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Analytical determination of Currents from Shunt Transformer Flux with losses used in the Magnetron Power Supply for Industrial Microwave Generators

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ABSTRACT

The magnetron power supply (800 W at 2450 Mhz) for industrial microwave generators includes a high voltage transformer with magnetic shunts, which feeds the magnetron through a voltage doubler. The experimental survey of the transformer flows allowed, by applying an analytical method, to find their equations. The knowledge of the equations of these fluxes, the use of the Ampère theorem, the identification of the equation of the curve B (H) of the material used in the magnetic circuit and the use of the values of the geometrical parameters of construction of the transformer allowed to determine the equations and curves of its currents. The present study, which deals with the magnetron power supply, can be extended to the 1000 W and 1200 W magnetrons.

Key wordS: Industrial microwave generators, High voltage magnetron power supply Shunt transformer, Ampère theorem

1. INTRODUCTION

The study of the operation of the magnetic state of the shunt transformer of the power supply for industrial microwave generators has never been carried out despite the existence of a recent theory [1,2,3] on modelling and the optimized realization of the transformer. This article focuses on the study of fluxes from electromotive forces through the law of Faraday and currents from the flows using Ampère's theorem.

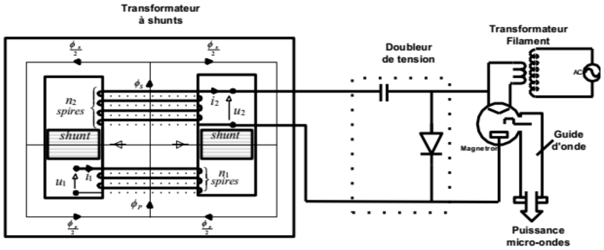

Figure 1: High voltage power for one magnetron.

2. MAGNETRON POWER SUPPLY

Figure 1 shows the basic circuitry of the magnetron power supply of a microwave generator [4,5,6,7,8] currently manufactured by industrial microwave oven manufacturers. This assembly, developed by E.G. DORGELOT [9], uses a single high-voltage, magnetic shunt, single-phase transformer that powers a voltage-doubling and current-stabilizing mono-alternating cell composed of a capacitor and a diode. The set (transformer + doubler) feeds in turn a single magnetron. Leaks of magnetic shunts regulate the current in the magnetron.

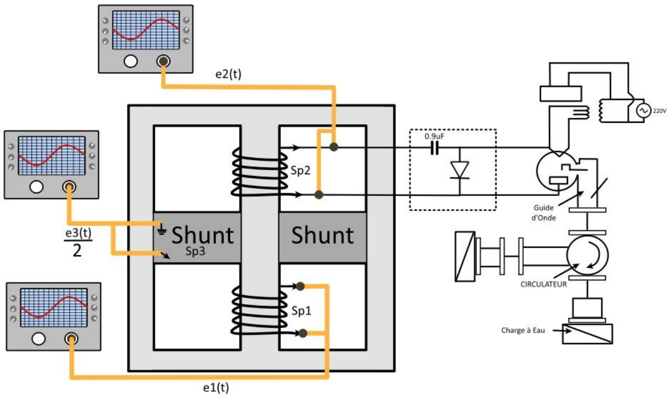

Figure 2: Magnetic circuit of the three-phase transformer.

3. DISTRIBUTION OF FLOWS

Figure 1 shows the armoured structure of the magnetic circuit of the leakage transformer. Its two identical shunts, consisting of a number of stacked sheets are interposed between the two windings of the central core. The resulting magnetomotive force of the ampere-turns of the two coils, makes it possible to obtain the distribution of three useful fluxes in the iron of the magnetic circuit [1,2,10,11]. $\Phi 1$ and $\Phi 2$ are channelled spire flows respectively in the iron of the central core on the primary and secondary side, $\Phi 3$ is the flux per turn corresponding to the total flow of magnetic leaks channelled in the iron part of the set of two identical shunts of which each is crossed by the flow. The law of conservation of the flows checks the equality

