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SIZE POWER RATIO OPTIMIZATION FOR THE CONVERTERS OF SWITCHED RELUCTANCE MOTORS

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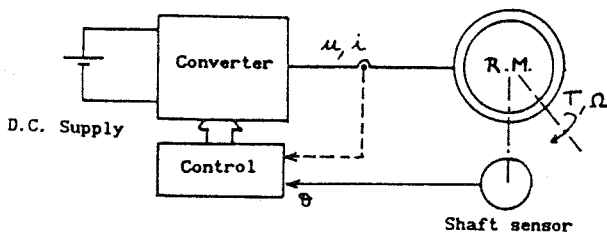
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ABSTRACT

In this paper, the authors present research results on the optimization of supply current shapes for switched reluctance motors (S.R.M.). After recording the advantages and disadvantages of S.R.M., and more specifically of the converter oversize, they define new size power ratios (S.P.R.) which take into account RMS and peak values of current and voltage. They describe the motor's numerical modelisation with magnetic saturation and any spatial waves of permeance. With a numerical simulation, they go on to determine optimal waves of current and voltage which minimize S.P.R. They demonstrate a theoretical absolute limit and define the ideal switched reluctance motor. They finally give experimental results to validate the numerical model.

1- INTRODUCTION

The switched reluctance motor (S.R.M.) is a brushless motor like the D.C. brushless motor or the induction motor with vector control. It is a doubly-salient motor like the reluctance stepper motor but, furthermore, the S.R.M. has a shaft sensor which gives control information to the converter (figure 1). Its structure can be cylindrical /1/ or discoidal /2/ with many airgaps for high performance.



The Switched Reluctance Motor
 Figure -1-

The instantaneous current or voltage value in each coil is defined by rotor position. It is theoretically possible to obtain any current wave by P.W.M. with the converter. Therefore, we can try to find out optimal current shapes which minimize the size of the converter switches for maximum motor power.

The advantages and disadvantages of S.R.M. /3/ are as follow :

Advantages : robustness and reliability

- there is no coil and permanent magnet in the rotor, therefore the bulk of losses appears on the stator and cooling is easier; furthermore, higher temperatures than with P.M. motors are permissible;

- The stator coils are easy to wind (salient poles);

- the torque is independent from current polarity, so converter topology can be simple, increasing its reliability and decreasing its cost. Furthermore, it is possible to have only one switch per phase /4/;

- the diversity of the structures is compatible with domestic appliances (low cost) with vernier cylindrical structures) and robotic appliances (high specific torque and power with multi-airgap structures).

Disadvantages : the ripple torque can be high and converter oversized (if no caution is taken).

- the nature of energy conversion provides a ripple torque which may contribute to acoustic noise, above all in large machines;

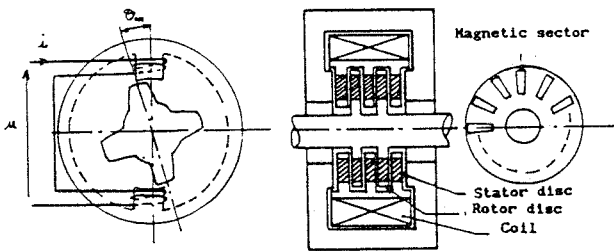
- Converter size is usually greater than that of the converters of classical motors for the same output power.

However, these two problems may be solved by use of current waves which are adapted to the operation point (torque-speed).

We propose to try and find out the ideal current wave which minimizes converter size. This study concerns only reluctance machines without magnetic coupling between phases like, for example, vernier doubly-salient and multistack machines.

2- THE RELUCTANCE MOTOR MODEL

Each phase is magnetically uncoupled with the others, so we can consider one phase of the simple structure as shown in Fig. 2a (vernier cylindrical motor) and Fig. 2b (axial multi-airgap motor).



Vernier cylindrical — Multi-airgap discoidal structures, only one phase is represented

Figure -2a-

Figure -2b-

Coil inductance l depends on rotor position θ_m and on current i because the magnetic circuit is saturable. The period of l is: $\frac{2\pi}{N_r}$ where N_r is the number of rotor teeth. We define the electrical angle θ :

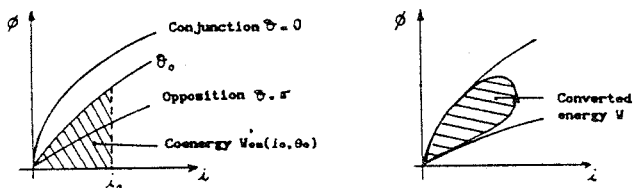
$$\theta = N_r \cdot \theta_m \quad 2.1$$

Electric angular velocity (supply) $\omega = 2\pi \cdot f$ is given by:

$$\omega = N_r \cdot \Omega \quad 2.2$$

where Ω is mechanical angular velocity.

