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PART
B

Contents

(continued from Part A)

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Design and Optimization of BLDC Generator for Wind Turbine Applications

S. M. M. Mirtalaei, B. Abdi, K. Shaloudegi, R. Ghasemi

Abstract – *Permanent magnet synchronous generators are used widely in wind power generation recently. The huge amount of torque during low speed and high power beside great amount of poles and slots make this kind of generators with the other applications. This paper presents a simplified analytic design method for brushless DC generators used in wind turbine application. Simplified proposed design is good for direct optimization. This manner of optimization is used in this paper because of its perspicuity. Efficiency and weight can be optimized together by utilizing this manner of optimization. Magneto-static and parametric finite element-based simulations are used to confirm the design and optimization process. Simulation results show less than 3% error in the design process.* ***Copyright © 2012 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: Wind Energy, Generator, PM, BLDC, Analytic Design, Optimization*

Nomenclature

A_s	Available area for copper or winding(m^2)
A_{cu}	Necessary area for copper or winding(m^2)
B_r	Magnet remanent(T)
B_p	operation point of air gap flux density (T)
B_{max}	Maximum flux density in stator core(T)
e	axial salient length of coil from stator(v)
E_{phase}	phase-induced voltage or BEMF(v)
ff	Winding filling factor
$\varphi_{t(coil)}$	Tooth flux produced by coil
$\varphi_{t(magnet)}$	Tooth flux produced by Magnets
$\varphi_{t(total)}$	Total tooth flux
i	Phase rms current (A)
K_{cu}	Necessary cupper area for one ampere
L_{phase}	Total length of each phase wire(m)
L_m	Permanent magnets thickness(m)
L_g	Air gap thickness(m)
m_{Fe}	Mass of stator iron(kg)
μ_r	Rotor permeability
μ_m	Magnets permeability
N	Winding turn number
N_t	Number of slots
p	Number of pole pairs
P_{cu}	Cupper loss(W)
ρ_{Fe}	Iron density(kg/m^2)
ρ_{cu}	Cupper density(kg/m^2)
R_r	Reluctance between rotor and stator
R_l	Leakage reluctance between the tooth
R_1	Inner radius of rotor(m)
R_2	Outer radius of rotor(m)
R_3	Outer radius of permanent magnets(m)
R_4	Outer radius of slots edge(m)
R_5	Inner radius of slots edge(m)
R_6	Inner radius of rotor yoke(m)
R_7	Outer radius of rotor yoke(m)
R_{phase}	Each phase resistance(Ω)
r	Radius in cylindrical system(m)
θ	Angle in cylindrical system(rad)
Vol_{Fe}	Stator iron volume (m^3)
ω	Angular rotational speed(rad/s)
w_t	Width of stator dent
w_y	Width of stator and rotor yoke
z	Rotor length(m)

I. Introduction

In the past decade, depletion of fossil energy resources and global concern about climate changes caused effort change to find new sources of energy. In this meanwhile, wind energy attract more interest than other sources. The average annual growth rate of wind turbine installation is around 30% during last 10years [1]. Wind energy owns this popularity to the large amount of power than can be extracted, lower price and more reliable in comparison with the other renewable sources like solar power [2]. Beside the great advantages, wind energy has some drawback such as more failure rate than fossil energy and needs more investment to produce a kWh compared with the conventional generation technologies.

From the other point of view, wind turbine has different drive train technologies. Two main technologies, which currently is used in the market, is the geared-drive wind turbine and direct drive wind turbine.

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They use double fed induction generator (DFIG) and sinusoidal permanent magnet synchronous generator (SPMSG) respectively as generator [1]-[4].

Wind turbines with DFIG have lower cost, especially in the range of MW [2], [3]. But they suffer from major inevitable drawbacks originated by gearbox and electrical machine. Periodical maintenance, gearbox high failure rate, low efficiency during gearbox and wound rotor induction machine and audible noise are some of these disadvantages [1]-[9].

