DESIGN AND IMPLEMENTATION OF THE DOUBLE-SIDED AXIAL-FLUX PMSG WITH SLOTTED STATOR BY USING SIZING EQUATION AND FEA SOFTWARE

[1]SAINT SAINT SOE, [2]YAN AUNG OO

[1,2]Department of Electrical Power Engineering, Mandalay Technological University, Myanmar
E-mail: seintssoe@gmail.com, yanaungoo@gmail.com

Abstract- Axial-flux permanent magnet (AFPM) machines have become an important subject of study because of the development of neodymium magnets over the past 20 years. Axial-flux machines have high power density and high torque. Axial-flux permanent magnet machines have many unique features. For being permanent magnet, they usually are more efficient, as field excitation losses are eliminated, reducing rotor losses significantly. Machine efficiency is thus greatly improved, and higher power density achieved. Axial-flux construction has less core material, so, high torque-to-weight ratio. The noise and vibration they produce are less than those of conventional machines. Their air gaps are planar and easily adjustable. The aim of this paper is to perform more accurate design calculation and analys of an axial-flux permanent magnet synchronous generator, double-sided with external rotors and internal slotted stato he evaluation is based on theoretical analysis by means of sizing equations and confirmed by finite-element analysis. Therefore, the AFPMSG topology considered in this paper is a three-phase double-rotor single-stator topology with 16 pole-pairs, 2kW rated power and 188 rpm rated speed. The performance of double-sided APMSG for slotted stator design is analyzed with finite element analysis (FEA).

Keywords- Axial-Flux Permanent Magnet Synchronous Generator (AFPMSG), Double-Sided, Finite Element Analysis (FEA), Slotted Stator.

I. INTRODUCTION

Axial-flux permanent magnet synchronous machines have found many uses in high torque, low speed applications. Axial-flux PM machines have an excellent flexibility at a variety of rotational speeds. Good performance at different rotational speeds is obtained by changing the number of magnets on the rotor discs and varying the diameter of the machine; a large diameter with high number of permanent magnets is perfectly suitable for low-speed-high-torque applications. This makes the axial-flux PM machine perfectly suitable for electric vehicle propulsion and direct-drive wind energy systems (low-speed-high-torque) [1].

Axial-flux PM machines are very compact. The axial length of the machine is much smaller compared to radial machines, which is very often crucial in built-in applications. The slim and light-weight structure results in a machine with a relatively high power density. Axial-flux PM machines have a good energy efficiency. As the magnetic field is generated by the permanent magnets, no field excitation current is necessary and the corresponding copper losses are absent. Axial-flux permanent magnet synchronous generator have a number of distinct advantages, i.e. they can be designed to have (i) higher power-to-weight ratio, resulting in less core material, (ii) planar and easily adjustable air-gaps, (iii) reduced noise and vibration levels[2]. There are possible many variations in the AFPMSG basic design, including single-sided, double-sided, toroidal, and multi-disc designs. The AFPMSG topology considered in this paper is a three-phase double-sided slotted stator topology. The magnets are of high-energy NdFeB-type, and are glued on both sides of the two solid-iron disc-rotors. The stator is made of non-magnetic material.

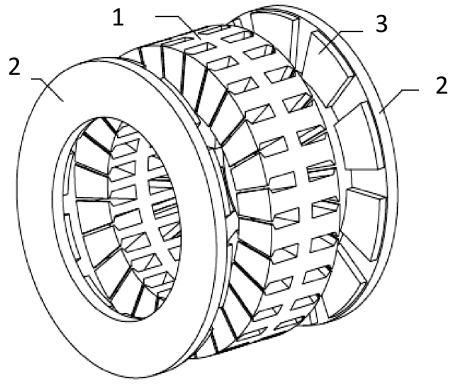


Fig. 1. Single-stator double-rotor axial flux PM machine topology (1) stator (2) rotor (3) permanent magnet

II. AXIAL-FLUX PM GENERATOR

Several axial-flux machine configurations can be found regarding the stators position with respect to the rotors positions and the winding arrangements giving freedoms to select the most suitable machine structure into the considered application. Among four possible configurations are structure with one rotor and one stator, structure, in which the stator is located between the rotors, structure, in which the rotor is located between the stators, multistage structure including several rotors and stators.

The AFPMSG topology considered in this paper is a three-phase double-rotor one-stator topology. It is

more compact than the generator with internal rotor. The magnets are of high-energy NdFeB-type. Two main classes in the stator construction can be distinguished: slotted stator and coreless stator. In case of slotted stator, the stator is made of high permeable material (laminated silicon steel, soft magnetic composite, amorphous iron) and the winding is placed in the stator slots.

