Genetic Algorithm for Optimal Design of PMSG for Direct-Drive Wind Turbines

Sofiane Mendaci, Messaoud Boulouh
Laboratoire d'Automatique et Informatique de Guelma
University of Guelma
Guelma, Algeria
sofiane.mendaci@yahoo.fr, messaoud_boulouh@yahoo.fr

Said Gouaidia, Abdelaziz Ladjimi
Laboratoire de Génie Electrique de Guelma
University of Guelma
Guelma, Algeria
s_gouaidia@yahoo.fr, aziz_ladjimi@yahoo.fr

***Abstract*—In this paper, an optimal design procedure of radial surface permanent-magnet generator (PMSG) with an outer rotor for wind energy application is investigated. Firstly, an analytical model based on the resolution of the Maxwell's equations using the separation of variable method is presented. From the same model analytical expressions of four constraint functions dedicated for the optimal design of the PMSG are developed. These constraints are: electromagnetic torque, electromotive force (EMF), flux density saturation in stator/rotor yoke and saturation in stator tooth. The genetic algorithm method is then employed to optimize two objective functions (weight and power loss of the generator) with the respect of the above mentioned constraints. Finally, the finite element method is used to validate the designed PMSG.**

Keywords-analytical model; finite element method; Genetic Algorithm; optimal design; permanent magnet synchronous generator

I. INTRODUCTION

The use of wind power is increasing all over the world, and there are several different types of electrical systems available for converting the wind power to electricity. Compared to conventional wind turbines using the induction machine and the gearbox, direct-driven permanent magnet synchronous generator (PMSG) without a gearbox is one of the most promising topologies for wind energy converters for small and medium-size wind turbine. In fact, direct drive eliminates losses, maintenance and costs associated with a gearbox. Also, the PMSGs can provide high efficient, high power density and high reliable power generation, which reduces the cost and weight of the wind turbine generator (WTG) system [1,2].

Different topologies of PMSG are available, e.g. radial flux machines, axial flux machines and transversal flux machines [3]. However, the direct driven wind turbines are characterized by low speed and high torque density, which requires generators with large number of poles. For these reasons, the PMSG with external rotor is very attractive for this type of application. The fact that the rotor is external allows the direct coupling of the blades, which enables minimizing the weight of the mechanical structure. Nevertheless, the performances of PMSGs are greatly depends on their optimal design and control [1,2].

In this paper, the authors attempt to provide helpful tools for the fast analysis and optimal design of PMSGs dedicated for direct-driven wind turbines. Firstly an analytical model, sufficiently accurate and fast, based on the resolution of the Maxwell's equations using the separation of variable method is presented. Then, the design problem was formulated as a mathematical optimization problem and solved by genetic algorithm method. Finally, validity of the proposed methodology is confirmed through the finite element analysis of the designed 1 kW PMSG.

II. DEVELOPMENT OF THE ANALYTICAL MODEL

The analytical method used in this paper is based on analysis of 2-D model in polar coordinates. The following assumptions are made [4]–[7].

- The stator and rotor cores are assumed to be infinitely permeable.
- Permanent magnets have a linear demagnetization characteristic.
- End effect and saturation are neglected.
- Eddy current effects are neglected (no eddy current loss in the magnets or armature windings).
- Stator current source is represented by a current sheet distributed over the stator inner radius.

Taking into account the above assumptions, we can present a generic section of the idealized PMSG as in the Fig. 1.

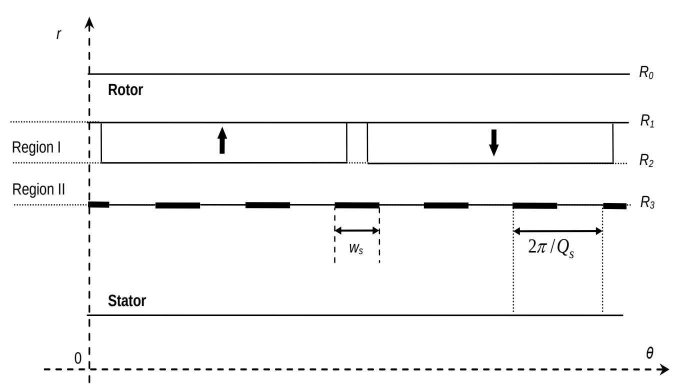

Figure 1. Unrolled cross sectional view of the studied PMSG.