The machine is represented by its function $\Phi(\theta, i)$ as shown in Fig. 3a.



Reluctance motor characteristics Figure -3a-

Working cycle Figure -3b-

For $\theta = 0$, the rotor is in conjunction with the stator. For $\theta = \pi$, it is in opposition.

Magnetic coenergy is defined by:

$$W_{em}(\theta_0, i_0) = \int_0^{i_0} \Phi \cdot di \quad 2.3$$

So the instantaneous torque is given by /5/:

$$t = \frac{\partial W_{em}}{\partial \theta} \quad 2.4$$

and voltage by:

$$u = \frac{d\Phi}{dt} = \omega \cdot \frac{d\Phi}{d\theta} = N_r \cdot \Omega \cdot \frac{d\Phi}{d\theta} \quad 2.5$$

If the magnetic circuit is not saturated, we can calculate the instantaneous torque with the inductance $l(\theta)$:

$$t = \frac{1}{2} \cdot i^2 \cdot \frac{dl}{d\theta} \quad 2.6$$

In this expression, we can see that torque is independent from current polarity and proportional to the inductance derivative. The torque is positive if there is a current when $l(\theta)$ is increasing and negative if $l(\theta)$ is decreasing. So it is possible to choose between motor or regenerative operation.

For a conversion cycle, work is:

$$W = \oint \Phi \cdot di \quad 2.7$$

This is represented by the cycle area in $\Phi(i)$ plane in Fig. 3b.

This energy is converted at supply frequency f and is equal to mechanical energy. So, for one phase, we have:

$$f \cdot W = T \cdot \Omega \quad 2.8$$

where T is the average torque produced by one phase, for a polyphase motor, this value may be multiplied by the number of phases.

We thus have, with expression 2.2:

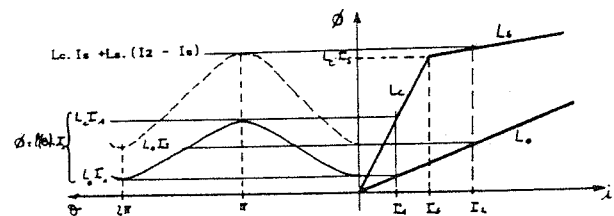
$$f = N_r \cdot \frac{\Omega}{2\pi} \quad 2.9$$

From 2.8 and 2.9, the average torque is:

$$T = \frac{N_r}{2\pi} W \quad 2.10$$

numerical model

To modelize the machine with a minimum number of parameters, we use a three slope electromagnetic model /6, 7/ with improvement (see description in Fig. 4).



Three slope model Figure -4-

In this model :

- L_c is the inductance in unsaturated conjunction;
- L_o is the inductance in opposition (never saturated in these machines);
- L_s is the inductance in saturated conjunction;
- I_s is the saturation current for all angles θ .

We define normalized parameters as follows; DLN being the relative variation of inductance and K describing the saturation :

$$DLN = \frac{L_c - L_o}{L_c + L_o}, \quad 0 < DLN < 1 \quad 2.11$$

$$K = \frac{L_s - L_o}{L_c - L_o} \quad 2.12$$

We observe that $K = 0$ if $L_s = L_o$.

The model must be determined for the operating area (saturation level) of the machine.

Another parameter, shown in Fig. 4, is the spatial inductance (or permeance) shape : $f(\theta)$ is supposed independent from the current level. $f(\theta)$ is defined by the following conditions :

$$\begin{cases} * f(\theta) = f(-\theta) \\ * f(0) = 1 \\ * f(\pi) = -1 \end{cases}$$

For example, if the permeance or inductance wave is sine :

$$f(\theta) = \cos \theta$$

if the reluctance wave is sine :

$$f(\theta) = \frac{DLN + \cos \theta}{1 + DLN \cdot \cos \theta}$$

So, $f(\theta)$ can be written with Fourier series.

