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Optimization of the design for a switched reluctance drive controlled by trapezoidal shaped currents

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Abstract— **This papers deals with an original way to optimize the pre-designing of a switched reluctance motor (SRM). The analytic equations are treated to make the complete design depend only on two parameters. Particular attention is paid to high rotational speeds and the hypotheses they induce on the design. The hypothesis of a current control is assumed and the methodology tackles the design problem through the angle of the power electronics constraints.**

The specific problem set by the trapezoidal current shape is highlighted, as much as the direct constraints induced on the motor shape design. Mechanical and thermal limitations, modeled in function of the main material characteristics are deterministically taken into account. An optimization is finally performed, reducing the losses of the motor in terms of the mere lasting parameter.

Index Terms— **Switched reluctance motor, optimization, very high speed, under constraints design, pre-dimensioning, analytical models, motor losses, thermal limitation.**

I. Introduction and problem setting

The increasing interest on the switched reluctance motors over the last ten years is owed to the numerous advantages many industries have been interested in, such as simple and rugged motor construction, high reliability and low cost [1]. The power electronics developments, particularly the increasing frequencies and the raise of the voltage levels, allow the use of this motor at higher and higher rotation speeds.

The classical high speed uses of the SRM are usually in flywheels, energy storage and wind turbines applications. This motor technology finds also its interest in high speed machining [2]. The field of research concerned with our work is the integration of a very high speed motor (200.000 rpm) in a high speed machining electrospindle.

The physical constraints which limits the realization of these very high speed motors are mechanic and thermal. Mechanic constraints deal with the ferromagnetic sheets breaking resistance and vibrations. Thermal constraints deal with the sheets heating, under high frequencies, unusual in their classic use and particularly with the rotor, which is difficult to cool.

In this paper, the problem we have chosen to solve is the influence of the motor control on the motor design. In this range of speed, the current cannot be considered as square shaped, as it is commonly, and opportunely, assumed in the low speed range. The current shape has been modeled as trapezoidal, which has great consequences on the copper losses. On the other hand, to put a current value in a very high speed motor, a high voltage value is needed because of its inductance. One second big influence is the dephasing of the currents due to the control delay time.

Design problems of switched reluctance motors are not always set in the same way, and designers always have to find a solution, the fastest and the simplest as possible, with the most accurate solution possible [3]. This is why some works, concerning analytic modeling and design methodology have been performed and applied to the SRM [4], [5], [6].

From the geometrical dimensions of the motor and from the physical principles occurring in the SRM described in simple equations, substitutions are performed. At the end of the substitutions, we can explicit all equations and criteria in terms of the stator teeth angle β_s and the stator height ratio $\gamma = h/r_s$ where h is the height of the stator teeth and r_s the inner radius of the stator.

The optimization can be performed on β_s and γ, very similarly to the work performed in [7] with the big difference that we are interested in a 6/2 SRM optimization. The 6/4 structure is far different, mechanically with the dynamic natural equilibrium [8], and magnetically with the spatial distribution of the teeth, giving a continuous available torque thanks to the overlap of the poles [9] .

The problem solved in this paper is the study of the design constraints relative to the control, the power electronics feeding and their consequences on the switched reluctance motor performances. An example of optimization with the objective function of minimization of the copper and magnetic losses illustrates the optimization methodology developed.

II. Physical principles occurring in the SRM

Different physical phenomena occur in a switched reluctance motor. First of all, the geometrical dimensions of the machine come from direct relations between angles in order to produce the required torque. Then, electrical equation transforms electrical power into magnetic one. This power comes directly from the air gap to the axis through the rotor material, usually in steel. On each step of this way to the axis, magnetic electric and mechanic losses appear and make the motor temperature raise. The presented motor model is not exhaustive. Iron saturation is not reached due to the high speed and is negleted because of the high switching frequency, magnetic induction must be low.