In the above considerations, the calculation region can be classified into two parts: PMs (Region I), and air-gap (Region II). The flux density and field intensity are expressed as

In Region I: $$\vec{B} = \mu_0 \vec{H}\ . \quad (1)$$

In Region II: $$\vec{B} = \mu_0 \mu_r \vec{H} + \mu_0 \vec{M}\ . \quad (2)$$

where μ_r is the relative recoil permeability, $\vec{M}$ is the magnetization vector of permanent magnets. In polar coordinates, the magnetization vector is expressed as

$$\vec{M} = M_r \vec{e}_r + M_\theta \vec{e}_\theta . \quad (3)$$

The governing field equations are as follows

In Region I: $$\nabla^2 \vec{A} = -\mu_0 \nabla \times \vec{M}\ . \quad (4)$$

In Region II: $$\nabla^2 \vec{A} = 0 . \quad (5)$$

$\vec{A}$ (the magnetic vector potential) only has A_z component which is independent of z (infinitely long machine in axial direction).

By using the method of separating variables, the general solution of (4) and (5) can be expressed as

$$A_z^I = \sum_{g=-\infty}^{+\infty} \left(C_1 r^{gp} + C_2 r^{-gp} + A_p \right) e^{jgp\theta} . \quad (6)$$

$$A_z^{II} = \sum_{g=-\infty}^{+\infty} \left(C_3 r^{gp} + C_4 r^{-gp} \right) e^{jgp\theta} . \quad (7)$$

where A_p is the particular solution of (4) for the permanent magnets region, given by

$$A_p(r) = \begin{cases} \mu_0 \dfrac{jgpM_{r,g} - M_{\theta,g}}{1-(gp)^2} r & \text{if } gp \neq 1 \\ \mu_0 \dfrac{jgpM_{r,g} - M_{\theta,g}}{2} r \ln(r) & \text{if } gp = 1 \end{cases} . \quad (8)$$

where $M_{r,g}$ and $M_{\theta,g}$ are the complex Fourier coefficients of the two components $M_r(\theta)$ and $M_\theta(\theta)$ of the magnetization vector $\vec{M}$. In the general case, the components of magnetization are given by

$$M_r(\theta) = \sum_{g=-\infty}^{+\infty} M_{r,g}\, e^{jgp(\theta - w_m t)} . \quad (9)$$

$$M_\theta(\theta) = \sum_{g=-\infty}^{+\infty} M_{\theta,g}\, e^{jgp(\theta - w_m t)} . \quad (10)$$

where p is the pole pair number and w_m is the rotor speed.

In (6) and (7), C_1, C_2, C_3, and C_4 are arbitrary constants to be determined by applying the boundary conditions on the interface between rotor and PMs (i.e., $r=R_1$), PMs and air gap (i.e., $r=R_2$) and between the air-gap and stator (i.e., $r=R_3$). These conditions can be defined as

$$\begin{cases} H_\theta^I(R_1,\theta) = 0 \\ H_\theta^I(R_2,\theta) = H_\theta^{II}(R_2,\theta) \\ B_r^I(R_2,\theta) = B_r^{II}(R_2,\theta) \\ H_\theta^{II}(R_3,\theta) = -\mu_0 J \end{cases} . \quad (11)$$