In the resent years, the price of permanent magnet materials decreased as a result of their technology development as well as power electronic devices [1]-[7]. Briefly, omitting the gearbox, higher efficiency and yielded annual energy, more power density, wide operational speed range and quick response to wind fluctuation are the most advantages of synchronous permanent magnet (SPM) machines over the induction one[6]-[15]. So, the implementation of SPM machines in wind turbine became more economic and popular especially in offshore applications [3], [4], [16], and [17]. As SPM machines became competitive in market, many researchers have been done to find new generator design and control strategies [13]-[15], [18]-[21]. There are two major types of PM machines, SPM with sinusoidal back electromotive force (BEMF) and Brushless DC (BLDC) with trapezoidal BEMF waveform [34]. In comparison with SPM machines, BLDC machines can produce more torque with the same mass and volume beside simpler and easier control strategy [22], [25]. From another point of view, the rectifier stage of the power converter causes high distortion of the current and voltage in SPM generators. This is implying several undesirable effects to the SPM generators, such as increasing iron and copper losses, lower efficiency and audible noise emission increasing [26]. To overcome these shortcomings, unity power factor is suggested which increases the complexity of control strategies and design cost [27]. In spite of mentioned disadvantages, most of recent researches are focused on permanent magnet generators in wind turbine applications [28]. In this paper, simplified analytical design and optimization of BLDC generator is presented for wind application. Proper approximation is assumed for air-gap magnetic flux density. This approximation causes less than 3% error in the design process but it extremely simplifies the design and optimization processes. Direct search optimization will be used for the generator's optimization. Results of design and optimization are validated by using Finite Element Method (FEM) simulations to insure low errors. Two-dimensional static and parametric simulations are used to achieve this aim.

Cogging torque is one of design issues in the permanent magnet machines. It is considered in the other works [29]-[32] and will not discuss here, but its effect on the produced torque will scrutinize by FEM simulations.

II. Simplified Design

Analytical design of BLDC machine is given here based on Fig. 1, for the specifications given in Table I.

The simple analytical design proposed here is suitable for optimization.

Design process of permanent magnet machines for wind turbine application can be organized as follows:

- Determination of air gap flux density function.
- Calculation of current and winding turn-number according to the required output voltage.
- Calculation of necessary Iron area to has the working point below the saturation.
- Calculation of necessary copper area based on to the copper and insulators area and filling factor.
- Determination of efficiency and mass for the optimization.

In the design process, it is assumed that iron permeability is infinite ($\mu_r = \infty$) and PM's permeability is unit ($\mu_m = 1$). The speed of generator is almost constant due to maximum power point tracking (MPPT) operation, and assumed to be 30 rpm. So, generator's pole pair is defined 100 according to turbine speed. maximum flux density in iron parts of machine is assumed to be 1.5T according electrical steels datasheets. Finally filling factor, the ratio of net copper area to occupied area by winding, is summed to be 0.7.

Magnetic flux density functions in the air gap are achieved by solving Poisson's equation in the polar coordinate system, which is given for BLDC machines in [33]. The final equation is given by (1):

$$B_{air}\left(r,\theta\right)=\sum_{n=1}^{\infty}\frac{M_n}{\mu_m}\frac{np}{np^2-1}R_5^{-(np-1)}\times$$
$$\times\left\{\frac{\left[\begin{array}{l}\left(np-1\right)R_5^{2np}+2R_6^{(np+1)}R_5^{(np-1)}+\\-\left(np+1\right)R_6^{2np}\end{array}\right]}{\left[\begin{array}{l}\frac{\mu_m+1}{\mu_m}\left[R_4^{2np}-R_6^{2np}\right]+\\-\frac{\mu_m-1}{\mu_m}\left[R_5^{2np}-R_4^{2np}\left(\frac{R_6}{R_5}\right)^{2np}\right]\end{array}\right]}\right\}\times \tag{1}$$
$$\times\left\{r^{(np-1)}+R_4^{2np}r^{-(np+1)}\right\}cos\left(np\theta\right)$$

where M_n is magnetic vector and for radially magnetized PM:

$$M_n=2B_r\alpha_p\frac{sin\left(\frac{2\pi\alpha_p}{2}\right)}{\left(\frac{n\pi\alpha_p}{2}\right)} \tag{2}$$

α_p is PM arc to pole pitch ratio, which is unity for BLDC machines.

Equation (1) is a complex series and deeply depends on PM and air gap width. It couldn't be converting to a simple equation. The design and optimization process using such equation will be too complex and time consuming.

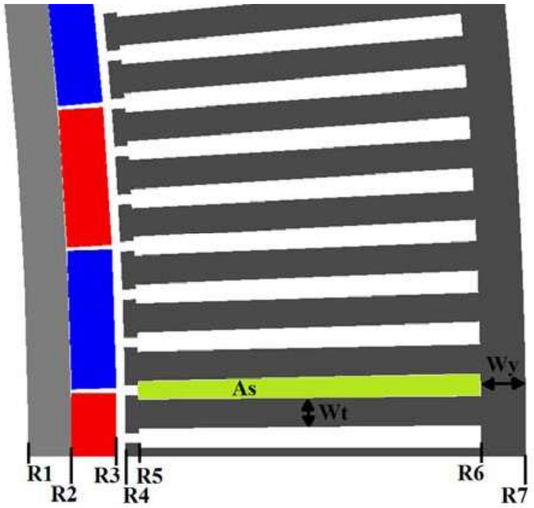

Fig. 1. Cross section of under design BLDC generator

On the other side, by assuming $\mu_m = 1$, $\mu_r = \infty$, air gap flux density, B_p, can be written as[30]:

