ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 3, Issue 3, May 2014

Designing an Efficient Permanent Magnet Generator for Outdoor Utilities

İlhan Tarımer

Abstract*— This paper deals with designing, modelling and production process of a permanent magnet axial flux structured generator to be used at wind turbines. Magnets and lamination parts used in the designed generator and its effects have been inspected. This paper also dealt with the effects of such magnets and laminations to the mass and efficacy of the resulted generator. Since the slots of the generator have been skewed for reducing cogging torque, a feasible product has been obtained as to be used at outdoor utility. It is confirmed that output of the developed generator entirely matches with high efficiency values in terms of axial flux structuring. The generator's total net weight and its efficiency values come up with technical acceptable limits. The net values of the torque, line current and efficiency have been ascertained that the designed generator might be produced and used as an efficient machine, most likely in outdoor applications.

Index Terms—**Axial flux structure, generator design, NdFeB35 permanent magnet.**

I. INTRODUCTION

It is known that there are two topology types which are axial and radial flux in designing permanent magnet generators [1, 2, 4]. In an axial flux machine, if magnetic flux linkages run through to axial direction, maximum power density can be obtained [1]. But manufacturing such structured machines is more expensive and several difficulties can be seen particularly over lamination of stators [1]. When comparing these two types of machine structures, it is seen that radial flux structured machines are available more commercial due to it could be manufactured easier than axial flux structured machine at current conditions. Though axial flux structured machines are being preferred for limited industrial applications [3].

Whereas a radial-flux generator is made with the permanent magnet poles which rotate within the stationary armature windings [4], an axial flux machine have got a back iron in which it rotates together with rotor [5]. Ferreira and Costa presented an axial flux PM synchronous generator, double sided with internal rotor and slotted stators [9]. Bumby and Martin have built a 3-phase axial-flux PM air-cored generator for using in wind turbines [10, 13]. Chen and et.al. Designed a PM generator using neodymium-iron-boron magnets for directly coupled wind turbines [11]. Parviainen and et.al. Realized an axial flux PM 1.6 kW generator to operate in wind application [12]. Touzhu and Slemon analyzed cogging torques with surface mounted and inset magnet rotors [14].

This paper deals with designing and modeling a 2.4 kW permanent magnet generator in terms of axial flux structure topology. The generator's structure and its magnets' effects which are presence in the frame of the generator have been essentially discussed and inspected in the study. Performance characteristics such as voltage, output power and efficiency of the designed generator have been also presented.

II. DIMENSIONAL ANALYSIS FOR AXIAL FLUX STRUCTURE GENERATOR

A. Generator Design Topologies

Dimensions and size expressions regarding to a PM generator are given in output equation (1) [6].

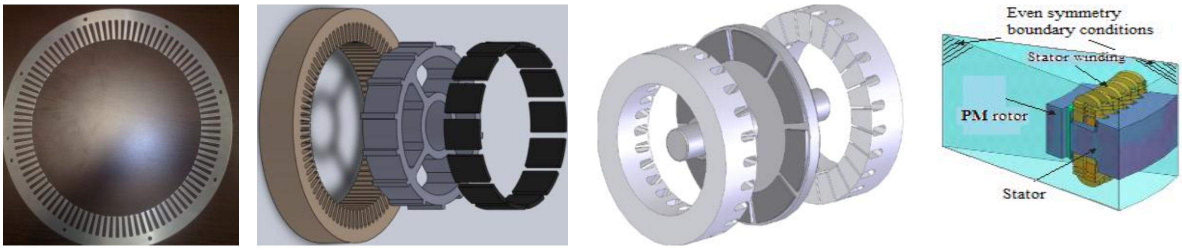
$$Q = C_0 D^2 l.n \quad (1)$$

where Q – output power (kVA), C_0– output equation, D – inner diameter of stator (m), l – length of generator (m), n – rated speed (revolution per second).
Since a low speed machine is obtained more costly and the volume is to be increased, the normal values of output coefficient (C) vary from 1.77 to 8.2 [6]. In order to estimate dimensions of a 2.4 kW PM generator, magnetic loading and specific electric loading (ac) must be determined as 0.75 T and 22000 a-c/m respectively. In addition to these, rated speed (η %), effective length of generator (l_s), length of air gap, stator slots (X), numbers of total

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 3, Issue 3, May 2014

conductors, number of pole (P), phase current, stator yoke and teeth, stator copper and iron losses, total losses (P_K), iron and copper weights (kg), rotor structure, stator leakage reactance, efficiency (η %) and operating temperature ought to be entered to the software tools for doing analytical design as well.