J is the total current density vector given by

$$J(\theta,t) = \sum_{n=1}^{m} J_n = \sum_{n=1}^{m} I_n C_n . \quad (12)$$

where m is the number of phase windings and J_n is the current density for phase n given by the product of the conductor density $C_n(\theta)$ and the stator current I_n. In the general case, the total stator current density can be written as a Fourier series by

$$J(\theta,t) = \sum_{g=-\infty}^{+\infty} J_g(t) e^{jgp\theta} . \quad (13)$$

where J_g is the complex Fourier coefficient given by

$$J_g(t) = \frac{S_g}{2j} \sum_{n=1}^{m} I_n(t) e^{-jg(n-1)\frac{2\pi}{m}} . \quad (14)$$

The Fourier coefficient S_g in (14) is determined by taking into account the windings characteristics, Fig.2.

From (11), we obtain the linear equations given by

$$\begin{bmatrix} gpR_1^{gp-1} & -gpR_1^{-gp-1} & 0 & 0 \\ 0 & 0 & gpR_3^{gp-1} & -gpR_3^{-gp-1} \\ R_2^{gp} & R_2^{-gp} & -R_2^{gp} & -R_2^{-gp} \\ gpR_2^{gp-1} & -gpR_2^{-gp-1} & -gp\dfrac{\mu_r}{\mu_0}R_2^{gp-1} & gp\dfrac{\mu_r}{\mu_0}R_2^{-gp-1} \end{bmatrix} \times \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} -\dfrac{dA_p(R_1)}{dr} - \mu_0 M_{\theta,g} \\ \mu_0 J_g \\ -A_p(R_2) \\ -\dfrac{dA_p(R_2)}{dr} - \mu_0 M_{\theta,g} \end{bmatrix} . \quad (15)$$

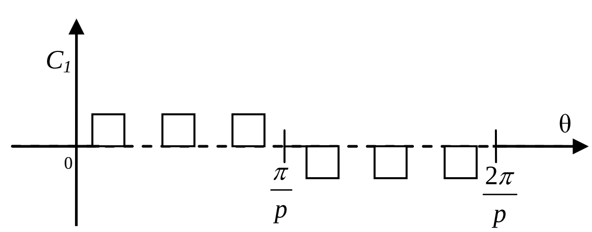

Figure 2. General generalized conductor density distribution of phase one.

The resolution of the above system (15) by an iterative method gives the constants C_1, C_2, C_3, and C_4.

In order to reduce the time for solving the system (15), we develop the analytical expressions of C_1, C_2, C_3, and C_4 as a function of the magnetic sources $M_{r,g}$, $M_{\theta,g}$ and I_n. After the substitution and the simplification, these expressions are given by

$$C_i = \mu_0\left(D_{i,2}M_{r,g} + D_{i,3}M_{\theta,g}\right)e^{-j(gpw_m t - \frac{\pi}{2})} + D_{i,1}S_g\sum_{n=1}^{m} I_n(t)e^{-j(g(n-1)\frac{2\pi}{m}+\frac{\pi}{2})} . \quad (16)$$

with i=1,2,3,4,

where

$$D_{1,1} = \mu_0 R_3^{1-gp} L_1 . \quad (17)$$

$$D_{1,2} = gp\frac{L_1}{2}\left[\frac{df(R_1)}{dr}L_2 + \frac{df(R_2)}{dr}L_3 + f(R_2)L_4\right]. \quad (18)$$

$$D_{1,3} = \frac{L_1}{2}\left[\left(\frac{df(R_1)}{dr}-1\right)L_2 + \left(\frac{df(R_2)}{dr}-1\right)L_3 + f(R_2)L_4\right]. \quad (19)$$

$$D_{2,1} = D_{1,1}R_1^{2gp} . \quad (20)$$

$$D_{2,2} = D_{2,2}R_1^{2gp} + \frac{df(R_1)}{dr}\frac{R_1^{1+gp}}{2} . \quad (21)$$

$$D_{2,3} = D_{2,3}R_1^{2gp} + \left(\frac{df(R_1)}{dr}-1\right)\frac{R_1^{1+gp}}{2gp} . \quad (22)$$