$$B_p = B_r \frac{L_m}{L_m + L_g} = B_r \frac{R_3 - R_2}{R_4 - R_2} \tag{3}$$

Difference between Amount of equations (1) and (3) for R_4=1519mm, R_5=1521 and R_6=1564mm, is less than 5% and acceptable for a simple design procedure.

Since equation (3) is independent from the radii, the overall phase-induced voltage can be determined by using E=-lVB lows as follows:

$$E_{phase} = 2pNB_pZ \frac{R_5 - R_6}{2} \omega \tag{4}$$

According Fig. 1 air gap reluctance in front of dent and pole can be calculated by (5) and (6) respectively:

$$R_t = R_r + R_l \tag{5}$$

$$R_p = R_t \frac{2p}{N_t} \tag{6}$$

R_l and R_r are achieved by equations (7) and (8):

$$R_r = \frac{2N_t\left(R_4 - R_2\right)}{\mu_0 Z\left(\dfrac{2\pi R_4 - w_t N_t}{N_p}\right)} \tag{7}$$

$$R_l = \frac{\dfrac{2\pi R_6}{N_t} - w_t}{\mu_0 Z\left(R_6 - R_4\right)} \tag{8}$$

During mechanical limitations the shaft radius of generator is R_1=1500mm. The overall generator radius, R_7, is less than 1600mm. So R_5 can be assuming to be equal with R_4 with a good accuracy.

The tooth flux produced by coil and magnet can be calculated as:

$$\varphi_{t(coil)} = \frac{Ni}{R_t} \tag{9}$$

$$\varphi_{t(magnet)} = \frac{2\pi R_3}{N_t} Z \cdot B_p \tag{10}$$

Two coils are energized instantaneously in BLDC machines. So maximum total flux of each dent determined by:

$$\varphi_{t(total)} = 2\varphi_{t(coil)} + \varphi_{t(magnet)} \tag{11}$$

width of stator and rotor yoke and dent can be calculated according to keep the working flux density point below the saturation point:

$$w_t = \frac{\varphi_{t(total)}}{Z \cdot B_{max}} \tag{12}$$

$$\varphi_{y(total)} = 2\varphi_{t(coil)} \frac{R_l}{R_l + R_r} + \frac{N_t}{2N_p} \varphi_{t(magnet)} \tag{13}$$

$$w_y = \frac{\varphi_{y(total)}}{Z \cdot B_{max}} \tag{14}$$

Coil current and turn number can be determined based on machine torque or induced voltage (eq. (4)) then the necessary slot space is:

$$A_{cu} = \frac{2N \cdot m \cdot p \cdot i \cdot K_{cu}}{N_t \cdot ff} \tag{15}$$

On the other hand according Fig. 1 available slot space is:

$$A_s = \frac{\pi\left(R_6^2 - R_5^2\right)}{N_t} - w_t\left(R_6 - R_5\right) \tag{16}$$

By equalizing necessary and available space, so:

$$\begin{gathered} A_s = A_{cu} \Rightarrow \\ R_6^2 - \frac{N_t w_t}{\pi} R_6 + \frac{N_t w_t}{\pi} R_5 - R_5^2 - \frac{A_{cu} N_t}{\pi} = 0 \end{gathered} \tag{17}$$

where:

$$R_6 = R_7 - w_y \tag{18}$$

By solving equation (17) all machine dimension will be find.

Wire length of each phase is:

$$l_{phase} = 4pN\left[\left(Z+2e\right)+\frac{\pi\left(R_5+R_6\right)}{2p}\right] \tag{19}$$

where e is the axial salient length of coil from stator. The resistance of each phase and total copper loss can be calculated as:

$$\begin{aligned} R_{phase} &= l_{phase}\cdot\rho_{cu} = \\ &= 4pN\left[\left(Z+2e\right)+\frac{\pi\left(R_5+R_6\right)}{2p}\right]\rho_{cu} \end{aligned} \tag{20}$$

$$P_{cu} = 3R_{phase}\cdot i^2 \tag{21}$$

Finally stator mass is determined by:

$$m_{fe} = Vol_{fe}\cdot D_{fe} = \begin{bmatrix}\pi\left(R_7^2-R_6^2\right)+ \\ +w_t N_t\left(R_6-R_4\right)\end{bmatrix}\cdot Z\cdot\rho_{fe} \tag{22}$$

Iron loss can be defined from factory datasheets. It is noticeable that the flux of rotor back iron is constant and its losses can be ignored.

