Modelling and Design of a Low Speed Flux Reversal Machine


Abstract — This paper is devoted to the electromagnetic design and the optimization of a 10 kW, 50 rpm direct drive Flux Reversal Machine, excited by NdFeB magnets located on the inner surface of the stator plots.

The optimization of the machine dimensions, focused on the maximization of the mass to torque ratio, is carried out by a genetic algorithm combined with the finite element method. The electromagnetic characteristics of the optimized machine, including flux, back electromotive forces EMF, static torque,…etc., obtained by finite elements are then analyzed. The results show that the machine presents good performances and can constitute an alternative to the direct drives at low speeds.

Key words — Flux reversal, finite element, genetic algorithms, low speed, permanent magnets.

I. INTRODUCTION

Nowadays, the use of electric machines, often of synchronous types, for direct drive applications to operate with high torque and low speed is becoming more and more frequent. The traditional structures of energy conversion require a gear reducer. This is very inconvenient because it adds weight, generates noise, increases losses and requires regular maintenance.

The elimination of the gearbox requires slow machines particularly adapted to direct drives called also direct attack machines.

During the last few years, we assist to a growing interest for the study and the design of this type of machines. They are indeed increasingly used as motor for propulsion of ships, cars, elevators and, as generator, for wind turbine. These structures are often of synchronous types (with field winding or magnets) with large number of poles and high torque. The machine can be radial, axial or with transverse flux. Other special configurations of direct attack machines are also given in the literature [1-6] such as the variable reluctance machines, excited or not.

Various studies show that by introducing permanent magnets in switched reluctance machines (SRM), new structures improving the performances can be obtained [5-9]. These structures are called Doubly Salient Permanent Magnet machines (DSPM) and Flux Reversal Machines (FRM). They are widely studied. However, they are generally with large teeth and inappropriate for low speed applications.

The low speed flux reversal machine, studied in this work and illustrated in Fig.1, can be regarded as a new member of the FRM family adapted to direct drives applications at low speed. It is a three-phase machine presenting a doubly salient structure and uses concentrated windings. Its field excitation is provided by non-rotating permanent magnet located in the stator without any magnet or winding in the dented rotor.

![Fig. 1 –Low Speed Flux Reversal Machine](image)

1-winding phase A, 2- stator yoke, 3-magnet, 4-rotor yoke

The aim of this work is the electromagnetic design and the optimization of a 10 kW, 50 rpm direct attack FRM excited by NdFeB magnets. The optimization of the machine dimensions is carried out by a genetic algorithm combined with the finite element method. The objective is to maximize the mass to torque ratio which represents an essential criterion for machines with high torque for low speed drives. The optimization applies on the local dimensions (teeth, magnets) as well as the global parameters such as the rotor and the stator yoke, rotor radius, coil height and the angular slot opening.

The electromagnetic characteristics of the optimized machine such as phase flux linkage, back EMFs, static torque… etc., are then determined and analyzed. The results show that the machine presents good performances and can constitute an alternative to the direct drives at low speeds.
II. PRESENTATION OF THE STUDIED MACHINE AND MODELLING

The flux reversal machine (FRM) is a doubly salient structure with permanent magnets glued onto the internal surfaces of the plots. The rotation of the dented rotor reverses the polarity of the magnetic flux, due to the magnets, generated in the stator phases windings.

Ndps pairs of North-South magnets are glued on the surface of each of Nps plots of the stator facing the air-gap. The magnets are alternately magnetized in opposite directions.

The rotor teeth pitch is identical to the stator pole pitch which corresponds to two successive North-South magnets.

The stator number of plots (Nps), the total number of magnets pairs of the stator (Np), the number of the rotor teeth (Nt) as well as the number of magnets per plot (Ndps) are related by the following relations [4-6, 9].

\[
K = \frac{N_t}{N_{ps}} \pm \frac{1}{q}
\]
\[
N_{ps} = \frac{N_s}{N_{dp}}
\]

K is integer number greater than 1. q is the number of phases. The rotor speed is given by:

\[
\Omega = \frac{\omega}{N_r} = \frac{2\pi f}{N_t}
\]

For an operation with speed near 50 rpm corresponding to a typical frequency of 50 Hz, the number of rotor teeth must be close to 60. Our choice fell on a three-phase structure for Nr=64 teeth, Ns=48 pairs of alternate magnets at a rate of 4 plots per phase and of 4 pairs of alternate magnets per plot (Fig.1). The stator and rotor of the FRM are formed of a stack of ferromagnetic sheet. The plots bear the stator windings of the three phases and the rotor is passive without winding.