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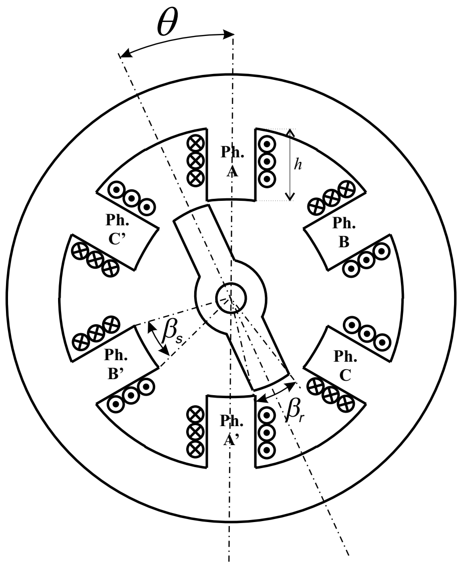

Fig. 1. 6/2 switched reluctance motor shape.

A. Geometrical considerations

The pre-dimensioning of a machine makes it possible to quickly know the essential elements of its dimensioning. These elements include dimensional sizes as well as physical sizes such as the phase voltage and the currents or the magnetic fields. The designing of a double saliency SRM requires the definition of the rotor teeth shape, the teeth width, the rotor length l and the turn number N_{turns} of stator windings.

Fig. 1 shows an SRM shape. The machine has 3 phases on the stator, $N_s = 6$ stator teeth and $N_r = 2$ rotor teeth. As noted on the figure, β_r and β_s define the rotor and stator teeth angles. In a first approximation [1], which is generally the case with first design problems, we can assume that $\beta_r = \beta_s$. In [10] has been underlined that $\beta_r > \beta_s$ minimizes torque ripples. We have also proved that, high speeds commutation healing is improved in this case [11]. Furthermore, this choice is better concerning starting torque.

A complete study of the influence of geometrical parameters on the rotor tooth shape has been performed with the finite element method [11]. The resolutions have proved that the maximal torque point can be positioned with an appropriate choice of the rotor tooth angle β_r and the radius of the rotor corner point. Performances can be considerably improved comparatively to normal straight teeth.

B. Electromagnetic equation

The usual electromagnetic equation assumed for the analytical study of a switched reluctance motor is the following.

$$u(t) = R\,i(t) + N_{turns}\,\frac{d\varphi}{dt} \quad (1)$$

Using the following equation setting a value for the inductance L, one can define a phase inductance in terms of physical constant parameters and simple design parameters.

$$L(\theta, i)\, i = N_{turns}\, \varphi \quad (2)$$

1) Stator: For a given stator geometry, the reluctance profile is given. The stator geometry gives a constraint on the copper surface for each phase windings. By extension, it constraints the number of turns of a stator winding N_{turns}.

2) Rotor: For the rotor, the design equations deal with the rotor teeth, the external rotor radius r_r and the teeth width.

The first parameter we can choice during the optimization is the rotor diameter. Raising this value directly reduces the air gap, raising the phase inductance L and the phase torque T_{motor}. Caution must be paid to the fact that, even if the torque is better with a thin air gap, off commutations are more difficult because of the high inductance.

$$T_{motor} = \frac{i^2}{2}\,\frac{dL}{d\theta} = \frac{i}{2}\,\frac{d\varphi}{d\theta} \quad (3)$$

In order to give to the electrical circuit the time to cut the current in the phase when the rotor speed is high, it is only necessary to enlarge the angle to widen the rotor teeth angle β_r.

The maximal external rotor radius is directly linked to the motor speed Ω or the peripheral rotor speed v_T and to rotor material characteristics. The usual mechanical parameters identification is quite hard, because the experimentation on such a little device (the external diameter of the rotor is around 20mm) requires the development of specific measurement tools. Furthermore, high rotational speeds aimed at with this motor forbid us to use the classical tools, as well for the rotational speed measurement as for design considerations [2].