After the analytical calculations, the obtained model is imported to Ansoft Rmxprt software environment for modifying computations [7] made before. When all computations and dimensioning of generator parts are verified, it is simulated and then re-sized; hence, last version of the model is created. That means that, the design is ready to be produced. The created designs (and its constructional views) are given in Fig. 1.



a) Stator lamination **(b) PM generator view.** **(c) Stator constructional view** **(d) View from inner part**

Fig. 1. Structural model of the designed PM generator

In Fig. 1, an axial flux permanent magnet generator's lamination, stator's assembly and construction and its internal part are presented. The properties of PM materials used in the machine are crucial from the angle of machine performance. The PM materials excite the machines which are to be designed within a range a 1 kW to 5 MW. The properties of NdFeB35 permanent magnet [8] are given in Table 1. In order to bring about analyzing results more accurate and feasible, a 3D simulator reckoned to static magnetic analyzing is used. Instead of examining the whole model, the smallest part of the model is inspected with the condition of even symmetry boundary appointed to the field boundaries. The figures above have been obtained by finite elements method together with boundary conditions by Rmxprt and Maxwell 3D. Electromagnetic characteristic of the designed PM generator has been determined by using finite elements method. The results produced are listed in Table 2.

Table I. Properties of NdFEB35 Magnet

Parameters	Values	Unit
Residual flux density	1.23	Tesla
Coercive force	890	kA/m
Maximum energy density	273.67	kJ/m^3
Relative recoil permeability	1.0998	--
Demagnetized flux density	0.0889	Tesla
Recoil residual flux density	1.23	Tesla
Recoil coercive force	890	kA/m

Table II. Values Obtained in the Design

Parameters	Values	Parameters	Values
Output power (W)	2400	Total losses (W)	230.456
RMS phase current (A)	6.6	Load resistance (Ω)	17.72
Load inductance (mH)	18.5	Phase voltages (V)	120
Total net weight (m) (kg)	16.87	Number of pole	14
Magnet thickness (t_m) (mm)	54	Number of slots	84
Length of stator stack (mm)	54	Frequency (Hz)	50
Stator outer diameter (ds) (mm)	280	Efficiency (%)	94

The induced voltages, total magnetic flux, magnetic flux density distribution counter in the air gap are calculated by finite elements method. On the other hand, slot structure and magnetic saturation in air gap have been solved by using 2D / 3D FEM.

Air gap flux density can be obtained from curl of magnetic vector potentials as in (2)

$$B = A \times \nabla \quad (2)$$

Where B – flux density (Tesla), ∇ – magnetic vector potentials and A – area.

Fig. 2 shows distribution of the flux density for the air gap.