A concentrated coil surrounds each stator plot and the winding of each of the three phases is constituted of four concentrated coils connected in series so that their magnetic fluxes are additive when they are fed by an electric current.

The magnets create a multipolar magnetomotive force which is modulated by the permeance variation of the slotted rotor. The motion of the rotor reverses the polarity of the stator phase flux linkage.

Subject to the stator excitation field, the magnets oriented in the direction of flux tend to be placed so as to face the rotor teeth.

The particular positions of conjunction and opposition of the flux reversal machine are determined according to the direction of the armature reaction flux linkage, the relative position of the rotor teeth and the direction of magnetization of the permanent magnets which face them.

So, when the magnets magnetized in the direction of the flux, due to the stator current, are facing the rotor teeth, total flux is maximal. This corresponds to the position of conjunction (Fig. 2). This would correspond to the position of opposition if the magnets, whose direction of magnetization coincides with the flux due to the current, faced the rotor slots; total flux in this case would be minimal (Fig. 3).

The instantaneous applied voltage to a phase of the machine is linked by Faraday's law to the total magnetic flux \( \Psi \) as:

\[
v = Ri + \frac{d\Psi}{dt}
\]

i and R represent respectively the current, the resistance per phase.

The winding flux linkage \( \Psi \) is composed of \( \Psi_{pm} \) flux due to the permanent magnets and of \( \Psi_w \) flux due to the phase current as shown in Fig. 4.

The reluctance of the magnetic circuit seen by each phase is overall constant for all the positions \( \theta \) of the rotor, flux \( \Psi_w \) is, of this fact, practically constant for a fixed phase current and can be expressed in linear mode by:

\[
\Psi_w = L i
\]

Where the phase inductance L is practically independent of \( \theta \), Total flux \( \Psi \) is then:

\[
\Psi = Li + \Psi_{pm}
\]
The electromagnetic torque $T_e$ for one phase on operation can be written as:

$$ T_e = \frac{1}{2} l^2 \frac{dL}{d\theta} + i \frac{d\psi_{pm}}{d\theta} $$

(6)

Torque $T_e$ is considered as the sum of two components $T_{pm}$ and $T_r$, so as:

$$ T_e = T_r + T_{pm} $$

(7)

$T_{pm}$: hybrid torque due to the interaction between the magnet flux and flux due to phase currents.

$T_r$: reluctance torque.

As the inductance $L$ is practically independent of the rotor position, its derivative is null and consequently the reluctance torque $T_r$ can be considered null. Hybrid torque $T_{pm}$ is thus the dominant component of the total torque and it can be produced by applying either a positive current to the phase winding (at the time of the growth of the flux of the magnets) or a negative current (when the flux is decreasing).

$$ T_e \approx T_{pm} = \frac{d\psi_{pm}}{d\theta} $$

(8)

Although the torque produced in this configuration is a hybrid torque, independent of the overall reluctance of the magnetic circuit, it also occurs however by the effect of the variation of reluctance. It is the local reluctance of the element of the magnetic circuit associated with the pair of magnets considered which varies. The total reluctance of the plot remains constant.

The FRM can be supplied by a bidirectional converter (currents positive and negative), but we consider, in this work, only the case where each phase is fed by a DC drive unidirectional by imposing a rectangular current shape according to the rotor position.

In 2D, for the studied machine, the system to be solved is expressed as follows:

$$ \psi_{pm} $$

(9)

$$ \frac{\partial}{\partial x} \left( \frac{1}{\mu} \frac{\partial A_z}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\mu} \frac{\partial A_z}{\partial y} \right) = -(J_z + J_{pm}) $$

Where $A_e$ and $J_e$ are the $z$ components of magnetic potential vector $A$ and the current density $J$, respectively; $J_{pm}$ is the equivalent surface current density of the magnet and $\mu$ the magnetic permeability of iron.

The Maxwell stress tensor is well adapted to calculate the electromagnetic torque of the machine, studied by the finite element method.

In two-dimensional, the electromagnetic torque $T_e$ is obtained from the integral along a closed contour $\Gamma$ surrounding the rotor and located in the air-gap:

$$ T_e = L \int_{\Gamma} r H_s B_n d\Gamma $$

(10)

$B_n$ and $H_s$ correspond respectively to the radial of the flux density and the tangential field components and $L$ the length of the machine (in axial direction $Z$).

Numerical errors can however be introduced particularly in computing $H_s$.