C. Losses equation

1) Magnetic losses: There are a lot of magnetic losses models. Some of them are very complicated and result from years of researches in this field [12], [13]. Researches are still being performed on new materials, from even better characteristics, but still too insufficient for designers, which always want new possibilities. Sometimes, the problem for the designer is to find an appropriate model to his needs. Indeed, in the first steps of the design of a motor, we do not need the most accurate (and often the more complicated!) model [14].

Meanwhile, even if we want to make it simple, it becomes quickly rather complex. Magnetic losses $P_{magnetic}$ takes into account hysteresis, eddy current effects and the excess losses [15] as follows:

$$P_{magnetic} = \left[K_h B_m^{\alpha} f + K_x B_m^{\frac{3}{2}} f^{\frac{3}{2}} + K_e B_m^2 f^2\right] \delta_f\, v_f \quad (4)$$

with B_m the maximal value of the induction, f the frequency, α a coefficient materials dependent, δ_f the iron density and v_f the considered volume of the magnetic material of the motor. Parameters K_h, K_x and K_e take respectively into account the hysteresis, excess and eddy current effects. The values assumed for the three constants are $K_h = 2.16\,10^{-4}\ \mathrm{W\,kg^{-1}\,T^{-\alpha}\,s}$, $K_x = 0.027\ \mathrm{W\,kg^{-1}\,T^{-\frac{3}{2}}\,s^{\frac{3}{2}}}$ and $K_e = 1.665\,10^{-5}\ \mathrm{m^4\,\Omega^{-1}\,kg^{-1}}$.

Neglecting the reluctance of the ferromagnetic parts, the Ampere theorem gives the maximal induction B_{ms}:

$$B_{ms} = \mu_0 \, \frac{N_{turns} \, I_M}{2 \, e} \tag{5}$$

where I_M is the maximal current value in the coils and e the air gap of the motor.

2) Electric losses: The generally assumed electric losses equation is $P_{electric} = 3 \, R \, i^2$. Replacing the winding resistance value R, and giving a value for the electric filling coefficient K_f, it becomes possible to transform this equation with an optimizing motor design aim:

$$P_{electric} = \rho \, K_f \, V_{winding} \, \delta^2 \tag{6}$$

where δ is the current density in the windings, whatever the thickness of the wires, ρ the copper resistivity and $V_{winding}$ the volume of the windings.

3) Mechanic losses: A first approximation, to perform accurately the motor designing steps [2], is given by:

$$P_{mechanic} = C_s \, \Omega + k_{visc} \, \Omega^{\frac{5}{3}} \tag{7}$$

with C_s the static friction torque and k_{visc} the viscosity friction torque coefficient.

D. Thermal equation

In order to perform a good design, we have to take firstly into account the thermal phenomena. The way of doing this sets on the sum of all the losses, whichever their origins.

$$\Sigma \, P = P_{mechanic} + P_{electric} + P_{magnetic} \tag{8}$$

with this sum, we know all the thermal power we have to evacuate from the motor. Considering the thermic resistance R_{th} and equation 8, we can predict the temperature elevation:

$$\Delta \, T = \Sigma \, P \, R_{th} \tag{9}$$

E. Power electronics considerations

For the design of the power electronics converter, the main parameters we are interested in are the DC supply voltage and the phase rated current. Indeed, this pair of values directly limits the instantaneous available power for a motor phase. Depending on the control strategy used, this power will limit the performances of the motor. We will study two cases of control strategy and the influence of the pair of values on the design of the motor.

Frequency is also another main parameter for the design of power electronics converters. The effect of frequency on the design parameters of a switched reluctance motor is a discretisation effect. The rated frequency imposes as much the dimension of a winding as the thickness of the ferromagnetic sheets. Nevertheless, the main design parameter for the converter is the pulse width modulation (PWM) frequency, because it mainly determines its heating. For the device we are interested in, our designing frequency of 100 kHz is the PWM frequency of the power electronics output signal.