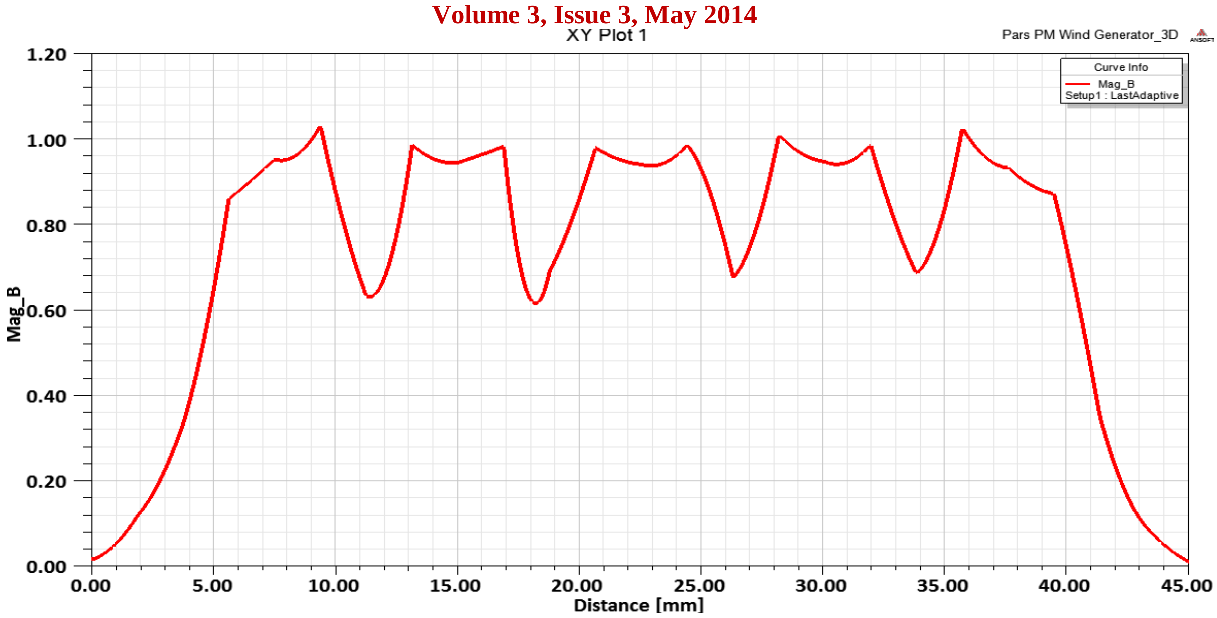


Fig. 2. Air gap magnetic flux density of the generator.

In Fig. 2, it is shown that distribution of the flux density is calculated approximately 0.9 T for air gap. This value is used for calculating the induced voltage as analytically given in (2, 3). Dispersion of the induced voltage per phase is accounted as in (3)

$$E = N_{ph} \sum_{n=1}^{K_n} - \left[k_w \frac{\partial \phi_n}{\partial t} \right] \quad (3)$$

where E – induced voltage, N_{ph} – number of series turn per phase, K_n – number of total harmonics, k_w – winding distribution factor, $\emptyset_n$ – average flux per pole.

RMS value of the induced voltage is given as shown in (4)

$$E = 4.44 \times f \times \phi_n \times n \times N_{ph} \times k_w \quad (4)$$

Where f – frequency, ϕ_n – average flux per pole, n – rated speed, N_{ph} – number of series turn per phase, k_w – winding distribution factor.

ϕ_n is accounted as seen in (5)

$$\phi_n \left(l \times \frac{\pi \times D}{P} \right) \times \frac{2}{P} \times B_m \quad (5)$$

Where l – length of stator core (m), D – stator diameter (m), P – number of pole , B_m – magnetic field density (T).

Under the limited conditions, larger magnet means that more efficiency can be obtained, because it composes more flux in the air gap. But when magnetic core saturation of non–oriented lamination materials is considered, the material must have high saturation to increase efficiency. In order to select suitable material, B–H curve is crucial for overall efficiency. In the research, M470–50A lamination material has been used.

Core losses versus magnetic flux density for the laminated material have been obtained at 50 and 100 *Hz* frequencies separately. Losses are changed from 0.1 *W/kg-T* to 100 *W/kg-T* for 100 *Hz* frequency. Losses are changed from 0.01 *W/kg-T* to 4 *W/kg-T* for 50 *Hz* frequency. Since Eddy currents are induced on the magnet by rotating magnetic field, magnetic losses on the surface of magnets could have occurred. Cutting of magnet could sophisticate to diminish Eddy currents on magnets' surfaces. Simulations have been performed with a ratio of 1 % error, and the model has been created by 50000 finite elements approximately. Fig. 3 shows meshed structure, and Fig. 4 shows magnetic flux density distribution of the model. The meshed structure of the model created by the finite elements is shown in Fig. 5. It indicates meshed structure of the designed generator.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 3, Issue 3, May 2014