$$D_{3,1} = D_{1,1} . \quad (23)$$

$$D_{3,2} = D_{1,2} + \frac{gpR_2^{-gp}}{4}f(R_2) + \frac{df(R_2)}{dr}\frac{R_2^{1-gp}}{4} . \quad (24)$$

$$D_{3,3} = D_{1,3} + \frac{R_2^{-gp}}{4}f(R_2) + \left(\frac{df(R_2)}{dr}-1\right)\frac{R_2^{1-gp}}{4gp} . \quad (25)$$

$$D_{4,1} = D_{2,1} . \quad (26)$$

$$D_{4,2} = D_{2,2} + \frac{gpR_2^{gp}}{4}f(R_2) - \frac{df(R_2)}{dr}\frac{R_2^{1+gp}}{4} . \quad (27)$$

$$D_{4,3} = D_{2,3} + \frac{R_2^{gp}}{4}f(R_2) - \left(\frac{df(R_2)}{dr}-1\right)\frac{R_2^{1+gp}}{4gp} . \quad (28)$$

with

$$L_1 = \frac{1}{2gp\left(1-R_1^{2gp}R_3^{-2gp}\right)} . \quad (29)$$

$$L_2 = 2R_1^{1+gp}R_3^{-2gp} . \quad (30)$$

$$L_3 = -\left(R_2^{1-gp} + R_2^{1+gp}R_3^{-2gp}\right). \quad (31)$$

$$L_4 = gp\left(R_2^{gp}R_3^{-2gp} - R_2^{-gp}\right). \quad (32)$$

$$f(r) = \begin{cases} \dfrac{r}{1-(gp)^2} & \text{if } gp \neq 1 \\ \dfrac{r}{2}\ln(r) & \text{if } gp = 1 \end{cases} . \quad (33)$$

Hence, the magnetic vector potential is completely defined in the two regions by (6) and (7). Therefore, the flux density in the air-gap and PMs domains is given by

$$B_r^i(r,\theta,t) = 2\sum_{g=1}^{\infty}\left[\begin{array}{l}\mu_0\left(N_{2,r}^i M_{r,g} + N_{3,r}^i M_{\theta,g}\right)\cos\left(gp(w_m t-\theta)\right) \\ -N_{1,r}^i S_g\sum_{n=1}^{m} I_n(t)\cos\left(g\left(p\theta-(n-1)\frac{2\pi}{m}\right)\right)\end{array}\right]. \quad (34)$$

$$B_\theta^i(r,\theta,t) = 2\sum_{g=1}^{\infty}\left[\begin{array}{l}\mu_0\left(T_{2,r}^i M_{r,g} + T_{3,r}^i M_{\theta,g}\right)\sin\left(gp(w_m t-\theta)\right) \\ +T_{1,r}^i S_g\sum_{n=1}^{m} I_n(t)\sin\left(g\left(p\theta-(n-1)\frac{2\pi}{m}\right)\right)\end{array}\right]. \quad (35)$$

where $i=I,II$ design the concerned region, and

$$\begin{cases} N_{l,r}^i = \dfrac{-gp}{r}P_{l,r}^i \\ T_{l,r}^i = -\dfrac{dP_{l,r}^i}{dr} \end{cases} . \text{ with } l=1,2,3,4 \quad (36)$$

where

$$P_{1,r}^1 = D_{1,1}r^{gp} + D_{2,1}r^{-gp} . \quad (37)$$

$$P_{2,r}^1 = D_{1,2}r^{gp} + D_{2,2}r^{-gp} + \frac{gp}{2}f(r) . \quad (38)$$

$$P_{3,r}^1 = D_{1,3}r^{gp} + D_{2,3}r^{-gp} + \frac{1}{2}f(r) . \quad (39)$$

$$P_{1,r}^2 = D_{3,1}r^{gp} + D_{4,1}r^{-gp} . \quad (40)$$

$$P_{2,r}^2 = D_{3,2}r^{gp} + D_{4,2}r^{-gp} . \quad (41)$$

$$P_{3,r}^2 = D_{3,3} r^{gp} + D_{4,3} r^{-gp}. \tag{42}$$

To improve the precision of this analytical model, Carter's coefficient K_c is applied to compensate the slots effects. In this case, a new air gap length e_c is defined by [8]