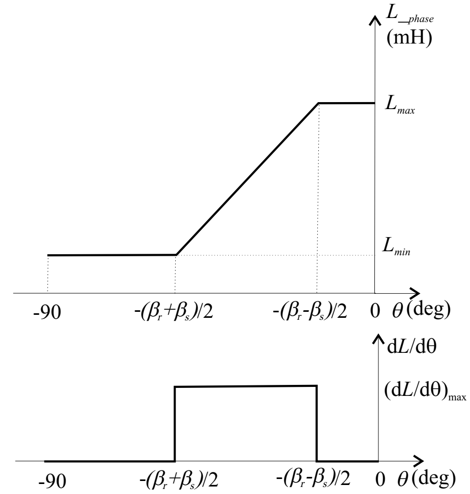

Fig. 2. Inductance profile in terms of the rotational angle.

III. Constraints

The different constraints with which we perform the optimization are the inductance, the power electronics converter, and the speed. The influence of the current shape on the losses forecast will be studied. In fact, the particular influence of the trapezoidal shape on the copper losses, in front of the low speed usually considered square shape, will be pointed out.

A. Inductance value

At the rotational speed aimed (200.000 rpm), the current raise time is not negligible in front of the time spent under a teeth. This relation is closely linking the frequency to the design of the inductance, and enforces the problem of a good design of the inductance. The inductance of a switched reluctance motor has to be:

- **variable** because the torque is directly linked to the inductance variation in terms of the rotational angle θ.
- **not too high** because of the power electronics problems it generates at the opening of a phase circuit. If the inductance is too high, the opening commutation is too difficult to foresee a pulse width modulation frequency increase, which would allow a better torque control.
- **not too small** because, at PWM frequency, the current variations would be more numerous and induce higher iron losses in the ferromagnetic material.

Nevertheless, in order to finely choose the inductance values for the SRM, we have to lessen the minimum value L_{min} and to heighten the maximal value L_{max}. For the design procedure of a high speed switched reluctance motor, we will take a linear model of the inductance between its maximal and minimal values such as presented in fig. 2. The parameter we have chosen for the optimization routine is the number of turns of the winding N_{turns}. As the inductance can easily be approached with (10), we can optimize N_{turns} in the different objective functions.

$$L = \frac{N_{turns}^2}{R_e} \tag{10}$$

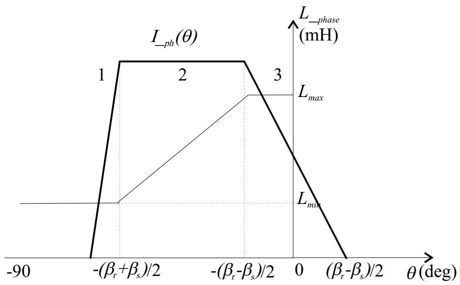

Fig. 3. Current wave shape in terms of inductance wave on a PWM current supply of a SRM phase.

As the inductance model is assumed to be piecewise linear, the derivative of the inductance in terms of the rotor angular position is also piecewise linear, as shown on fig. 2.

B. Speed equation

For high rotational speed, designers have to make the least number of stator poles, because of the limits imposed by the electric maximal frequency of the converter. In order not to let the rotor turn in the sense it wants, the number of stator phases has to be 3. For the same objective of maximizing the speed, the number of rotor poles is preferentially of 2. This give also a 6/2 SRM.

As a consequence, the electric frequency f_{stator} of the stator phases feeding is $f_{stator} = \Omega/\pi$, with Ω the rotational speed of the rotor in $\mathrm{rad\,s^{-1}}$. To illustrate the weight of such an equation, we can say that the time spent under a teeth at a speed of 200.000 rpm is 50μs and $f_{stator} = 6.67$kHz.

C. Power supply

The supply voltage and current are the two main designing parameters for the power electronics converters. In order to perform a current control of the motor phases, the converter which supplies the phases of the motor is operated with a PWM current control. As the speed is assumed to be constant, the current waveform has the same profile in terms of the rotor angular position as in terms of time.

The pulse width modulation current supply wave shape is as presented on fig. 3.