$$\phi 1(t) = \phi 2(t) + \phi 3(t)$$

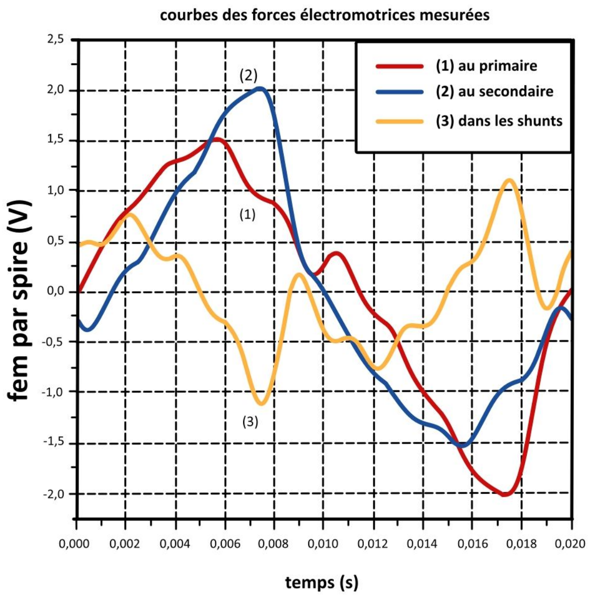

Figure 3: Measured electromotive forces

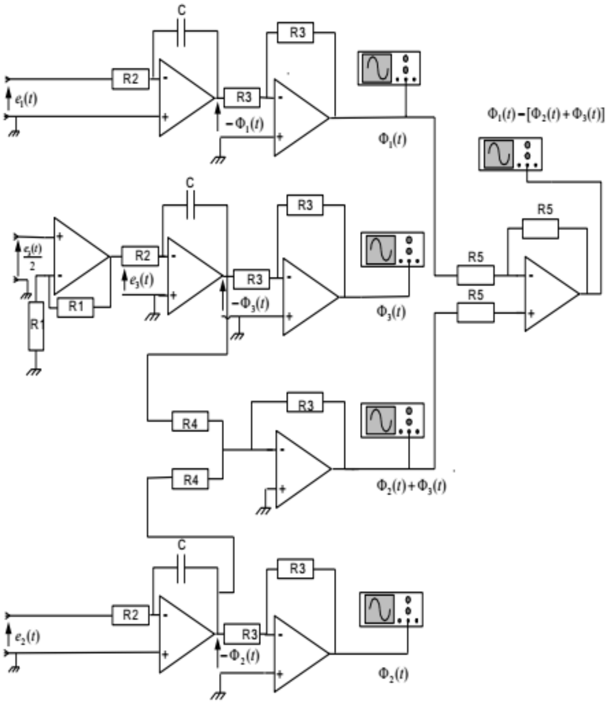

Figure 4: realization of the mounting of the analogue electronic card

4. EXPERIMENTAL STUDY OF FLOWS

The tests were carried out during the nominal operation of the magnetron power supply of a microwave generator delivering 800 W at 2450 MHz, using a Moulinex brand shunt transformer with characteristics 220 / 2200V, 50 Hz, 1500 VA. During the tests, the variation of the flows Φ1,Φ2 et Φ3 through the sections respective turns Sp1, Sp2 and Sp3 was used to record on the oscilloscope according to Faraday's law the time curves of the corresponding electromotive forces. FIG. 3 shows that the curves obtained from the electromotive forces per turn at the primary e1(t), the secondary e2(t) and in the shunts e3(t) are periodic and non-sinusoidal variables.