$$e_c = K_c e . \tag{43}$$

where

$$K_c \approx \frac{P_t}{\left(P_t - \frac{b_s^2}{5e + b_s}\right)}, \quad \text{with } P_t = \frac{2\pi R_3}{2pmN_s} . \tag{44}$$

where P_t is the stator tooth pitch; N_s is the number of slots per pole per phase; and b_s is the slot width.

III. CONSTRAINTS DEDUCED FROM THE PROPOSED MODEL

A. Torque Constraint

The torque developed on the PMSG can be obtained by calculating the Maxwell stress tensors in the air-gap [4], [6], [7], [9].

$$T_m = \frac{LR_2^2}{\mu_o} \int_0^{2\pi} B_r^{II} B_\theta^{II} \, d\theta . \tag{45}$$

where L is the axial length.

Incorporating (34) and (35) in (45) and integrating on the tangential direction yields to the final expression of the torque in terms of field sources ($M_{r,g}$, $M_{\theta,g}$ and I_n)

$$T_m = \frac{8\pi L p^2}{\mu_0} \left[\sum_{g=1}^{\infty} g^2 N_g S_g \times \left(\sum_{n=1}^{m} I_n(t) \sin\left(gp \left(w_m t - \frac{(n-1)}{p} \frac{2\pi}{m} \right) \right) \right) \right]. \tag{46}$$

where

$$N_g = \mu_0 \left(\left(D_{3,1} D_{4,2} - D_{3,2} D_{4,1} \right) M_{r,g} + \left(D_{3,1} D_{4,3} - D_{3,3} D_{4,1} \right) M_{\theta,g} \right). \tag{47}$$

The torque expression (46) depends on the design parameters. Therefore, this expression can be used as objective function or as constraint in the preliminary PMSG design.

B. Stator and Rotor Yoke Saturation Constraint

The definition of the no saturation constraint of rotor/stator yoke needs the acknowledgement of the flux density in these regions.

We assume that the magnetic flux in rotor yoke $\Phi_r(t)$ is equal to the flux in a half PM pole $\Phi_{hp}(t)$.

$$\Phi_r(t) = \Phi_{hp}(t) . \tag{48}$$

From the Fig. 1, the rotor flux yoke is given by

$$\Phi_r(t) = B_r(t) S_r = L\left(R_0 - R_1\right) B_r(t) . \tag{49}$$

where $B_r(t)$ is the tangential component of flux density in the rotor and S_r is the cross section area of the rotor yoke.

In other hand, the magnetic flux in half PM pole at R_1 is given by

$$\Phi_{hp}(t) = \int_{\theta_1=0}^{\theta_2=\frac{\pi}{2p}} A_z^I(R_1) dl = L\left[A_z^I(R_1,\theta_2,t) - A_z^I(R_1,\theta_1,t) \right]. \tag{50}$$

By using (48), (49) and (50) we obtain the analytical expression of the flux density in the rotor/stator yoke (supposed to have the same dimensions).

$$B_r(t) = \frac{\left[A_z^I(R_1,\theta_2,t) - A_z^I(R_1,\theta_1,t) \right]}{\left(R_1 - R_0\right)}. \tag{51}$$

Usually, to avoid excessive saturation, the maximum flux density of iron core is limited to the range 1.6-1.9 T [10].

C. Stator Tooth Saturation Constraint

In the case of slotted stator, we can introduce a constraint for no stator tooth saturation. If we neglecting the flux leakage, the flux in the stator tooth $\Phi_{tooth}(t)$ is given by

$$\Phi_{tooth}(t) = \frac{2\Phi_{hp}(t)}{mN_s} . \tag{52}$$

The stator tooth flux can be also expressed as

$$\Phi_{tooth}(t) = B_{st}(t) S_{st} . \tag{53}$$

where $B_{st}(t)$ and S_{st} are the flux density and the small cross section area of stator tooth respectively.