The current control can be cut in three different periods. The first period is when the current rises under the constant and maximal voltage. In the second period, the current is constant and maximal and PWM supplied voltage. To make the current drop to zero during the third period, the voltage is inverted in the converter. As a natural consequence, the points in the current curve where the supply is the most solicited are all those in the plate of the curve with the maximal current and the maximal voltage.

In order to cut correctly the current in a phase of the motor, it has to be completely cut at the time the inductance begins to slow down. Indeed, if there is any current left after this time, the torque produced would be negative. The on commutation does not set any problem, because the inductance value is minimum at this time, and the available angle for this commutation is usually more than twice the first one.

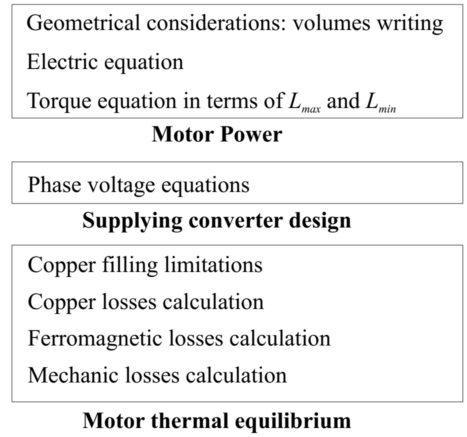

Fig. 4. Modeling methodology for the SRM optimization.

Nevertheless, the addition of the first and third period on the usually considered square shape make the current rms value raise from a factor ζ, where $\zeta = \frac{2(1+\kappa_P)}{3\,\kappa_P}$ and κ_P is the coefficient defined by the relation:

$$\kappa_P = 1 - \frac{L_{min}}{L_{max}} \qquad (11)$$

This coefficient stands for the magnetic quality of the stator and rotor teeth shapes. It can be estimated by finite element resolution. The ζ factor introduction comes from the fact that trapezoidal current shape has to depend on the geometry of the motor, and especially on β_r and β_s.

D. Thermal model

In a design problem, one always try to solve an inverse problem. In the most cases, the continuous service is asked to the constructors, in order not to have heating surprises. For designers, this working service is the one which allows to take the heating equation as it is presented below.

With those two characteristics, the optimization problem can be initialized. Indeed, the rated losses power which can be dissipated is deterministically calculable. For the optimization problem we are interested in, the assumed continuous service, and the allowed heating is from $60°K$. This corresponds to the A insulation class, with a common insulating materials quality.

IV. Optimization results

To design the switched reluctance motor, the methodology we propose is based on the above presented models. The optimization program has been developed on the Matlab Software. Optimization algorithm is presented in fig. 4. On the first step, the motor is designed to give the rated power. Then, the converter constraints are taken into consideration with the continuous supply characteristics. The motor thermal equilibrium integrates the losses to deterministically give a value to the lasting parameters [16].

A. Motor power

Assuming the inductance equation (2), expressing the average torque with (3), the average power of the switched reluctance motor becomes naturally:

$$P = T_{motor}\,\Omega = \frac{3\,\mu_0}{\pi}\,\kappa_P\,\beta_s\,\Omega\,\frac{r_s\,l}{2\,e}\,N_{turns}^2\,I_M^2 \qquad (12)$$

with l the stack length of the motor.

B. Converter design

Equation (1) defines the phase voltage. Taking φ from (2), the general electric equation of the motor phase is obtained:

$$u(t) = R\,i(t) + L(\theta)\,\frac{di}{dt} + i\,\Omega\,\frac{dL(\theta)}{d\theta} \qquad (13)$$