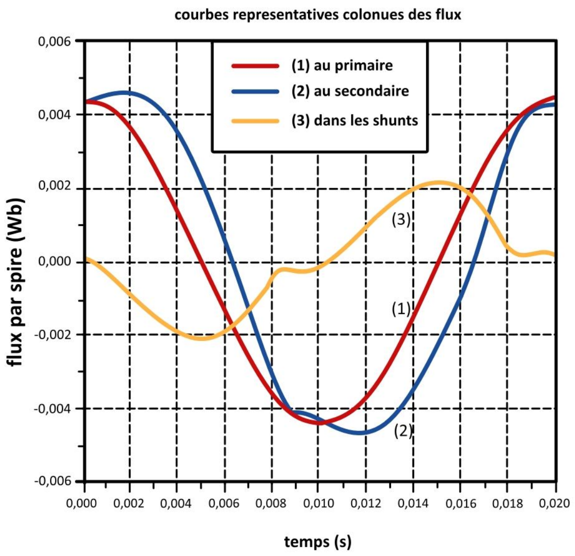

Figure 5: the representative flow curve obtained

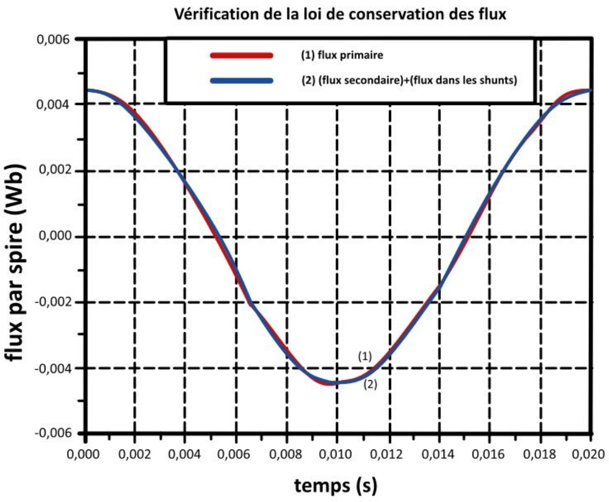

Figure 6:verification of the law of flow conservation

The realization of the mounting of the analogue electronic card [12, 13, 14] of FIG. 4 allows, by application of the Faraday law, to make the linear integration of the measured electromotive forces to find the corresponding flows of FIG 5 same assembly compares the flow with the primary one and the sum of the flows with secondary and in the shunts thus making it possible to check the law of conservation of the flows of figure 6.

5. FLOW EQUATIONS

5.1.Equation of flows

The application of the discrete Fourrier series development method [15,16] to the measured flux curves of the transformer has made it possible to find the temporal equations of the fluxes. In fact, the trend of the measured curves of the fluxes without continuous component, which satisfies the relation $\Phi(\omega t+\pi)=-\Phi(\omega t)$ makes the following development for each flow only with harmonics of odd rank

$$\Phi(\mathrm{t}) = \sum_{K=0}^{\infty}\Big(A_{2K+1}\sin\big((2\mathrm{k}+1)\omega\mathrm{t}\big) + B_{2k+1}\cos\big((2\mathrm{k}+1)\omega\mathrm{t}\big)\Big)$$

The shape of the experimental curves of the fluxes [6] also leads to the calculation of the amplitudes of the harmonics A2k + 1 and B2k + 1 of the flow development according to the expressions

$$A_{2K+1} = (2\,/\,p) * \sum_{j=1}^{p}(Ø[j] * \sin[(j(2k+1) * \pi)\,/\,p])$$

$$B_{2K+1} = (2\,/\,p) * \sum_{j=1}^{p}(Ø[j] * \cos[(j(2k+1) * \pi)\,/\,p])$$

With:

2p: total number of equal intervals decomposed over a period of the experimental curve of each stream

Φ [j]: experimental data due to the replacement in each interval of the corresponding portion of the curve by a horizontal whose amplitude is equal to that of the end of the interval.

