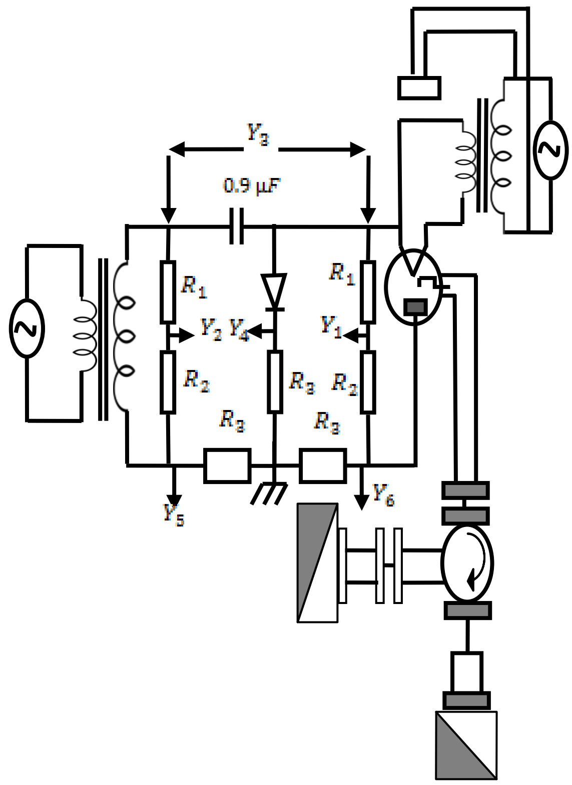

Fig. 12. Experimental set up for measuring of the characteristics: current and voltage of the power supply HV for magnetron in nominal operation.

With :

Y_1: magnetron voltage,

Y_2: secondary voltage,

Y_3: condansator voltage,

Y_4: diode current,

Y_5: secondary current,

Y_6: magnetron current,

R_1= 10MΩ, R_2=10 KΩ, R_3=22 Ω

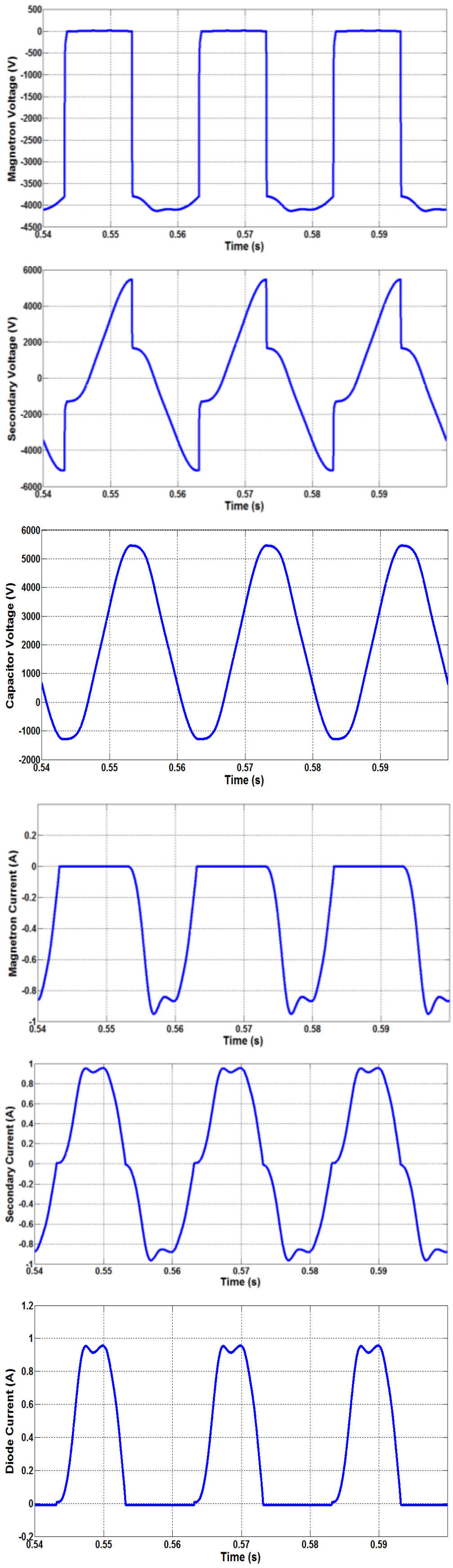

Fig. 13. Simulation of a new model with MATLAB SIMULINK: Forms of currents and voltages waves.