III. Optimization

In design section, the machine dimensions (R_1 to R_7 and z) are unknown. R_1 and L_g are defined base on mechanical constraints. Stator and rotor yoke are the same so one more of unknown parameters is eliminate. In the other hand the turn numbers of each coil (N) has to be calculated from given parameters.

Finally we have six unknown parameters and four equations in the design process ((4), (12), (14) and (17)). So, two of the unknown parameters are remaining free and have to be chosen arbitrary.

In ordered, to obtain maximum efficiency and minimum mass, two unknown parameters must be optimized. Efficiency is the objective function and Z and L_m are variables of optimization. Boundaries of the variables are chosen as below:

$$100\text{mm} < Z < 5000\text{mm}$$
$$1\text{mm} < L_m < 10\text{mm}$$

The behavior of efficiency and weight regard to variation of L_m and Z are illustrated in Figs. 2 and 3.

As Fig. 3 shows, high efficiency can be achieve either low Z with high L_m or high Z with low L_m. However the higher Z with lower L_m leads to higher machine mass.

The optimum generator's parameters can be obtained using over lapping Figs. 2 and 3. Result of optimization and design for given parameters of Table I are given in Table II.

TABLE I
PARAMETERS OF UNDER DESIGN GENERATOR

Turbine speed	Output power	Output voltage	Pole pair
30 rpm	1 MW	6 KV (L-L)	100
Slot Number	B_{max}	Filling Factor	Nominal torque
600	1.6(T)	0.7	318.3 KN.m

TABLE II
RESULTS OF ANALYTIC DESIGN AND OPTIMIZATION FOR CASE STUDY GENERATOR

L_m	L_g	B_{max}	Z	W_t	W_y	N
5	1	1.6T	1700	9	13	2
R_1	R_2	R_3	R_4	R_5	R_6	R_7
1500	1513	1518	1519	1521	1564	1577

* All dimensions are in mm

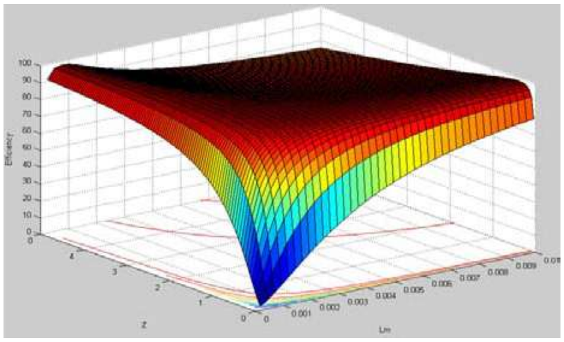

Fig. 2. Efficiency of BLDC generator versus PM and rotor axial length (Lm & Z)

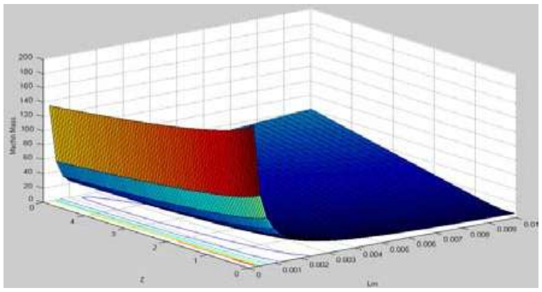

Fig. 3. Weight of BLDC generator versus PM and rotor axial length (Lm & Z)(×103Kg)

IV. Design Validation by FEM Simulation

Two-dimensional finite element simulations with ANSOFT Maxwell-2D software were carried out for analytical design validation. Two types of simulation are done for this aim.

The first one is the magneto-static simulation which investigates the maximum flux density in the static condition and the second one is the parametric simulation that investigates the dynamic performances of machine, like torque in the nominal speed and frequency. Fig. 4 shows the magnetic flux density distribution resulted by magneto-static simulation of machine with given parameters in Tables I and II. It is clear that the flux density in stator is less than 1.6 Tesla. So, magneto static design including generator dimension are verified.

Fig. 5 shows net produced torque for the machine resulted from parametric simulations. It is noticeable that, cogging torque and produced torque are determined for achieving this curve.

Then the net torque is driven by decreasing cogging torque from the produced torque.

Referring to Table I, nominal torque of machine in 30rpm is 318.3 kN·m.