5.2. Results of flow equations

A numerical processing program allowed, after the numerical computation of the preceding formulas, to graph curves of the development for each value of the rank of the highest harmonic and to compare them with the experimental control curves. By varying this rank and after analyzing the figures obtained, we see that it is appropriate to adopt simultaneously, for the three flows, the value 9 at the highest rank so that the 'theoretical' curves are superimposed as closely as possible to experimental curves. In this case, the numerical equations of the flows in milliWebers are written respectively at the primary, the secondary and in the shunts:

$$Ø_1(t)= 0.0299 \sin(1\omega t)+ 4{,}4372\cos(1\omega t)-0{,}0258\sin(3\omega t)-0{,}0262 \cos(3\omega t) + 0{,}0103 \sin(5\omega t)+0{,}0250 \cos(5\omega t)-0{,}0176 \sin(7\omega t) - 0{,}0055 \cos(7\omega t)+0{,}0111 \sin(9\omega t) -0{,}0152 \cos(9\omega t)$$

$$Ø_2(t)= 2{,}0656 \sin(1\omega t)+ 4{,}5360\cos(1\omega t)-0{,}3972\sin(3\omega t)- 0{,}0331 \cos(3\omega t) - 0{,}0589\sin(5\omega t) - 0{,}1247\cos(5\omega t)+ 0{,}0169 \sin(7\omega t) - 0{,}0540 \cos(7\omega t)+0{,}0173 \sin(9\omega t)- 0{,}0278 \cos(9\omega t)$$

$$Ø_3(t) = -1{,}8539\sin(1\omega t) - 0{,}0849 \cos(1\omega t) + 0{,}3606 \sin(3\omega t)+0{,}0686 \cos(3\omega t) + 0{,}0599\sin(5\omega t)+ 0{,}1336 \cos(5\omega t)-0{,}0467 \sin(7\omega t) + 0{,}0384\cos(7\omega t)- 0{,}0543 \sin(9\omega t)- 0{,}0121 \cos(9\omega tt)$$

These expressions represent the curves of FIG. 5 and verify the law of conservation of the flows of FIG 6.

Current equations

The determination of the equations of currents first requires the determination of the equation of the curve B (H) of the material used for the construction of the transformer. The case treated below corresponds to the case where the material used for the magnetic circuit of the shunts is identical to that of the rest of the transformer.

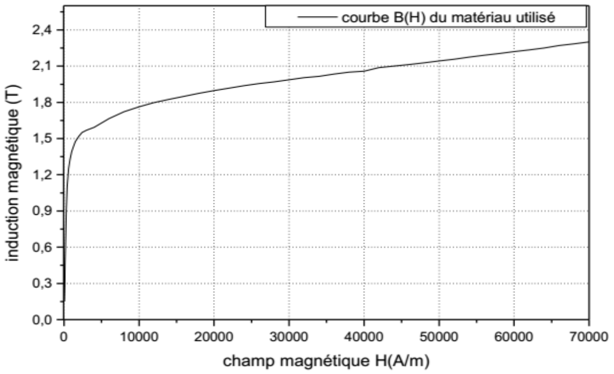

Figure 7: Magnetic fields

Equation of the magnetization curve B (H)

The ferromagnetic material used to channel the lines of force of the magnetic circuit has properties by the magnetomotive forces and flux, which results in the phenomena hysteresis, eddy current loss and saturation. In what follows, we are content to introduce the effects of saturation by admitting that any saturable part of the transformer has a characteristic whose shape is given in figure 8. The least squares method [18,19] was used to find the equation of the experimental curve. B (H) of figure 8 of the material used from Rougé's' theoretical 'formula [20] giving the relationship between magnetic field H and induction B:

$$\mathbf{H = aB + cB^{2n+1}}$$

At each experimental value Bexpj of B, there is a difference between the experimental value Hexpj of corresponding Hthj which corresponds to it on the theoretical curve. The values of the coefficients a, c and the exponent 2n + 1 of the best-fit least squares curve, so that the difference between the experimental curve B (H) and the theoretical curve of the formula (10) is the lowest possible, are those that make the following S amount:

$$S=\sum_{j=1}^{N}(H_j^{th}-H_j^{\exp})^2$$

$$S=\sum_{j=1}^{N}(a.B_j^{th}+c(B_j^{th})^{2n+1}-H_j^{\exp})^2$$

$$a=\frac{(\sum_j(B_j^{th}H_j^{\exp})\sum_j(B_j^{th})^{4n+2})-(\sum_j(B_J^{th})^{2n+1}H_j^{\exp})(\sum_j(B_j^{th})^{2n+2})}{(\sum_j(B_j^{th})^2\sum_j(B_j^{th})^{4n+2}-\sum_j(B_j^{th})^{2n+2}(\sum_j(B_j^{th})^{2n+2})}$$

$$c=\frac{(\sum_j(B_j^{th}H_j^{\exp})\sum_j(B_j^{th})^{2n+2})-(\sum_j(B_J^{th})^{2n+1}H_j^{\exp})(\sum_j(B_j^{th})^2)}{(\sum_j(B_j^{th})^{2n+2}\sum_j(B_j^{th})^{2n+2}-\sum_j(B_j^{th})^{4n+2}(\sum_j(B_j^{th})^2)}$$

A numerical treatment program made it possible, by using the two preceding formulas and the experimental curve B (H), to select the values of a = -7458, c = 1432 and n = 2 which give, in the useful field of exploitation the widest of the curve B (H), an error rate of less than 5% between experience and fit.

Equations of currents with losses

The use of the equations (2), (3), (4), (7), (8), (9) and (10) allowed, by replacing in each part of the magnetic circuit the induction Bj by the quantity corresponding Φj / Sj, to lead to the following expressions of the formulas of the two currents, primary and secondary, of the transformer:

$$i_1=\frac{\ell_1}{n_1}\frac{c}{S_1^{2n+1}}[\sum_{k=0}^{4}A_{2k+1}^{1}\sin(2k+1)\omega t+B_{2k+1}^{1}\cos(2k+1)\omega t]$$
$$+\frac{\ell_1}{n_1}\frac{c}{S_1^{2n+1}}[\sum_{k=0}^{4}A_{2k+1}^{1}\sin(2k+1)\omega t+B_{2k+1}^{1}\cos(2k+1)\omega t]^{2n+1}$$
$$+(\frac{\ell_3}{n_1}\frac{a}{S_3}+\frac{\ell_e}{n_1}\frac{1}{\mu_0 S_e})[\sum_{k=0}^{4}A_{2k+1}^{3}\sin(2k+1)\omega t+B_{2k+1}^{3}\cos(2k+1)\omega t]$$
$$+\frac{\ell_3}{n_1}\frac{c}{S_{Sh}^{2n+1}}[\sum_{k=0}^{4}A_{2k+1}^{3}\sin(2k+1)\omega t+B_{2k+1}^{3}\cos(2k+1)\omega t]^{2n+1}$$

$$i_2(t)=-\frac{\ell_2}{n_2}\frac{a}{S_2}[\sum_{k=0}^{4}A_{2k+1}^{2}\sin(2k+1)\omega t+B_{2k+1}^{2}\cos(2k+1)\omega t]$$
$$+\frac{\ell_2}{n_2}\frac{c}{S_2^{2n+1}}[\sum_{k=0}^{4}A_{2k+1}^{2}\sin(2k+1)\omega t+B_{2k+1}^{2}\cos(2k+1)\omega t]^{2n+1}$$
$$+(\frac{\ell_3}{n_2}\frac{a}{S_3}+\frac{\ell_e}{n_2}\frac{1}{\mu_0 S_e})[\sum_{k=0}^{4}A_{2k+1}^{3}\sin(2k+1)\omega t+B_{2k+1}^{3}\cos(2k+1)\omega t]$$
$$+\frac{\ell_3}{n_2}\frac{c}{S_3^{2n+1}}[\sum_{k=0}^{4}A_{2k+1}^{3}\sin(2k+1)\omega t+B_{2k+1}^{3}\cos(2k+1)\omega t]^{2n+1}$$