Therefore, the reluctance motor can be defined by the three parameters : DLN , K and $f(\theta)$.

* if $i \leq I_s$:

$$l(\theta) = \frac{L_c + L_o}{2} [1 - DLN \cdot f(\theta)]$$

$$\text{and } \phi(i, \theta) = l(\theta) \cdot i \quad 2.13$$

* if $i \geq I_s$, we can calculate :

$$\phi(i, \theta) = l(\theta) \cdot I_s + [(K-1) \cdot DLN + 1 + K \cdot (l(\theta) - \frac{L_c + L_o}{2})] \cdot (i - I_s) \quad 2.14$$

3- SIZE POWER RATIOS AND OPTIMIZATION

We define the "Sizing factor" f_d of a converter by :

$$f_d = \frac{n \cdot U_M \cdot I_M}{P} \quad 3.1$$

where : n is the number of power switches (including the freewheeling diodes)

U_M and I_M are the maximum voltage and

current;

P is the electric power.

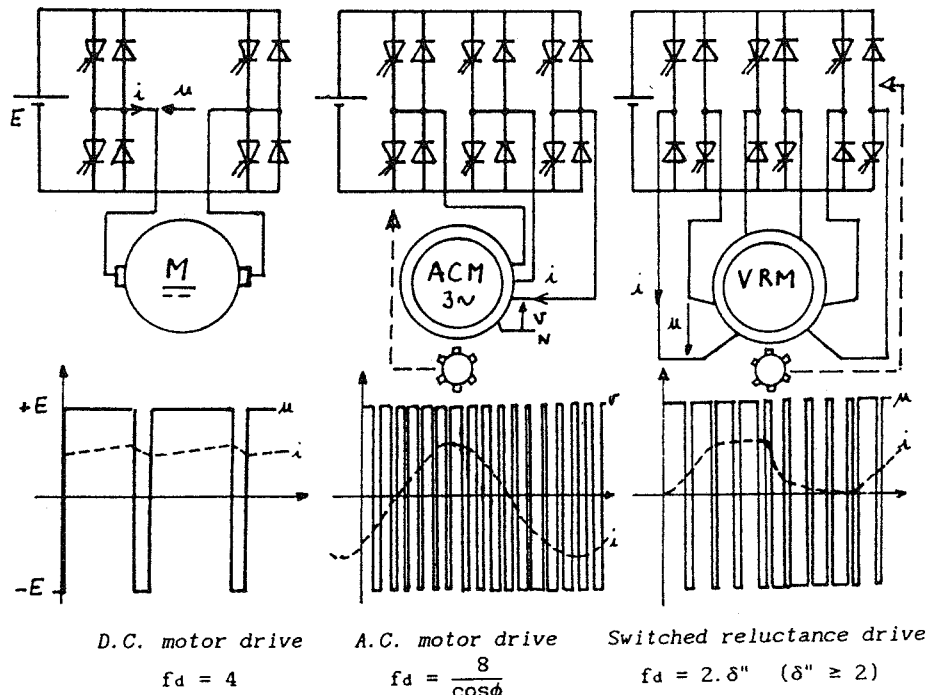


Figure -5-

Figure 5 shows the converters, voltage and current shapes and the sizing factor for D.C. Brush Motors, A.C. Motors (DC brushless or induction) and Switched Reluctance Motors. In the case of S.R.M., it's possible to supply it with many current shapes and the sizing factor is highly dependent on these shapes.

To determine δ'' , we define the size power ratio δ'' /8, 9/ :

$$\delta'' = \frac{U_M \cdot I_M}{P_1} \quad 3.2$$

where P_1 is the power per phase.

This S.P.R. is used with power switches which are sized by maximum current. We can also take R.M.S. current into account, therefore defining another S.P.R. δ' by :

$$\delta' = \frac{U_M \cdot I_{eff}}{P_1} \quad 3.3$$

To minimize the sizing power of the converter, we propose to optimize current shape by trying to find out the minimum value of δ' or δ'' . In the case of switched reluctance motors, we can obtain S.P.R. values with the characteristic $\Phi(i, \theta)$:

$$\delta'' = \frac{\text{Max} \left[\frac{d\Phi}{dt} \right] \cdot \text{Max}[i(t)]}{T \cdot \Omega} \quad 3.4$$