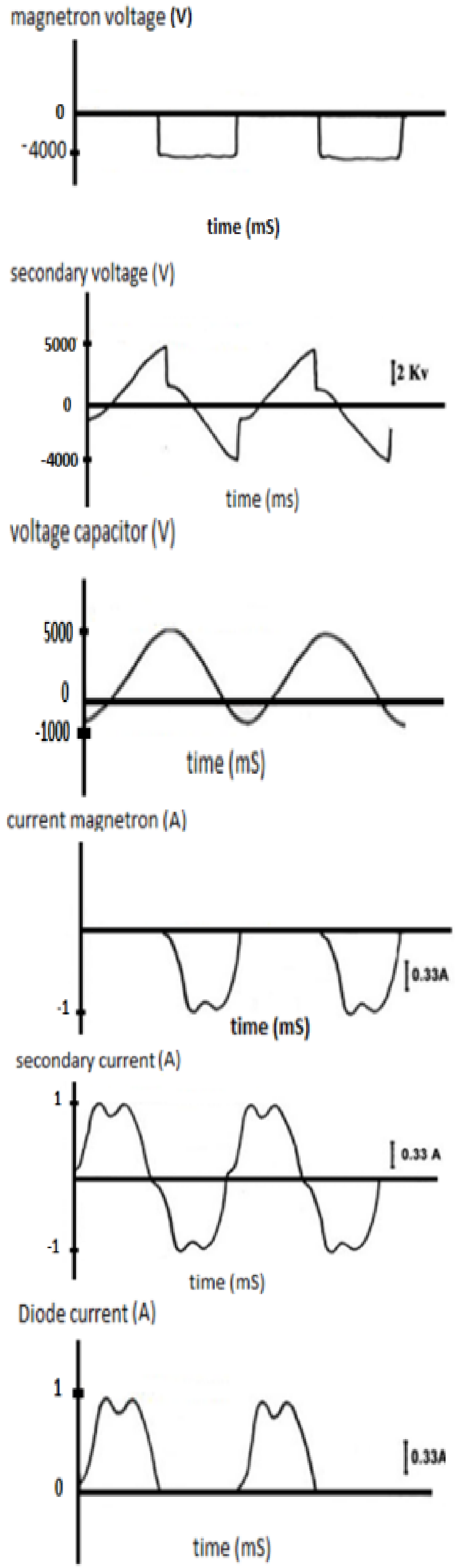

Fig. 14. Experimental waveforms of currents and voltages (nominal mode)

The shapes of voltages and currents quantities resulting from Simulation of a new model with MATLAB SIMULINK under nominal operation (U1=220V, f=50Hz) are identical to those obtained in practice (Fig. 13) [1, 8], especially the magnetron current curves which respect the maximum current magnetron constraint (Ipeak<1.2A) recommended by the manufacturer of magnetron. The current magnetron peak value obtained by MATLAB-SIMULINK code is approximately -1 A, which is identical to experimental value. In general, between peak to peak values, the relative variations never exceed 1%.

5. CONCLUSION

In this paper, an improved modeling of nonlinear magnetization curves of a ferromagnetic material has been presented. Starting with a discrete set of measurement data of B and H, we have improved a new block diagram of the nonlinear inductance on the base of the adaptive network-based fuzzy inference system (ANFIS). The proposed method proves to be easier, more accurate and more efficient than any other method.

It has been observed that the results obtained with our new π model of the transformer with magnetic shunts have shown a significant agreement with experimental results.

As perspectives, this work can be extended for modeling and optimization of new three-phase or six-phase power supply for several magnetrons by phase.

APPENDIX

During this work, we have taken as reference the following geometrical dimensions of the transformer HV with magnetic shunts (fig 15):

- The width of the non-wound core: a = 25 mm
- The width of the magnetic circuit: b = 60 mm
- Number of stacked sheets of the shunt: n_3 = 18
- Number of turns in the primary: n_1 = 224
- Number of secondary turns: n_2 = 2400
- Height of the sheet stack of shunts: h = 0.5 n3.
- Surface of the core: $S_1 = S_2 = 2.a.b$
- Surface of shunt: S_3 =h.b
- Thickness of the air gap: e = 0.75 mm

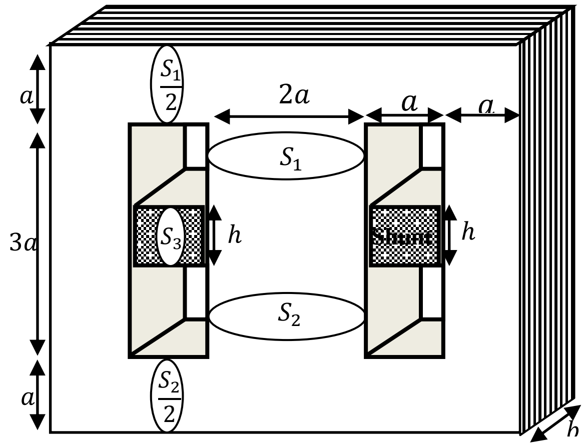

Fig. 15. Geometry of transformer with magnetic shunt

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