By using (50), (52) and (53) we obtain the analytical expression of the flux density in the stator tooth as

$$B_{st}(t) = \frac{2L\left[A_z^I(R_1,\theta_2,t) - A_z^I(R_1,\theta_1,t) \right]}{S_{st} m N_s}. \tag{54}$$

D. Electromotive Force Constraint

The EMF created by the permanent magnet can be obtained by Faraday's law

$$E_n(t) = -\frac{\partial \Phi_{n0}(t)}{\partial t} . \tag{55}$$

where $\Phi_{n0}(t)$ is the phase n flux linkage created by PMs.

Based on Stokes theorem, the flux linkage $\Phi_{n0}(t)$ is calculated by

$$\Phi_{n0}(t) = \int_s B ds = \int_\Gamma A dl = LR_3 \int_0^{2\pi} A^{II}(R_3,\theta,t) C_n(\theta) d\theta . \tag{56}$$

After the substitution and the simplification, the final expression of $\Phi_{n0}(t)$ is given by

$$\Phi_{n0}(t) = 2\pi R_3 L \sum_{g=1}^{\infty} \Phi_{AP}(R_3) \cos\left(g \left(pw_m t - (n-1)\frac{2\pi}{m} \right) \right). \quad (57)$$

with

$$\Phi_{AP}(R_3) = -\mu_0 S_g \left[P_{2,r}^2(R_3) M_{r,g} + P_{3,r}^2(R_3) M_{\theta,g} \right]. \quad (58)$$

From the equations (55) and (57), the EMF created by PMs is given by

$$E_n(t) = 2\pi R_3 L p \Omega \times \sum_{g=1}^{\infty} g \Phi_{AP}(R_3) \sin\left(g \left(pw_m t - (n-1)\frac{2\pi}{m} \right) \right). \quad (59)$$

IV. Design Optimization Procedure

A. Optimization Problem Definition

In order to present the design optimization procedure of surface mounted PMSG with an outer rotor, based on the above analytical model, we designed a 1 kW PMSG with the following assumptions: 14 poles, 42 slots, one slot per pole per phase (N_s=1), based speed w_{base}=428 rpm, maximal speed w_{max}=1284 rpm, current density J= 5 A/mm2, permanent magnet remanence has a value of 1.2 T.

The objective functions fixed for this optimization are

- Minimizing the weight of the motor (M).
- Minimizing the total power loss (P_L).

The mass M of the active part is given by

$$M = M_C + M_{PM} + M_S + M_R. \quad (60)$$

where M_C, M_{PM}, M_S and M_R are respectively the weight of: the copper, the permanent magnet, the stator iron and the rotor iron. These masses are given by the following expressions

$$M_C = 2\,pmN_s S_s \left(L + 1.6 \left(\frac{2\pi R_3}{2p} \right) \right) \rho_{copper}. \quad (61)$$

$$M_{PM} = \pi \left(R_1^2 - R_2^2 \right) L K_{PM} \rho_{PM}. \quad (62)$$

$$M_S = \left(\pi \left(R_3^2 - R_4^2 \right) - 2\,pmN_s P_s b_s \right) L \rho_{iron}. \quad (63)$$

$$M_R = \pi \left(R_0^2 - R_1^2 \right) L \rho_{iron}. \quad (64)$$

where S_s is the section of copper in slot, K_{PM} is the magnet-arc to pole-pitch ratio and P_s is the slot depth. Also, ρ_{copper}, ρ_{PM} and ρ_{iron} are respectively the density of: copper, permanent magnet and iron.

