# Design Optimization of an Interior PMSM for Electric Vehicle Application

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***Abstract*—The aim of this paper is to optimize the performances of an Interior Permanent Magnet Synchronous Machine (IPMSM) for an electric vehicle application. The originality of this work concerns the use of a Reluctance Network (RN) method which furnishes the harmonics of output parameters (i.e. torque and back-emf) and automatically generates the derivative of the model. Then, precise and very fast optimizations are performed own to gradient method as SQP. Results are also compared to Finite Element Analysis (FEA) and several mono-objective optimizations are presented. Finally, the proposed method helps engineers to have a better sense of machines behavior and to quickly optimize the geometry of their machines during preliminary design process.**

***Index Terms*— Permanent magnet machines, Fourier series, Finite element method, Design optimization, Gradient methods.**

## I. Introduction

Due to its high performances, PMSM have found wide attention in industrial and transportation applications including Electric Vehicle (EV) [1]. In the same time, specifications of such applications present severe constraints and the challenge of designers is to find the optimal machine giving the best performances.

In terms of optimization, modeling is a key point. Although analytical models are well known and offer a very fast computation time, they have the drawback to not be precise and to give only fundamental values of magnitudes. Conversely, Finite Element Analysis (FEA) gives quite precise results but computation times could be very long chiefly during optimization process.

In contrast, RN models have a good compromise between precision and rapidity and can be used for the preliminary design processes [2]. Traditionally, RN are modeled on d-q axis and only overall performances are calculated. In this paper, harmonics values of the torque and the back-emf are also obtained thanks to an angular rotation performed between rotor and stator [3].

Previous works include precise models of PMSM [3-4], but no optimization with deterministic method is yet feasible. In this study, the derivative, including the gradients and the Jacobian, of the RN model is automatically generated thanks to the software *RelucTOOL* [5]. Thus, deterministic algorithms as SQP are employed for the optimization in order to rapidly converge toward the optimal machine. In the followings, several optimizations with single objective are presented and results are also compared to FEA.

Ultimately, section II introduces the PMSM and the associated RN model. Then, section III presents the optimizations results and optimal geometries obtained for each objective(s). Finally, section IV gives the conclusion this paper and prospect for future works are also given.

## II. Reluctance Network Model

The RN model employed retakes the work of [3]. Then, general characteristics of the machine and the modeling method are given in the followings.

### A. Characteristics of the IPMSM

Main characteristics of the PMSM are given in table I:

TABLE I
MAIN FEATURES OF THE IPMSM

| | |
|---|---|
| Number of stator slots | 12 |
| Number of rotor poles | 8 |
| Max. Power | 58 kW |
| Max. torque @ 1,500 rpm | 215 N.m |
| Max. current (RMS) | 63.6 A |
| Number of turns (coils) | 58 |
| Outer diameter | 200 mm |
| Depth (Stack length) | 200 mm |
| Air-gap | 0.9 mm |

### B. Reluctance network of the machine

For the multistatic model, the RN of the 12/8 machine is modeled in the software *RelucTOOL* and is represented in fig. 1.