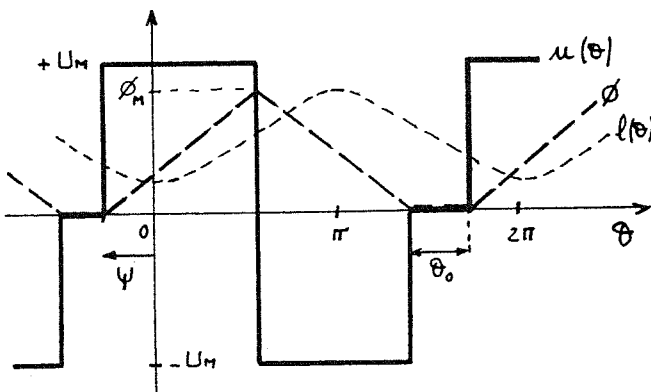
where T is the average torque produced by one phase.

From expressions 2.5, 2.7 and 2.10, S.P.R. δ'' can be written as follows :

$$\delta'' = \frac{\text{Max} \left[\frac{d\Phi(\theta, i)}{d\theta} \right] \cdot \text{Max}[i(\theta)]}{\frac{1}{2\pi} \int \Phi \cdot di} \quad 3.5$$

In this expression, δ'' is only dependent on the shape $i(\theta)$, therefore we can begin current optimization.

We have written a numerical optimization programme. We found that the optimum current wave is such that the corresponding voltage wave is square, as shown in Fig. 6.



Optimal voltage wave form

Figure -6-

The optimal parameters Φ_M , ψ and θ_0 depend on the motor parameters defined in chapter 2 and on the required torque. So we have :

$$U_{Max} = N_r \cdot \Omega \cdot \frac{\Phi_M}{\pi - \theta_0} \quad 3.6$$

In the case of unsaturated motor, the optimal parameters ψ and θ_0 are constant for any torque and : $T = k \cdot \Phi_M^2$.

Generally /7/, to have minimum S.P.R. we must have :

$$0^\circ \leq \theta_0 \leq 30^\circ \text{ and } 30^\circ \leq \psi \leq 80^\circ$$

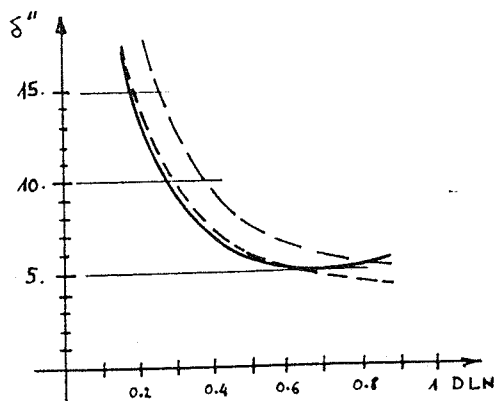
and : $T = k \cdot \left[\frac{U_M}{\Omega} \right]^2$ for unsaturated operation

$$T \approx k \cdot \left[\frac{U_M}{\Omega} \right] \text{ for saturated operation}$$

So, to minimize converter size, one can use this optimum voltage wave for maximum power P_M of the motor. Under P_M , it's possible to switch with P.W.M. the voltage wave to regulate the torque.

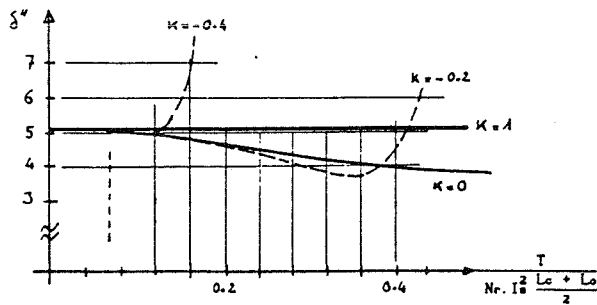
4- SIZE POWER RATIO VALUES AND AN IDEAL SWITCHED RELUCTANCE MOTOR

The smaller values for δ'' are highly dependent on the motor parameters defined in chapter 2 : DLN, K and $f(\theta)$. Figure 7 gives results for $K = 1$ (unsaturated magnetic circuit), for sine and triangular inductances and for sine reluctance shapes.



Minimum Size Power Ratios vs. relative inductance variation for unsaturated motors
Figure -7-

Saturation is very effective to cause S.P.R. to decrease, above all with great DLN values; in Fig 8, we show S.P.R. reduction.