The power loss in the PMSG is given by the sum of the power loss in the stator winding (P_{Lcop}) and the core loss (hysteresis P_{Lhys} and eddy current loss P_{Leddy}) [10], [11].

$$P_L = P_{Lcop} + (P_{Lhys} + P_{Leddy}) V_{volume\_iron}. \quad (65)$$

with

$$P_{Lcop}(W) = 3 R_s I_{neff}^2. \quad (66)$$

$$P_{Lhys}(W.m^{-3}) = K_{hys} B^{\beta} w_s. \quad (67)$$

$$P_{Leddy}(W.m^{-3}) = \frac{2}{T} \int_0^T K_{eddy} \left(\frac{dB}{dt} \right)^2 dt. \quad (68)$$

where K_{hys} and K_{eddy} are the classical eddy and hysteresis loss coefficients which can be calculated at various frequencies and flux densities from curve fitting of manufacturer data sheets.

Finally, the multi-objective constrained optimization problem is defined as

Minimize:

$$F = b_1 M + b_2 P_L \text{, with } b_1, b_2 \in [0,1] \quad (69)$$

Subject to the following constraints:

- Electromagnetic torque value, T = 22.28 N.m
- EMF at maximum speed, $E_{max} \leq 150$ V
- Stator/Rotor yoke flux density, $B_{yoke} \leq 1.6$ T
- Stator tooth flux density, $B_{tooth} \leq 1.6$ T

Firstly, before solving the above problem (69), we have dimensioning our PMSG by using the direct method proposed in [10], [11], however, we have adapted this procedure to the case of PMSG with external rotor before using. Then, from the initial PMSG, we have chosen seven variables, given in table 1 with their exploration domain, to solve the final problem (69). We noticed that these parameters have a great influence on the performance of the PMSG.

TABLE 1. The Exploration Domain for each Variable

Variable	Symbol	Min	Max
Inner radius of the rotor yoke (m)	R_0	0.085	0.1
Axial length (m)	L	0.05	0.08
Thickness of magnet (m)	L_{PM}	0.003	0.006
Radius of the rotor yoke surface (m)	R_1	0.05	0.084
Magnet-arc to pole-pitch ratio	K_{PM}	0.7	0.9
Slot-opening to slot-pitch ratio	K_{SO}	0.3	0.6
Slot depth (m)	P_s	0.007	0.01

B. Genetic Algorithm Method (GA)

To optimize the highly nonlinear constrained multi-objective problem (69), the genetic algorithm method is applied. A general sketch of the GA procedure can be described as [12], [13]:

a) Initialization of population and control parameters.

b) Evaluation the objective function of each solution.

c) Applying selection, crossover and mutation.

d) Repeat (b) and (c) until a termination condition has been reached.

In this paper, the following control parameters are used in GA method: population size N=60, maximum number of iterations tmax=600, crossover probability Pc=0.9. Also, the variables are treated as real numbers and the Breeder Genetic Crossover (BGX) and the real-parameter mutation operator are used [14].

C. Results

Fig. 3 shows the evolution of the best solution versus the iterations. Also, the variables and the performances of the optimized PMSG are presented in table 2. As shown, the four optimization constraints are respected, especially the value of the electromagnetic torque.

In order to validate the proposed design procedure, the analytical results have been compared with 2D finite element simulations. Fig. 4 and 5 show respectively the magnetic flux line distribution and the EMF of the optimized PMSG. We can observe that the values of the EMF (in the base speed), obtained by finite element simulations, are in good agreement with analytical result.