By neglecting the winding resistance, the expressions of the voltage $u(t)$ become:

$$U_1 = \frac{L_{min}}{\Delta\theta_1}\,I_M\,\Omega \qquad (14)$$

$$U_2 = \frac{\kappa_P\,L_{max}}{\beta_s}\,I_M\,\Omega \qquad (15)$$

$$U_3 = -\frac{L_{max}}{\Delta\theta_3}\,I_M\,\Omega \qquad (16)$$

Considering fig.3, since the supplying converter voltage value is once and for all ddefined, the equality $U_1 = U_2 =| U_3 |$ has to be observed. This leads to the relation between $\Delta\theta_1$ and $\Delta\theta_3$. Since $\Delta\theta_3 \leq \beta_r - \beta_s$ to avoid negative torque, the equality $U_1 =| U_3 |$ gives, when $\Delta\theta_3$ is maximum:

$$\Delta\theta_1 = \frac{L_{min}}{L_{max}}\,(\beta_r - \beta_s) \qquad (17)$$

The second equality $|U_3| = U_2$ gives quite a strong constraint on the teeth angle design:

$$\beta_r = \beta_s\,\frac{1+\kappa_P}{\kappa_P} \qquad (18)$$

This means that, for the best value of κ_P, the rotor teeth angle has to be more than twice larger than the stator one. This confirms what we have already shown in [11].

In terms of the maximal values of the motor, the converter is defined with $I_{max} = I_M$ and $V_{max} = U_2$. The supplied power $P_{max} = V_{max}\,I_{max}$ is given for each phase with:

$$P_{max} = \frac{\kappa_P\,L_{max}}{\beta_s}\,I_M^2\,\Omega \qquad (19)$$

Generally speaking, when it is possible to take $\beta_s = \frac{1}{2}\,\frac{\pi}{3}$, the installed power on the converter has to be twice the useful power of the motor. This result will have strong consequences on the converter cost.

C. Thermal equilibrium

1) Structural limitation: The free space between the stator teeth is never completely filled with the wires. Usually, a filling K_f and a windows section S_f coefficients are used. If δ is the current density in the wires, this inequality has to be satisfied:

$$N_{turns}\,\frac{i}{\delta} \leq K_f\,S_f \qquad (20)$$

In a way, if we want to fill all the available space, this equation becomes an equality.

2) Copper losses: Copper losses concentrate in the motor windings. Every phase is composed of two coils of $N_{turns}/2$ wires each. The total copper losses is so expressed:

$$P_{electric} = 3\,R\,I_{rms}^2 \qquad (21)$$

The current chosen for the control is trapezoidal. The rms value of the current presented in fig. 3 is expressed in terms of the two inductances L_{min} and L_{max} in (22).

$$I_{rms} = I_M\,\sqrt{\frac{\beta_s}{\pi} + \frac{\beta_r - \beta_s}{3\,\pi}\,\left(1 + \frac{L_{min}}{L_{max}}\right)} \qquad (22)$$

The total copper losses in the motor are so expressed:

$$P_{electric} = \frac{12}{\pi}\,\rho\,k_l\,K_f\,\zeta\,S_f\,\beta_s\,(\beta_s + \lambda)\,r_s\,\delta^2 \qquad (23)$$

with λ the iron stack length out of the stator inner radius, and k_l is the coils head coefficient.

3) Iron losses: Iron losses exist in all the ferromagnetic parts of an electric machine exposed to a flux variation. The shape and the variations of the flux are not the same in the different parts of the machine and the different contributions of each motor part can be dissociated. Nevertheless, in the aim of keeping to the designing problem its relative easiness and with the use of (4), we can approach the iron losses with the next equation:

$$P_{magnetic} = (K_a + K_b\,\gamma)\lambda\,\beta_s\,r_s^3\,B_{ms}^2 \qquad (24)$$

with B_{ms} the induction in the stator teeth. We can notice that this equation is linear in terms of γ, the ratio between the height of stator teeth and the internal stator radius, K_a and K_b are coefficients obtained from equation (4).