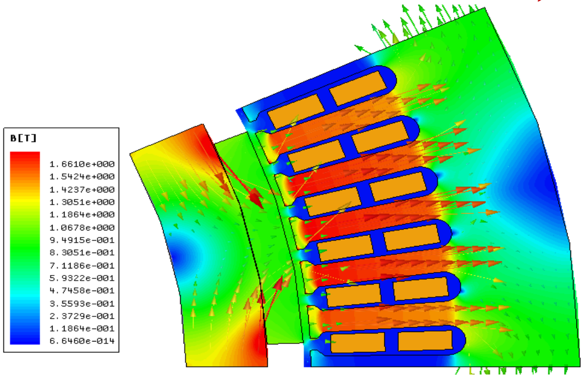


Fig. 3. Magnetic flux density distribution of the generator (2D)

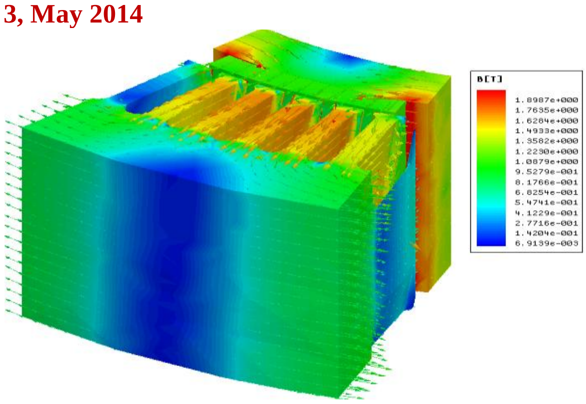


Fig. 4. Magnetic flux density distribution of the generator (3D)

The obtained 3D results consider that the fringe effect is fewer than the 2D results at the end of slots in the machine. Maximum magnetic saturation in a well–designed machine is occurred where the slots are being narrowed (Fig. 6). Therefore saturation at surfaces diminishes efficiency and affects thermal parameters of the machine. Partial saturation could be occurred in a narrow section of the generator. Since this saturation is neglected, it concludes that the design is accepted within the certain constraints. 3D analysis shows that fringe effect is fewer than 2D results.

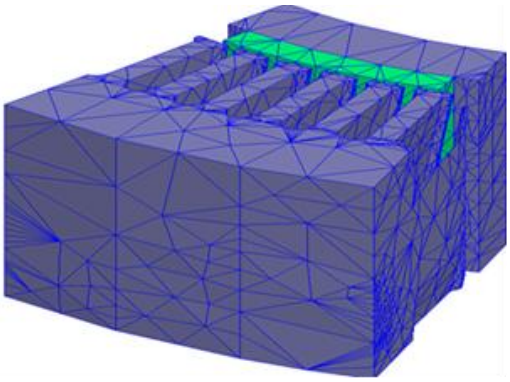


Fig. 5. Mesh analysis for the designed generator.

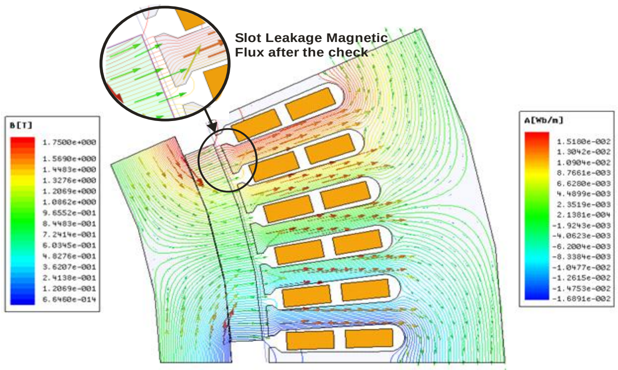


Fig. 6. Magnetic flux and flux density vectors.

Cogging torque has an interactive effect over stator core and magnets of the generator at no-load condition. Once the generator is loaded as unstably, it struggles to catch the force which is cogging. Therefore, it's necessary to know necessity of decreasing cogging torque at generator design. In the research, to do this, the slots were skewed as 0.83°. This case is simulated as shown in Fig 7. Fig. 8 shows efficiency versus speed of the designed generator under load circumstances. The designed generator gives 2.4 *kW* output power when it's rotating at 440 *rpm* under load. The efficiency was obtained as 94 % under load.