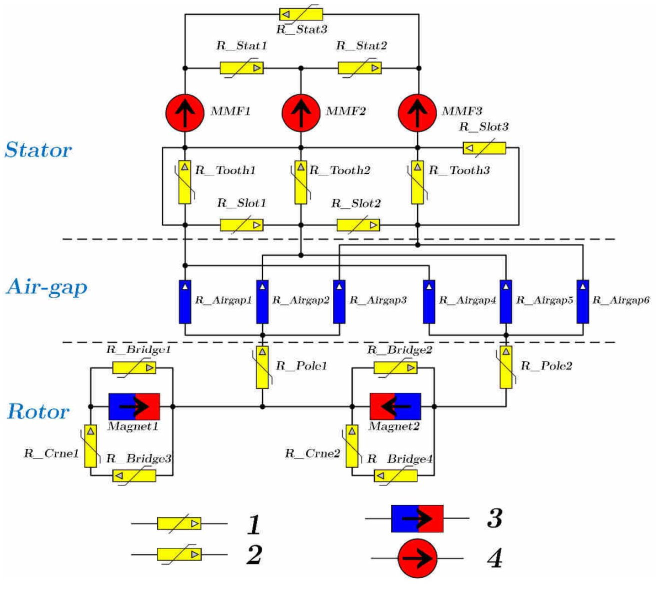


Fig.1 Reluctance network of the 12/8 PMSM (1- non starurable air gap reluctance sign, 2- saturable iron reluctance sign, 3- magnet sign, 4- MMF sign)

Magneto-motive forces (MMF) are expressed as $N_s.I$ where $N_s$ is the number of turns of the coils and $I$ is the current. Also, the parameters that characterize the magnets are the length, the surface and the remanent induction. For the reluctances, the general expression is:

$$\Re = \frac{1}{\mu_0 \cdot \mu_r} \cdot \frac{L}{S} \quad (1)$$

with $\mu_r$, the relative permeability; $L$, the length and $S$, the surface of the reluctance. For air-gap reluctances, the expression becomes:

$$\Re_{air-gap} = \frac{1}{\mu_0} \cdot \frac{air\text{-}gap}{depth \cdot width} \quad (2)$$

The *depth* and the *air-gap* values are the same for all air-gap reluctances of the circuit. Then, the only one parameter that has to be determined is the *width* for each reluctance. Besides, during the rotation of the rotor, all parameters are fixed except the widths of the air-gap reluctances which have to be calculated for each angular pitch. In this paper, the calculation of the widths resumes the Fourier series method introduced in [3].

### C. *Results and comparison to FEA*

Considering table II, very good accordance of the results obtained with FEA (software *Flux2D*) can be observed. Values of the mean torque and fundamental of the back-emf are very close to FEA. Solely the $5^{th}$ and $7^{th}$ order harmonics of the back-emf ($H_5$ and $H_7$) are overestimated. Note that iron losses are not estimated by the RN model, but copper losses are calculated. Finally, this method can be used for optimization processes which require fast and precise models.

TABLE II
SIMULATION RESULTS - (RELUCTOOL & FEA) @ 1,500 RPM & 63.6 A RMS

| | ReluсTOOL | FEA (Flux2D) |
|---|---|---|
| Mean Torque | 249.6 N.m | 251.2 N.m |
| Ripple torque – $H_6$ | 16.8 N.m | 16 N.m |
| Back-emf – $H_1$ | 493.4 V | 502 V |
| Back-emf – $H_3$ | 6.3 V | 12.8 V |
| Back-emf – $H_5$ | 138 V | 94 V |
| Back-emf – $H_7$ | 45 V | 18.4 V |
| Iron losses | / | 156 W |
| Copper losses ($H_1$) | 5,000 W | / |
| Computation time | 126 sec. | 340 ms |

Note that $H_n$ designate the $n^{th}$ order harmonic of the output parameter.

## III. OPTIMIZATION RESULTS

### A. *Conditions of optimizations*

There are 13 parameters to be optimized during the optimization process and 31 electrical and geometrical constraints. Current density, volume of the machine and volume of the magnets cannot be increased. Mean torque has to be over above 226 N.m.