A. Double-Rotor Single-Slotted Stator Structure

Fig. 2 is a double-rotor single-stator AFPM machine. Torus concept AFPM machines are external rotors and internal stator structures. The stator has a slotted structure with strip wound stator steel. Polyphase windings are placed into slots. Slotted stator increases remarkably the amplitude of the air gap flux density due to shorter air gap. This reduces the required amount of permanent magnets, which yields saving in the generator price [3].

The two disc shape rotors carry the axially magnetized arch-shaped permanent magnets mounted on the inner surfaces of the rotor discs. Two different Torus machines, Torus NN and Torus NS, can be derived based on the direction of the flux using this structure. In this paper, the NS magnet type topology is used for AFPMSG.

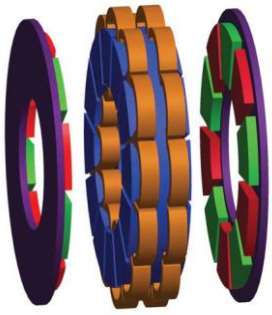


Fig. 2. Concentrated winding or lap winding configuration is used in Torus NS type

III. PROPOSED MACHINE TOPOLOGY

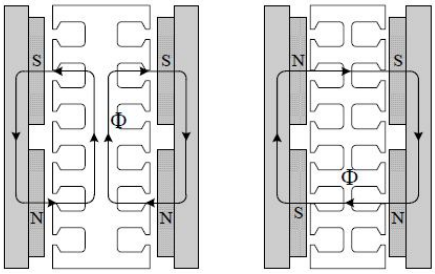
Double-sided dual rotor AFPM machines provides better winding utilization, increased power density with reduced copper and iron losses. The flux return paths are in the rotor discs. Cooling is much easier for this type of machine since the rotors with surface mounted permanent magnets rotating next to the sides of the windings, act as a fan. The generator consists of 16 pole pairs permanent magnet. The stator and rotor core are made of lamination steel.

A. Types of Rotor Construction

The permanent magnets can either be mounted on the surface of the rotor disk or they can be embedded into the rotor disk. The AFPMG discussed in this study is of the surface-mounted topology. Advantage is that the surface-mounted permanent magnets naturally act as fans which have a ventilation effect on the stator windings at higher rotational speeds. Moreover, there are two types of rotor construction for an AFPMSG. They are the NN magnet type rotor structure and NS magnet type rotor structure.

1) NN Type Rotor: In the NN type machine as shown in Fig. 3(a), magnet driven flux enters the stator and travels circumferentially along the stator core. Moreover, while a back-to-back wrapped winding configuration is used in NN type machine in order to produce torque.

2) NS Type Rotor: In the Torus NS type machine as shown in Fig. 3(b), the flux enters the stator and travels axially along the machine axis of rotation resulting in theoretically no thick stator yoke. Moreover, concentrate winding configuration is used in Torus NS type machine in order to produce torque.



(a) (b)

Fig. 3. Flux paths in 2D plane for slotted stator of single-stator double-rotor AFPM machine. (a) NN magnet arrangement and (b) NS magnet arrangement

By comparison of the NS and NN structure, the shorter stator yoke in the NS topology results in a increasing power density and lower stator core loss compared to the NN topology[4]. The axial thickness of the stator can be less than NN type machine. The NS feature results in less weight, less iron loss and higher efficiency than NN type machine[5]. Here, NS construction has been selected because as stator core loss is less than NN type.

B. Type of Stator Construction

In a slotted AFPM machine the stator is located between the two opposing rotor discs. The stator lamination is made of non-magnetic material. Slotted stators in the AFPMSG machine increase notably the amplitude of the air gap flux density due to shorter air gap. This reduces the required amount of rotor PMs, thus leading to savings in the slotless stator counterpart [6]. The machine winding type is a conventional double layer lap winding for which the number of slots per pole and phase is equal to one. The assigned value parameters of the AFPMSG for slotted stator are shown in Table I.

Table I. Specifications of AFPMSG

Parameters	Units	Assigned Value
Number of phases		3
Number of pole pairs		16
Frequency	Hz	50
Air gap distance	mm	1.5
Air gap flux density	T	1.24
Specific electromagnetic	A/m	12000

loading		
Connection of stator winding		star

C. Design Equation for AFPMSG

The axial-flux permanent magnet machine configuration consists of the following components. They are external double-rotor and internal slotted stator. Design calculation of 2kW AFPMSG with slotted stator by using sizing equations is described in this section of the paper.