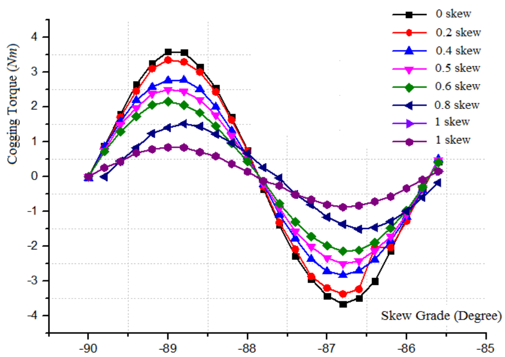


Fig. 7. Levels of cogging torque at several skewed slot angles.

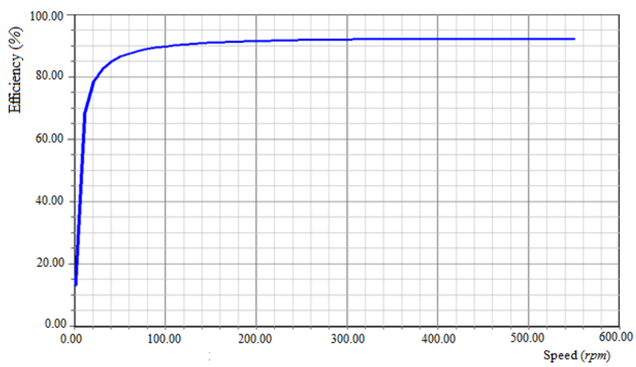


Fig. 8. Efficiency versus speed under load

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 3, Issue 3, May 2014

III. RESULTS

In this paper, a PM and axial flux structured generator has been designed, modelled and analyzed for using at outdoor utility. A producible generator model according to the desired specifications has been obtained in the study. Design parameters of the generator are arranged not only for structural frame, but also they are brought about in terms of magnetic parameters in the study. The designed generator is proposed to produce for industrial demands. In order to realize design, analysis, modeling and producing processes seamlessly, it needs to have a speed up to 500 *rpm* for a 2.4 *kW* output power with 94 % efficient generator. This generator is also arranged for decreasing cogging torque by skewing the stator slots. Skewing slots up to maximum 1.0° resulted that the generator would almost be produced with very small cogging torques. Moreover the operating values which were obtained from the generator after production have been accurate and acceptable ones. As result of this, net values of torque, line current and efficiency have been proved that the designed generator might be produced as an efficient machine for outdoor appliances. The generator designed in the study can be used in a wind turbine, due to its lighter mass weight and good performance.

IV. CONCLUSIONS

For this study, the rated torque and line current values have been calculated by skewing the slot angles from 0° up to 1.0° with intervals of 0.2°. When the slot angle is skewed 0°, rated torque is obtained about 167.75 *Nm*. At the end (skew angle is 1.0°), the rated torque is being obtained as 164.75 *Nm*. In same manner, line current values have been obtained from 31.35 *A* to 30.95 *A*, spanning slot angle skewing from 1.0° to 0.0°. Meanwhile the cogging torque increased up to 4 *Nm* would do decrease to 0.6 *Nm* by skewing the stator slots from 0° to 1°. Once the slots are skewed from 0° to 1°, cogging torque level at the machine drops to 0.6 *Nm*. As result of these, it can be said that the developed generator's torque will become 3.3 *Nm* less and line current of the machine will become 0.4 *A* less than their initial values. Hence, 94 % efficiency, 164.5 *Nm* torque and 30.95 *A* current prove that the designed generator is an efficient machine.

REFERENCES

[1] J.F. Gieras, R.J. Wang, M.J. Kamper, "Axial Flux Permanent Magnet Brushless Machines", 2. Edition, Springer, 2008, ISBN: 978-1-4020-2661-4 (Print) 978-1-4020-2720-8 (Online), USA.

[2] W. Ouyang, "Permanent Magnet Machine Drive System With Fault Tolerant Capability", The University of Wisconsin–Madison, UMI Number: 3294182, USA, 2007.