Minimum S.P.R. for a saturated motor vs. torque
Figure -8-

If $K = 1$, there is no saturation (formula 2.12) and minimum S.P.R. is the same as for any torque value.

If $K = 0$, we can see minimum S.P.R. is decreasing when saturation level is increasing.

If K is negative, cycle area is limited to a maximum value. When the torque approaches the limit, δ'' increases.

An ideal switched reluctance motor

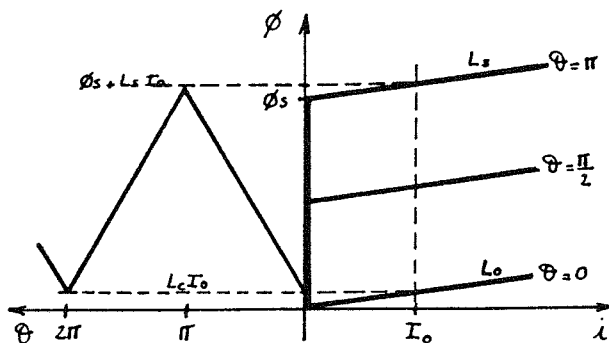
After numerous computations, we obtained interesting results. We give in Fig. 9a the motor's characteristics and, in Fig 9b the supply voltage and flux waves.

Optimal parameters of motor are : $I_s = 0$, $K = 0$, DLN 1 and triangular inductance wave.

Optimal parameters of supply are : $\Psi = \theta_0 = 0$.

According to figure 9a, flux is given by :

$$\Phi(i_0, \theta) = (\Phi_s + L_s \cdot i_0) \cdot \frac{\theta}{\pi} \quad 4.1$$



Characteristics of the Ideal Switched Reluctance Motor
Figure -9a-

Flux is compelled by voltage supply and its expressions are :

$$\text{* for : } 0 \leq \theta \leq \pi : \Phi(\theta) = \frac{U_M}{N_r \cdot \Omega} \cdot \theta \quad 4.2$$

$$\text{* for : } \pi \leq \theta \leq 2\pi :$$

$$\Phi(\theta) = \frac{U_M \cdot \pi}{N_r \cdot \Omega} - \frac{U_M}{N_r \cdot \Omega} \cdot (\theta - \pi) \quad 4.3$$

Maximum flux Φ_M is :

$$\Phi_M = \frac{U_M \cdot \pi}{N_r \cdot \Omega} \quad 4.4$$

So, with formulae 4.1, 4.2 and 4.4, current wave can be calculated approximately :

$$\text{* for : } 0 \leq \theta \leq \pi : i(\theta) = \frac{\Phi_M - \Phi_s}{L_s} = I_M \quad 4.5$$

$$\text{* for : } \pi \leq \theta \leq 2\pi : i(\theta) = 0$$

In reality, increasing duration of current is not null. It corresponds at the angle $\Delta\theta$:

$$\Delta\theta = \frac{L_o \cdot N_r \cdot \Omega \cdot I_M}{U_M} \quad 4.6$$

With expressions 4.4, 4.5 and 4.6, we have :

$$\Delta\theta = \pi \frac{\Phi_M - \Phi_s}{\Phi_M} \quad 4.7$$

Therefore, this angle is small (several 10°) and can be neglected in first rough estimate. Figure 10a shows voltage and current waves and figure 10b gives optimal cycle.

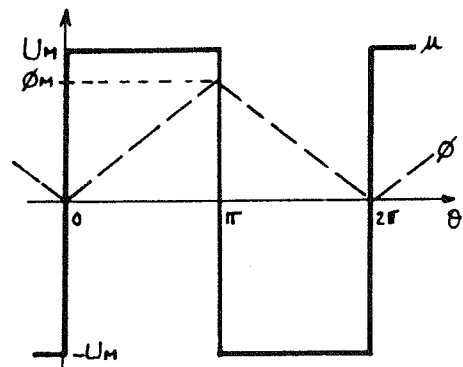
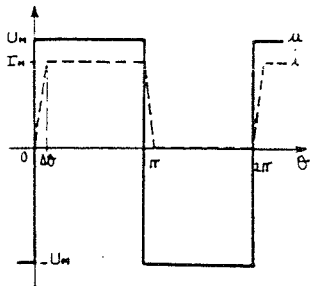


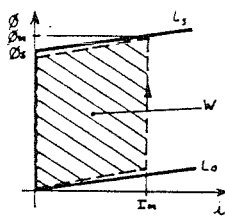
Figure -9b-



Current and voltage shapes

for the ideal S.R.M.