The stator outer diameter for AFPMSG can be calculated by the following equation,

$$D_{out} = \sqrt[3]{\varepsilon P_{out} / (\pi^2 \lambda k_w n_s B_g A_m \eta \cos\phi)}$$

(1)

k_w = stator winding factor

P_{out} =output power rating

ε = the ratio of EMF to phase voltage

A_m = specific electromagnetic loading

The stator inner diameter for the AFPMSG,

$$D_{in} = D_{out} \times K_d$$

(2)

K_d = ratio of inner and outer diameter of machine

The average radius of the stator winding can be calculated by,

$$r_e = (r_o + r_{in})/2$$

(3)

Active length of stator winding is the following equation,

$$l_s = r_o - r_{in}$$

(4)

r_o = outer radius of the stator

r_{in} = inner radius of the stator

The peak value of air-gap flux density,

$$B_p = (2\sqrt{3} \times B_g)/\pi$$

(5)

The number of slot per pole per phase can be calculated by the following equation,

$$q_1 = Z_1/(2pm)$$

(6)

Z_1 = the number of slot

The average slot pitch can be calculated by the following equation,

$$\tau_s = (\pi D_{avg})/Z_1$$

(7)

The average pole pitch can be calculated by,

$$\tau_p = (\pi D_{avg})/2p$$

(8)

The relative magnet width can be calculated by the following equation,

$$\alpha_p = b_p/\tau_p$$

(9)

The stator winding factor is defined as,

$$k_w = \left[2\sin(n\omega_c\pi/2\tau_p)\sin(n\pi/2m)\right] / \left[(Z_1/mp)\sin(m\pi p/Z_1)\right]$$

(10)

Z_1 = the number of slot

m = the number of phases

w_c = the coil span

The RMS value of the induced back-EMF of the winding can be calculated by the following equation,

$$E_{ph} = (4 \times f \times k_w \times N_{ph} \times B_g \times \tau_p \times l_s)/\sqrt{2}$$

(11)

l_s = the active length of stator winding

k_w = the stator winding factor

B_g = the air gap flux density

τ_p = the average pole pitch

The total length of the phase coil turn is calculated based on the following equation,

$$l_{Cu} = 2N_{ph}(l_s + (0.083p + 1.217)\tau_p + 0.02m)$$

(12)

N_{ph} = the number of coil turns per phase

The phase DC resistance is calculated based on the equation,

$$R_{ph,DC} = \left[l_{Cu}(1 + k_{Cu}(T - 20))\right]/(\sigma_{Cu} S_{Cu} a)$$

(13)

k_{Cu} = the temperature coefficient of copper resistivity

T = the average temperature of the coil

σ_{Cu} = the electric conductivity of the copper

S_{Cu} = the cross-sectional area of copper in one coil turn

For the AC current the resistance is larger than for the DC current because of the effects caused by the alternating current[7].

The phase resistance is further increased and may be approximated as,

$$R_{ph} \approx R_{ph,DC}\left[1 + (1/9)(y/\chi)^2 (d_w/\chi)^2\right]$$

(14)

y = the depth of the slot

d_w = the diameter of the single conductor

χ = the skin depth of the conductor in free space

The skin depth of the conductor in free space can be calculated by the following equation,

$$\chi = \sqrt{2/(\omega\mu\sigma_{Cu})}$$

(15)

ω = the angular frequency

Based on the calculated phase current and phase resistance, the copper losses in a stator winding can be calculated as,

$$P_{Cu} = mR_{ph}I_{ph}^2$$

(16)

m = the number of phases

I_{ph} = the RMS value of the phase current

In the analytical approach the axial-flux PM machine is subdivided into yoke and teeth parts and the iron losses are calculated as,

$$P_{Fe} = \left[k_{Fe,y} P_{1.0} G_y B_y{}^2 (f/50)^{1.5} + k_{Fe,t} P_{1.0} G_t B_t{}^2 (f/50)^{1.5} \right]$$

(17)

$k_{Fe,y}$ = the loss coefficient for the yoke

$k_{Fe,t}$ = the loss coefficient for the teeth

$P_{1.0}$ = the loss value of the steel grade at 50 Hz and at flux density of 1.0 T