[3] T. Ackermann, "Wind Power in Power Systems", John Wiley & Sons Ltd., ISBN: 0–470 – 85508 – 8, 2005, England.

[4] İ. Tarımer, C. Ocak, "Performance Comparison of Internal and External Rotor Structured Wind Generators Mounted from Same Permanent Magnets on Same Geometry", Electronic Ir Elektrotechnika, ISSN: 1392 – 1215, p.p. 65–70, No. 4(92), 2009.

[5] M. Sadeghierad, H. Lesani, H. Monsef, A. Darabi, "Back-iron Consideration in High-Speed Axial-Flux Machine", Elektronika Ir Elektrotechnika, ISSN: 1392 – 1215, p.p. 87–90, No. 1(89), 2009.

[6] O. Gürdal, "Designing of Electrical Machines", Atlas–Nobel Publishing, Distribution House, 2001, ISBN: 975–6574–07–0, Ankara Turkey.

[7] Ansoft Rmxprt software, http://www.ansys.com/staticassets/ANSYS/staticassets/resourcelibrary/brochure/electromagnetics- brochure.pdf, 09.05.2014.

[8] C. Kumar, "Magnetic Nanomaterials", Wiley-VCH Verlag GmbH, 2009, ISBN: 978–3–527–32154–4, p.p. 648, Germany.

[9] A.P. Ferreira, A.F. Costa, "Direct Driven Axial Flux Permanent Magnet Generator for Small-Scale Wind Power Applications", International Conference on Renewable Energies and Power Quality, Las Palmas Spain, 13th to 15th April, 2010.

[10] J.R. Bumby, R. Martin, "Axial-flux permanent-magnet air-cored generator for small-scale wind turbines", IEE Proc.-Electr. Power Appl., Vol. 152, No. 5, p.p. 1065–1075, September 2005.

[11] J. Chen, C.V. Nayar and L. Xu, "Design and Finite-Element Analysis of an Outer-Rotor Permanent-Magnet Generator for Directly Coupled Wind Turbines", IEEE Transactıons On Magnetics, Vol. 36, No. 5, p.p. 3802–3809, September 2000.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 3, Issue 3, May 2014

[12]] A. Parviainen, J. Pyrhönen and P. Kontkanen, "Axial Flux Permanent Magnet Generator with Concentrated Winding for Small Wind Power Applications", E-ISBN: 0–7803–8988–3, p.p. 1187–1191, 15 May 2005.

[13] J.R. Bumby, N. Stannard, J. Dominy and L. McLeod, "A Permanent Magnet Generator for Small Scale Wind and Water Turbines", Proceedings of the 18th International Conference on Electrical Machines, Paper ID: 733, ISBN: 978–1–4244–1735–3, 6–9 Sept. 2008.

[14] Touzhu L., Slemon G., "Reduction of Cogging Torque In Permanent Magnet Motors", IEEE Transactions on Magnetics, Vol. 24, No. 6, p.p. 2901-2903, November 1988.

AUTHOR BIOGRAPHY

İlhan Tarımer was born in Manisa in 1963. He completed primary, secondary schools, and technical high school education in Manisa. Then he graduated from electrical electronics engineering education in Ankara, Turkey. He received the BSc, MSc and PhD degrees in 1984, 1991 and 2003 respectively from Technical Education Faculty and Institute of Science and Technology, Gazi University. He attended to the World Bank and Turkey Council of Higher Education (YÖK)'s Industrial Education Project in the U.K. between 1986 and 1987. Then he worked as a lecturer at Ankara University between 1988 and 1995. Then he was attended as lecturer to Muğla University. He works currently as an associate professor at Technology Faculty, Muğla Sıtkı Koçman University. His research interests are in the areas of design, modeling and analysis of electrical machines, industrial automation, developing software for instrumentation, machine - human interaction and information / communication. He published more than 50 indexed papers. He carried out 16 projects. He is author of 4 books and book chapters. He supervised 7 post graduate students. He gives lectures as a visiting professor in Warsaw University of Technology. İlhan Tarımer is now member of Polish National Committee on Lightning Protection since September 2012. He has 29 years of experience in education, engineering and research.