Arkko [10] proposes the calculation of the average value of the torque operated in the space which constitutes the air-gap.

$$ T_e = \frac{1}{(r_e - r_i)} \left( r_i T_e dr \right) $$

(11)

Where $r_i$ and $r_e$ are the outer and the inner radii of the air gap. And by considering the section of the air-gap $S_{ag}$, the torque can be obtained as follows

$$ T_e = \frac{L}{(r_e - r_i)} \int_{S_{ag}} r H_s B_n dS $$

(12)

III. THE DESIGN PROCEDURE AND OPTIMIZATION

The aim is the electromagnetic design and the optimization of a 10 kW low speed flux reversal machine thanks to a genetic algorithm coupled with the finite element method.

A. Machine dimensions and design approach

For the dimensioning of the machine (Fig.1), we set the following constraints and requirements.

- Power : 10 kW
- Torque : 2000 Nm
- Maximum external diameter of the machine : 600 mm
- Current density: 5 A/mm².
- Copper fill factor: 0.5
- Air-gap: 0.5 mm.

The steel lamination used is of type: FeV 400-50 ha, [9, 10]

The permanent magnet is an Nd-Fe-B, with a linear demagnetizing characteristic, characterized by: $B_r=1,29T$, $\mu_r=1.049$.
Various magnets and rotor teeth shapes can be chosen in order to improve particularly the machine performance in term of torque production.

The shape of permanent magnets is selected to be rectangular. Their design and their addition to the stator plots are therefore easy to carry out.

The rotor teeth shape retained are trapezoidal. The trapezoidal shape being easy to realize, constitutes a general case of other shapes of teeth [4, 6].

The magnets as well as the rotor teeth are defined thanks to the following parameters (Fig.5):
- Magnet height \( h_m \)
- Rotor teeth depth \( h_r \)
- Rotor teeth cyclic ratio \( \alpha_1 \) and \( \alpha_2 \).
- Teeth pitch angle \( \tau = 2\pi/N_r \).

![Image 67x157 to 269x374](https://example.com/image)

**Fig. 5 – Trapezoidal rotor teeth shape and magnet dimensions**

The global structure (Fig.6) is entirely determined from the following 10 parameters:
- The width of the rotor and stator yokes \( E_s \) and \( E_r \).
- Coil height \( h_c \).
- Angular plot opening \( \beta \).
- The A point opening (\( R_{a}, \beta_4 \)) With \( R_\alpha \) being the distance between A point and the machine centre O
- Trapezoidal teeth parameters \( h_r, \alpha_1, \alpha_2 \).
- Magnet height \( h_m \).

![Image 265x149](https://example.com/image)

**Fig.6 – Global designs parameters**

**B. Design process by genetic algorithm coupled with the finite element method**

The genetic algorithms developed for the purpose of optimization, are evolutionary search algorithms and allow the search for a global extremum. They are well adapted for the design of electrical machines and electromagnetic devices [11-13].

Starting from an initial population created randomly, a new population of individuals is generated, at each iteration, using three operators: crossover, mutation and selection.

The two first are operators of exploration of space, while the purpose of the selection is to promote the fittest and evolve the population towards the optimum of the problem so that the objective function is minimized (or maximized). The search continues until the stopping criterion is satisfied. The stopping criterion may be the number of generations. The final version of the genetic algorithm developed for our work is as follows:

1. Define the objective function.
2. Random initialization of a population of N machines
3. Evaluations of the objective function of each machine.
4. Selection of the best machines
5. Apply the genetic operators: crossover and mutation to generate a new population.
6. Evaluate the new population.
7. Stop criterion is not satisfied go to Step 4.
8. End

The search region of the 10 geometric parameters of the FRM is restricted in order to improve the search for the optimum. The higher and lower limits of each of the variables to be optimized are summarized in Table 1.

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass to torque ratio ( f )</td>
<td>( M = \frac{T}{M} )</td>
</tr>
<tr>
<td>( h_m ) ≤ 50mm</td>
<td>( h_m ) ≤ 50mm</td>
</tr>
<tr>
<td>( \beta ) ≤ 15° (angles mécaniques)</td>
<td>( \beta ) ≤ 15°</td>
</tr>
<tr>
<td>( R_{c}/3 ) ≤ ( R_{r}, R_{a} ) ≤ 0.9 ( R_c )</td>
<td>( R_{c}/3 ) ≤ ( R_{r}, R_{a} ) ≤ 0.9 ( R_c )</td>
</tr>
<tr>
<td>( 0.2 ) mm (( h_m, h_r )) ≤ ( t_2 ) (pas dentaire en mm)</td>
<td>( 0.2 ) mm (( h_m, h_r )) ≤ ( t_2 )</td>
</tr>
<tr>
<td>( R_r-hr-Er &gt; R_c/3 )</td>
<td>( R_r-hr-Er &gt; R_c/3 )</td>
</tr>
<tr>
<td>( 0.2 ) ≤ ( \alpha_1, \alpha_2 ) ≤ 0.5</td>
<td>( 0.2 ) ≤ ( \alpha_1, \alpha_2 ) ≤ 0.5</td>
</tr>
</tbody>
</table>

**Tab.1 – Parameters constraints**

The mass to torque ratio is the optimization criterion chosen for the design of our machine. Maximizing the mass to torque ratio would mean minimizing the objective function \( f \) defined as follows:

\[
f = \left( \frac{T}{M} \right)^{-1}
\]

(13)

\( M \) represents the active mass of the machine (copper, iron and magnets).