### B. *Mono-objective optimization: minimize the fundamental of the back-emf*

TABLE III
OPTIMIZATION RESULTS - (RELUCTOOL & FEA) @ 1,500 RPM & 63.6 A RMS

| | Initial geometry (FEA) | Optimal geometry (ReluсTOOL) | Optimal geometry (FEA) |
|---|---|---|---|
| Mean Torque | 251.2 N.m | 225.2 N.m | 214.8 N.m |
| Ripple torque – $H_6$ | 16 N.m | 8.1 N.m | 10.1 N.m |
| Back-emf – $H_1$ | 502 V | 276.9 V | 309 V |
| Back-emf – $H_3$ | 12.8 V | 2.1 V | 15.2 V |
| Back-emf – $H_5$ | 94 V | 69.6 V | 28.8 V |
| Back-emf – $H_7$ | 18.4 V | 45 V | 10.1 V |
| Iron losses | 156 W | / | 145 W |
| Copper losses ($H_1$) | 5,000 W | 2,393 W | / |
| Machine's volume | 6,283 $cm^3$ | 4,149 $cm^3$ | / |
| Magnet's volume | 42.9 $cm^3$ | 42.88 $cm^3$ | / |

Fig. 2 shows the evolution of the geometry between the initial and optimized machine. Depth of the motor is represented by the rectangle in green.

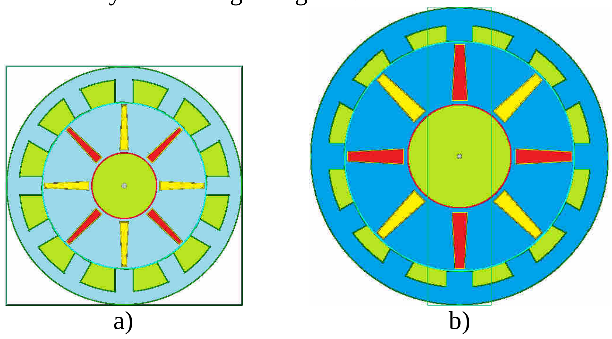

Fig.2 a) Initial and b) Optimized geometry of the machine (Min. back-emf)

### C. *Multi-objectives optimization: Weighting of two objectives (Copper losses & Machine's volume)*

TABLE IV
OPTIMIZATION RESULTS - (RELUCTOOL & FEA) @ 1,500 RPM & 63.6 A RMS

| | Initial geometry (FEA) | Optimal geometry (ReluсTOOL) | Optimal geometry (FEA) |
|---|---|---|---|
| Mean Torque | 251.2 N.m | 226 N.m | 222.1 N.m |
| Ripple torque – $H_6$ | 16 N.m | 2.1 N.m | 10.6 N.m |
| Back-emf – $H_1$ | 502 V | 319.2 V | 340 V |
| Back-emf – $H_3$ | 12.8 V | 2.7 V | 1.6 V |
| Back-emf – $H_5$ | 94 V | 29.9 V | 43.7 V |
| Back-emf – $H_7$ | 18.4 V | 13.4 V | 6.8 V |
| Iron losses | 156 W | / | 131.6 W |
| Copper losses ($H_1$) | 5,000 W | 1,883 W | / |
| Machine's volume | 6,283 $cm^3$ | 3,770 $cm^3$ | / |
| Magnet's volume | 42.9 $cm^3$ | 42.9 $cm^3$ | / |

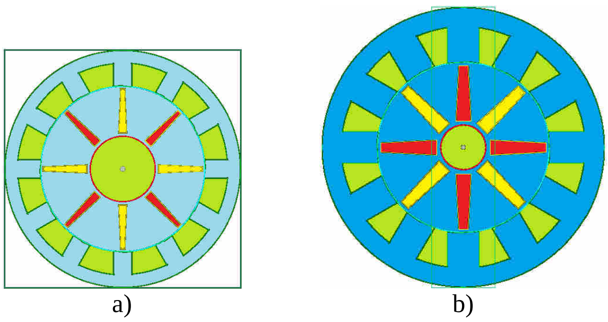

Fig.5 a) Initial and b) Optimized geometry (Minimize of the back-emf fund.)

## IV. Conclusion

In this paper, RN modeling has been considered for the optimization of an IPMSM. Optimal machines are quickly obtained and results show very close results to FEA. Then, sensitivity analysis and preliminary design processes can be performed in order to find the optimal machines.

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