G_y = the masses of the yoke

G_t = the masses of the teeth

B_y = the peak flux density value of the yoke

B_t = the peak flux density value of the teeth

The peak flux density value of tooth is defined as,

$$B_t = B_g \times (\tau_s / b_t)$$

(18)

b_t = the width of the tooth

The peak flux density of the yoke can be calculated by the following equation,

$$B_y = B_g \times \left[\tau_p / (\pi b_y) \right]$$

(19)

b_y = the height of the stator yoke

The stray load losses are often considered to be a fraction of the output power,

$$P_{str} = k_{str} P_{out}$$

(20)

k_{str} = the coefficient for stray load losses

The stray loss coefficient may to vary between 0.03 and 0.05 for machines rated up to 10kW [8].

The leakage inductance can be evaluated based on the leakage coefficients, which are slot leakage permeance coefficient λ_{slot}, end connection leakage permeance coefficient λ_{end}, differential leakage permeance coefficient λ_{dif}, tooth-tip leakage coefficient λ_{tt} [9].

Based on the calculated leakage coefficients the leakage inductance can be calculated by the following equation,

$$L_\sigma = 2\mu_0 \left[(N_{ph}^2 l_{eff}) / (pq) \right] \left[\lambda_{slot} + (l_{end} / l_{eff}) \lambda_{end} + \lambda_{dif} + \lambda_{tt} \right]$$

(21)

l_{end} = the average length of the end connection

l_{eff} = the effective length of stator stack

The electromagnetic torque for axial- flux permanent magnet machine can be calculated by the following equation,

$$T_d = (m/\sqrt{2}) \times 2p \times N_{ph} \times k_w \times \varphi_f \times I_{ph}$$

(22)

The magnetic flux per pole pitch can be calculated by the following equation,

$$\varphi_f = (1/8) \times \alpha_p \times (\pi/p) \times B_p \times D_{out}{}^2 \times (1 - K_d{}^2)$$

(23)

The output power of the machine can be calculated by the following equation,

$$P_{out} = mE_{ph} I_{ph} \cos\varphi$$

(24)

E_{ph} = the RMS Value of the phase voltage

I_{ph} = the phase current

The input power of AFPMSG for slotted stator can be calculated by the following equation,

$$P_{in} = P_{out} + P_{Cu} + P_{Fe} + P_{str}$$

(25)

The machine efficiency is obtained by using the input power and output power as,

$$\eta = \frac{P_{out}}{P_{in}}$$

(26)

D. Design Results for AFPMSG

The mechanical design parameters of the axial-flux permanent magnet synchronous generator consist of the two parts. They are the rotor part and the stator part. The mechanical design parameters for rotor are shown in Table II.

Table II. Mechanical Design Parameters for Rotor

Parameters	Units	Value
The outer diameter of machine	cm	52.8
The inner diameter of machine	cm	30.5
The outer radius of machine	cm	26.4
The inner radius of machine	cm	15.3
The average radius of machine	cm	20.9
The average pole pitch	cm	8.2
The length of PM	cm	1.3
The width of PM	cm	6
The air gap flux density	T	1.24
The peak value of air gap flux density	T	1.37

The mechanical design parameters of the AFPMSG for slotted stator are shown in Table III.

Table III. Mechanical Design Parameters for Stator

Parameters	Units	Value
The number of slot per pole per phase		1
The number of total slot		96
The number of coil turns per phase	turns	96
The number of coil per phase		32
The number of turns per coil	turns	3
The axial length of the stator	cm	3.8
The yoke of the stator	cm	1.7
The depth of slot	cm	1.05
The width of tooth	cm	1.82
The average slot pitch	cm	2.72
The width of slot	cm	0.9

The output results of the axial-flux permanent magnet synchronous generator for slotted stator are shown in Table IV.

Table IV. Electrical Design Results for AFPMSG

Parameters	Units	Value
The RMS value of the induced phase voltage	V	56
The phase current	A	14
The per phase stator resistance	Ω	0.109
The stator leakage inductance	mH	0.49
The copper losses	W	64.09
The iron losses	W	93.14
The stray load losses	W	80
The input power	kW	2.24
The output power	kW	2
The torque of the machine	Nm	112
The machine efficiency	%	89

IV. PERFORMANCE ANALYSIS OF AFPMSG

For accurately solving original problems containing partial differential equations or integral equations an effective computer program based on the finite element method (FEM) is a useful tool. At present, several commercial 2D/3D finite element packages are available and may be applied also to permanent magnet machine design[10].