4) Thermal equation: At the thermal equilibrium, all the losses are evacuated by the machine external surface. Depending on the cooling mode, the coefficient k_{th} can vary from 10, in the case of natural convection with ambient air, to 100 for a forced convection cooling with fluid different from air [16]. The classic expression of the thermal resistance of the motor becomes with this coefficient:

$$R_{th} = \frac{1}{2\,\pi\,k_{th}\,(1+\gamma)\lambda\,{r_s}^2} \qquad (25)$$

D. Optimization of the total losses

The parameter substitution achieved, all the equations are coming to a system of four equations with six unknowns. The Ampere theorem, the torque expression (3), the thermal equation (9) and the copper space filling inequality (20). The unknowns are inner stator radius, stator teeth angle, air gap, copper available area, current density and stator teeth induction.

To be able to achieve the design, the peripheral speed of the rotor determines the stator radius. The equality between magnetic and copper losses is the arbitrary fixed supplementary condition on the parameters we have taken. Now, taking a value for a parameter gives, with the use of a numeric algorithm, the solution for the only unknown and spreads over all the model to completely define the motor. Fig. 5 presents the results of an optimization performed on

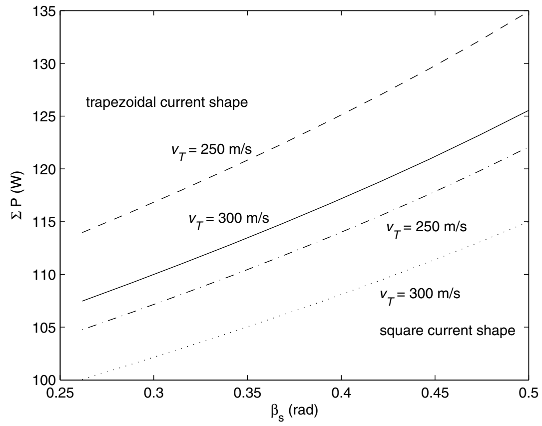

Fig. 5. Optimization result: minimal losses in terms of stator teeth angle.

the model with the peripheral speed taken successively at $v_T = 250\ \mathrm{m.s}^{-1}$ and $v_T = 300\ \mathrm{m.s}^{-1}$.

The curves corresponding to the trapezoidal current shapes are those which give the highest total losses. One must recall here that for the κ_P taken value, the mere copper losses are increased of 50%. It can partly explain the difference between the two minimal curves of $10\,\mathrm{W}$ out of $120\,\mathrm{W}$, as much for $v_T = 250\ \mathrm{m.s}^{-1}$ as for $v_T = 300\ \mathrm{m.s}^{-1}$.

We can clearly see on fig. 5 that, whatever the current shape, the faster peripheral speed, the less power losses. For a 25 degrees stator teeth and a peripheral speed of 250 $\mathrm{m.s}^{-1}$, the minimum losses obtainable in a 6/2, 2 kW SRM are $117\,\mathrm{W}$ for a square current and $130\,\mathrm{W}$ for a trapezoidal shaped current. This means a maximal efficiency of 94%.

V. Conclusion

In this paper, physical principles that occur in a switched reluctance motor have been explained and some design rules deduced. Their use has allowed an original constrained optimization.

The power electronics specific constraints have been studied. Their consequences on a high speed switched reluctance motor design have been highlighted. This study assumed a stable functioning in the very high rotational speed field (up to 100.000 rpm).

Specific power electronics requirements have been taken into account in the design of the switched reluctance drive, under the current control assumption.

The current rising time is taken into account and contributes to the design, especially for the rotor teeth width. The consideration of this parameter has been proved to be useful in the high speed range.

The model treatment methodology for the optimization takes successively into account the rated motor power, the supplying converter and the motor thermal equilibrium. The optimization performed with the presented model has demonstrated that the motor power losses are linearly dependent on the stator teeth angle.

This original way to design switched reluctance motors will open in the future researches a new angle for tackling the solution research to an SRM design problem. It may be very helpful to determine the exhaustive theoretical limits of the 6/2 SRM technology for very high speed applications. The particular point treated in this paper as shown that the higher the rotational speed will be, the greater the integration of the power electronics specific constraints will be.

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