\( T \) is the maximum torque value.

For this studied machine, \( T \) corresponds to the position of the rotor \( \theta = 90° \) electric [6]. The opposition position corresponds to \( \theta = 0° \) while the conjunction position is at \( \theta = 180° \) electrical. This torque is calculated by the finite element method.
The genetic algorithm is coupled with the finite element method. FEMM [14] is the software used. It is a whole of programs for the resolution, in low frequency, by the finite element method, the two-dimensional magnetostatic and electrostatic problems in a plane or axisymmetric domain.

IV. RESULTS OF OPTIMIZATION

The algorithm is run with an initial population of 50 machines. The crossover and mutation operators’ are fixed respectively to be 0.8 and 0.02. The search is stopped after 50 iterations. The duration of one optimization is 2 days using a 3 GHz processor.

A) Evolution of the optimized parameters according to the generations

Fig.7 represents the evolution of the average value as well as the best value of the objective function of each generation of machines. The electromagnetic torque obtained over generations is shown in Fig.8. After the 30 first generations, the improvement of the objective function and the electromagnetic torque is insignificant. The optimal mass to torque ratio correspondent is of 13.65 Nm/kg.

Fig.7 – Objective function values over generations

Fig.8 – Torque over generations

B) Geometrical parameters and electromagnetic characteristics of the optimized

The dimensions of the optimized machine are presented in Table 2.

<table>
<thead>
<tr>
<th>Geometrical parameters</th>
<th>Selected machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>E [mm]</td>
<td>25,6</td>
</tr>
<tr>
<td>E_r [mm]</td>
<td>28,95</td>
</tr>
<tr>
<td>H_b [mm]</td>
<td>47,2</td>
</tr>
<tr>
<td>β [°]</td>
<td>5,6</td>
</tr>
<tr>
<td>R_d [mm]</td>
<td>248,75</td>
</tr>
<tr>
<td>B_d [°]</td>
<td>5,74</td>
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<tr>
<td>R [mm]</td>
<td>223,8</td>
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<tr>
<td>α1</td>
<td>0.26</td>
</tr>
<tr>
<td>α2</td>
<td>0.33</td>
</tr>
<tr>
<td>h_l [mm]</td>
<td>12,6</td>
</tr>
<tr>
<td>hm [mm]</td>
<td>3,4</td>
</tr>
<tr>
<td>ρ^{-1} (Nm/kg)</td>
<td>13.65</td>
</tr>
</tbody>
</table>

Tab.2 – Optimized machine data

I) Magnetic flux linkage and electromotive force

Fig.9 illustrates, for one phase, the magnetic flux characteristic ψ (θ, I) according to the current and rotor position. These characteristics determined by the finite element method, are obtained for currents varying from 0 to 120 A.

Fig.9 – Phase flux linkage ψ (i, θ) versus current for different rotor position

At no load, the back EMF induced by the magnets in the phase winding is given by:

\[ e = \frac{d\Psi}{dt} = \frac{d\Psi}{d\theta} \frac{2\pi n}{60} \]  

(14)

\( \Psi \), \( \theta \) and \( n \) represent respectively, the magnetic flux due to the permanent magnets, the rotor angle and the rotor speed in rpm.

Fig.10 shows the layout of the induced electromotive forces in the three phases of the FRM at the rated speed of 50 rpm. One can observe that their waveform is almost sinusoidal. This waveform is typical to flux reversal machines. [6-8]
This cogging torque is due to the interaction between the permanent magnets glued on the surface of plots and the rotor teeth which face them. It is determined by the FEM by imposing a null current in the three phases of the machine. Thus, the cogging torque obtained present for the optimized FRM a relatively weak peak (3% of the maximum torque) and exhibits a periodicity of 120° electrical angle.

V. CONCLUSION

A new topology of flux reversal machine FRM was presented, modelled and designed for low speed electric drives. This original structure is doubly salient. The optimization, focussed on the maximization of the mass to torque ratio of the machine, which represents an essential feature in low speed applications, is carried out by a genetic algorithm combined with the finite element method. The results obtained show that the optimized machine present good performances and can be an alternative in the direct-drives and low speed applications.

REFERENCES