TABLE 2. VARIABLES AND PERFORMANCES OF OPTIMIZED PMSG

Variables and performances	Optimized PMSG
R_0 (m)	0.0943
L (m)	0.074
L_{PM} (m)	0.0048
R_1 (m)	0.084
K_{PM}	0.7007
K_{SO}	0.3908
P_s (m)	0.01
Copper section (mm^2)	2
Electromagnetic torque (N.m)	22.22
EMF at 1284 rpm (V)	161.2993
EMF at 428 rpm (V)	53.7
Maximum yoke flux density (T)	1.6
Maximum tooth flux density (T)	1.5
Mass (kg)	9.6
Total power loss (W)	78.4
Efficiency (%)	92.71

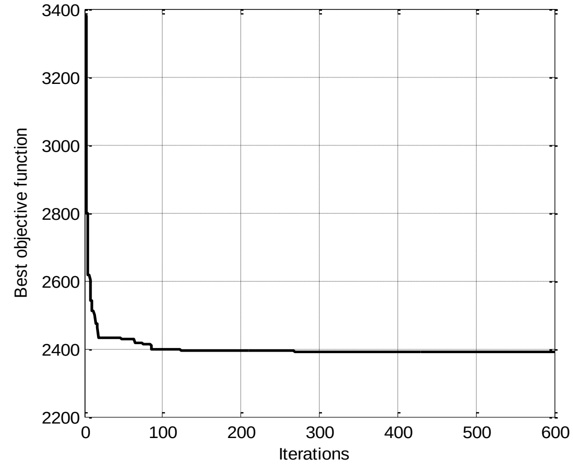

Figure 3. Evolution of the best solution.

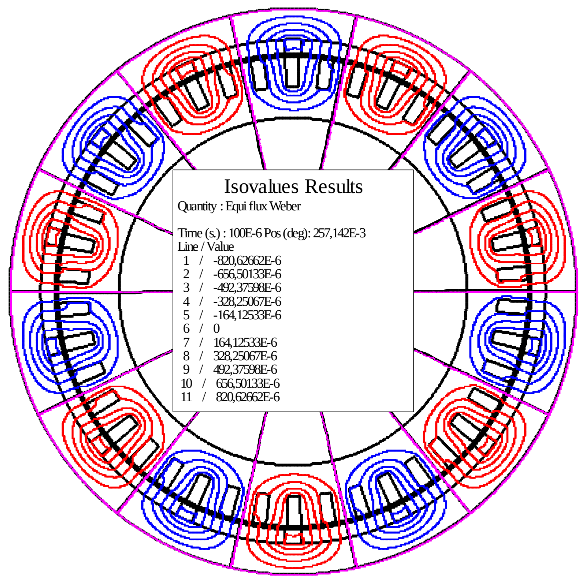

Figure 4. Magnetic flux line in the optimized PMSG.

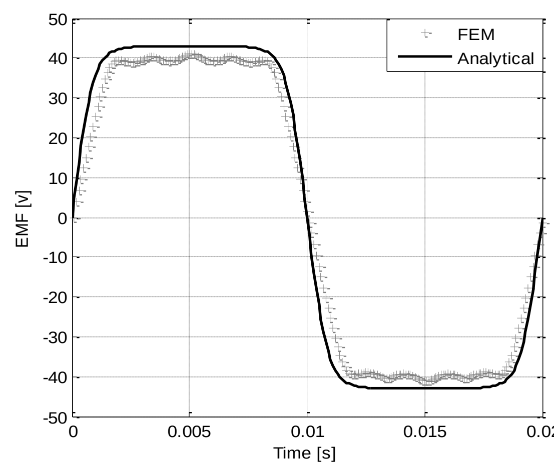

Figure 5. EMF obtained by anlytical calculation and by finite element method (FEM) at 428 rpm.

V. Conclusion

In this paper, an optimal design procedure of surface mounted PMSG with an outer rotor dedicated for wind energy application is investigated. Firstly, an analytical model of PMSG is presented. This model is sufficiently accurate and fast to be used in the design optimization with stochastic methods. Then, the GA method is proposed to solve the multi-objective constrained problem formed by two objectives (motor weight and total power loss) and four important constraints (demanded value of electromagnetic torque, maximum limit of FEM, flux density saturation in stator/rotor yoke and saturation in stator tooth).

Finally, this design procedure, based on the proposed analytical model and AG method, has been successfully applied for optimal design of 1 kW/428 rpm PMSG.

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