Figure -10a-



working cycle

Figure -10b-

Converted energy is given by the cycle area :

$$W \cong \Phi_s \cdot I_M \quad 4.8$$

This expression is valid only if $\Phi_M > \Phi_s$.

So, with expressions 2.10 and 4.4, average torque is given by :

$$T \cong \frac{\Phi_s \cdot I_M}{2 \cdot \pi} \quad 4.9$$

We can see that torque is proportional to current I_M .

The S.P.R. δ'' is calculated with 3.4, 4.4 and 4.9 :

$$\delta'' \cong 2 \frac{\Phi_M}{\Phi_s} \quad 4.10$$

So, $\delta'' \cong 2$ because inductance $L_s = L_0$ is very small and Φ_M is higher to Φ_s by only very little. Sizing factor f_d is equal to 4 as is the case for D.C. brush motors and with a four quadrant operation.

To obtain these ideal characteristics, the reluctance motor must have a small airgap with regard to other sizes and it must have particular tooth forms /1/.

Furthermore, as instantaneous torque shape is square for each phase, using a 4 phase motor makes. It is appreciable to have a constant instantaneous torque.

5- EXPERIMENTAL RESULTS

We validate S.R. model and S.P.R. computation with a single phase motor supplied by an asymmetrical half-bridge. We had to take into account coil resistance on account of small motor (power about 150 W).

Inductance shape is written with Fourier series, the other parameters are : $DLN \cong 0.62$, $K \cong -0.1$ and $I_s \cong 1.5$ A.

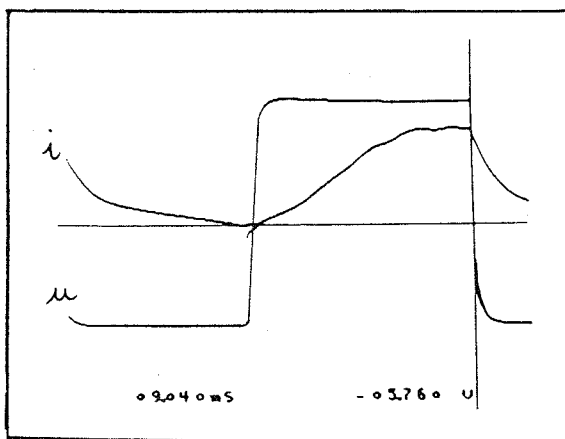
Figure 11 shows a comparison between numerical simulation and measures.

Therefore, we achieved significant S.P.R. reduction with saturation effect as shown in fig. 8.

6- CONCLUSIONS

Minimum converter size for S.R.M. is obtained with square voltage shapes. This supply wave is often used to supply S.R.M. but our optimization enabled us to make sure that is was the optimum wave for all reluctance motor, whatever their characteristics. Therefore we have thus found out special characteristics to obtain an ideal S.R.M..

The motor's characteristics have a great influence on drive performances. So, it is very important to design at the same time machine and supply.

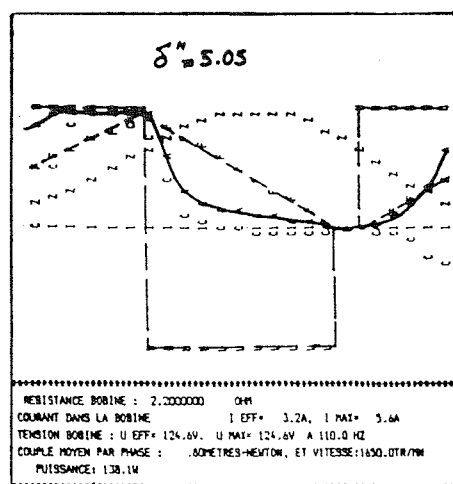


voltage and current

$$\Psi = 90^\circ, I_M = 5.6 \text{ A}, I_{RMS} = 3.2 \text{ A}$$

$$U_M = 125 \text{ V}, P = 139 \text{ W}, \delta'' = 5$$

Measures



Numerical simulation

Figure -11-

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