In Fig. 5 nominal torque is 326 (kN·m) that shows about 2.5% errors for produced torque. This amount off error can be originated by air gap flux density approximation (eq. (3)) and finite element method simulations.

It is verify the produced torque by machine.

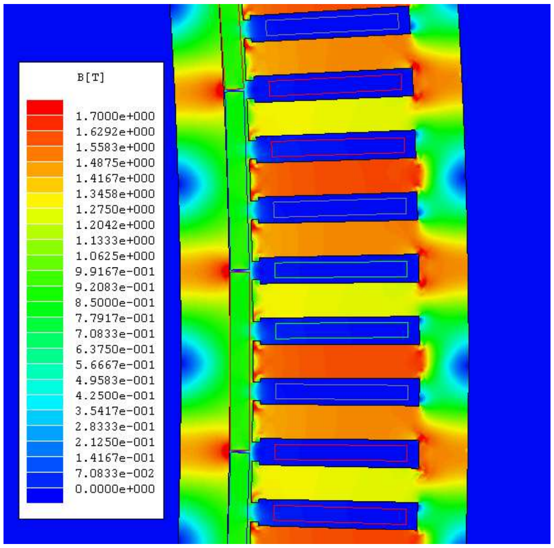

Fig. 4. Magnetic flux distribution in BLDC generator resulted by magneto-static FEM simulation

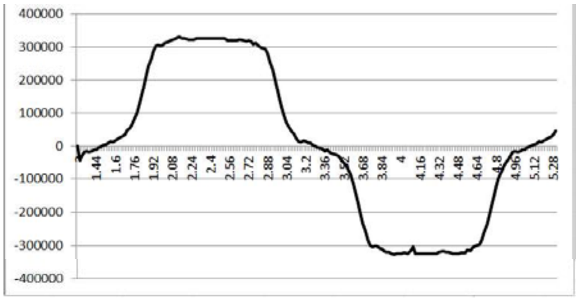

Fig. 5. Produced torque by BLDC generator resulted by parametric FEM simulations

V. Conclusion

In this paper, a synchronous permanent magnet BLDC machine is designed and optimized for wind turbine applications. An approximation is used for air gap flux density calculation of the machines for parametric design simplification.

The error of this approximation, which simplifies the design process extremely, is less than 3%. Direct optimization manner is used for optimizing the machine efficiency. Static and dynamic finite element simulations are used to validate the design and optimization processes.

Simulations confirmed the design accuracy.

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Authors' information

Damavand Branch, Islamic Azad University, Damavand, Tehran, Iran.

Sayyed Mohammad Mehdi Mirtalaei was born in Shahreza-Isfahan, Iran, in 1983. He received his B.S. degree in electrical engineering from Isfan University of Technology, Iran, in 2005. he received his MS and Ph.D in electrical engineering from Amirkabir University of Technology, Tehran, Iran, in 2007 and 2012 respectively. His research interest is power electronics, EMI/EMC and numerical method in electromagnetic.

Babak Abdi was born in Tehran, in 1976. He received his BS and MS degree in electrical engineering in 2002 and 2005 from University of Hormozgan, Hormozgan, Iran and Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, respectively. He is currently a Ph.D student at Amirkabir University of Technology (AUT). He is also graduate student member of IEEE and faculty member of Islamic Azad University, Damavand branch, Tehran, Iran. His research interests include flywheel energy storage systems, power electronics, application of reliability in power electronics, Electromagnetic Interferences (EMI), electrical machines and drives.

Kiarash Shaloudegi was born in 1986, Tehran, Iran. He received his B.Sc. degree in Electrical Engineering from K.N.Toosi University of Tech. and M.Sc. degree in Electrical Engineering from Amirkabir University of Tech. (Tehran Polytechnic), Tehran, Iran in 2009 and 2011, respectively. He is currently pursuing his Ph.D. program in Electrical Engineering at University of Alberta, Canada. His main fields of research are Power Market, Power Quality, and Power System Optimization.

Reza Ghasemi (M'09) was born in Tehran, Iran in 1979. He received his B.Sc degrees in Electrical engineering from Semnan University in 2000 and M.Sc. degrees and Ph.D. in control engineering from Amirkabir University of Technology, Tehran, Iran, in 2004 and 2009, respectively. His research interests include large-Scale Systems, Adaptive Control, Robust Control, Nonlinear Control, and Intelligent Systems. Dr. Reza Ghasemi joined the Department of Electrical Engineering, Islamic Azad University, Damavand Branch, Damavand, Iran, where he is currently an Assistant Professor of electrical engineering.

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