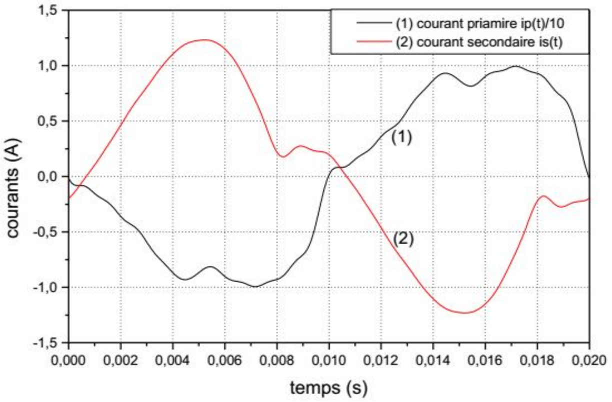

Figure 8: Representation of current

Results of current curves

By introducing in the expressions of the currents of the preceding paragraph the numerical values:

- coefficients a, c and n of the least squares method for adjusting curve B (H)

geometrical construction parameters ℓ1, ℓ2, ℓ3, ℓe, S1, S2, S3, Se, n1 et n2

- amplitudes of the harmonics of the flow identification method A numerical treatment program allowed to draw the two currents, primary and secondary, of the transformer of figure 10 resulting from the theorem of Ampère and to show that they are in opposition phase in accordance with the same winding direction and sign conventions adopted for currents and voltages corresponding to the normal direction of the power transfer.

6. CONCLUSIONS

- The realization of an analogue electronic card made it possible, during the nominal operation of the shunt transformer from the magnetron power supply 800 Watts to 2450 MHz, the experimental study of flows from that of the electromotive forces corresponding (Faraday's law).

- The experimental results found validate the law of conservation of the flows: the flow in the shunts (not negligible) is equal to the difference between the flow with the primary and the flow with the secondary.

- The analytical method developed, based on the experimental measurement of the flow of the transformer made it possible to find by numerical treatment the equations and graphical curves representative of these flows. The analysis of the results found confirmed the existence of a perfect resemblance between the measured and 'theoretical' curves resulting from the analytical method of identification also checking the law of conservation of flows.

- The time equations and the curves of the primary and secondary currents of the transformer have been determined with sufficient approximation from:

- the use of Ampère's theorem

- the identification of the magnetization curve B (H) of the material used in the magnetic circuit of the transformer

- knowledge of the values of the construction parameters

- knowledge of the temporal equations of the three flows

-The use of flow and current equations that translate saturation-related nonlinear phenomena into the electrical and magnetic equations governing transformer operation can help to actually model the transformer under saturated conditions during the nominal operation of the transformer power supply for industrial microwave generators with magnetron.

- The saturated operation of the shunt transformer, which renders the equivalent models of conventional transformers irrelevant and unsuitable for it, justifies the recent development of a new adequate and suitable equivalent electric model [1], capable of taking into account the presence of the flow in the shunts, to really represent the nonlinear operation of this special transformer and to make the link between its saturation and the regulation of the current in the magnetron imposed by the manufacturer.

- The results obtained in this article will contribute to the development of technological innovation in the manufacturing industry of magnetron power supplies. This development can be realized by the development of a new type of power supply for microwave generators which presents, in relation to the current supply, certain and multiple advantages with regard to the weight, the volume, the importance of electrical wiring and the cost. The future trend is focused on a new generation of power supply [21] using a single-phase transformer to supply N magnetrons in parallel and not, as in the present case, N single-phase transformers feeding N magnetrons. This trend can be extended to the case of three-phase or six-phase where each phase feeds N magnetrons in parallel.

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