With the 2D FEA modelling axial-flux machines is possible in a similar way as it is with the analytical computation, i.e. by using the average radius of the machine as a design plane. In this study, the performance of 2kW AFPMSG with slotted stator is calculated with 2D finite element analysis.

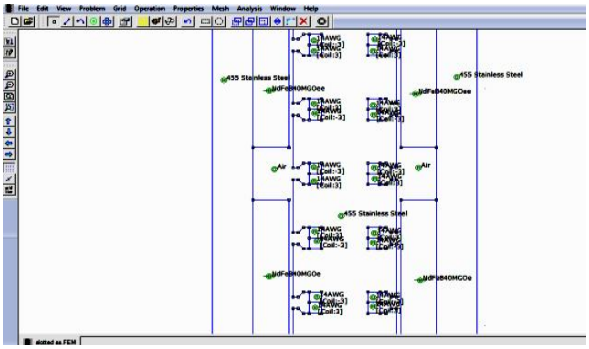


Fig. 4. Completed model running condition by NdFeB 40 MOGe

To run the FEA software, the first step is to draw the machine geometry with the calculated design parameters on the working plane. And then, material selection for each and every portion is made as shown in Fig. 4. The next step, mesh presentation is running condition which can be adjusted the mesh size defined in the properties of each material.

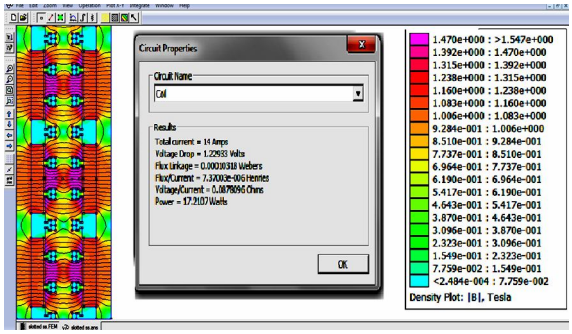


Fig. 5. The magnetic flux density for AFPMSG

Fig. 5 shows the magnetic flux density values for AFPMSG by using FEM software. After running, these model display FEM result output, flux density which can be plotted as a colour density plot.

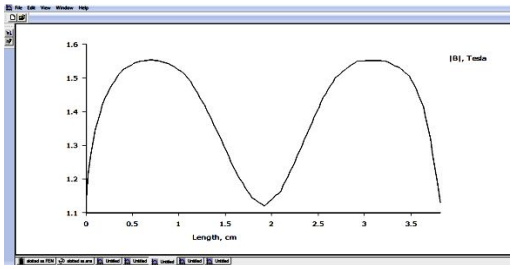


Fig. 6. The magnetic flux density plot for teeth and yoke

Fig. 6 illustrates the magnetic flux density plot for stator teeth and stator yoke by using the finite-element analysis. In this figure, the flux density in the teeth (which appears at 075 cm and the value is 1.55T) is slightly higher than the flux density in the stator yoke section (which appears at 0.4 cm and the value is 1.5T).

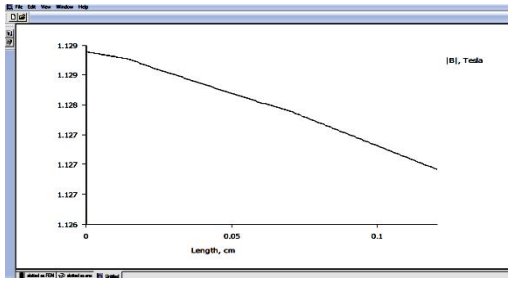


Fig. 7. The air gap flux density plot for AFPMSG

Fig. 7 is the air gap flux density plot for axial-flux permanent magnet synchronous generator by using the finite-element analysis.

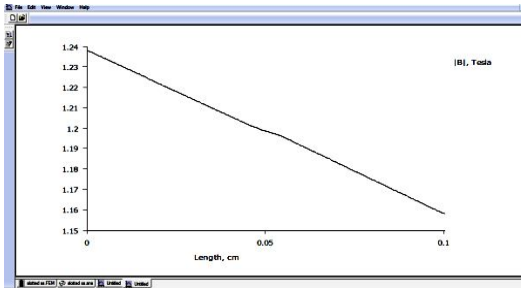


Fig. 8. The peak value of air gap flux density plot for AFPMSG

Fig. 8 is running result that is the peak value of air gap flux density plot for AFPMSG by using the finite-element analysis. In this figure, the peak value of air gap flux density is 1.238 T.

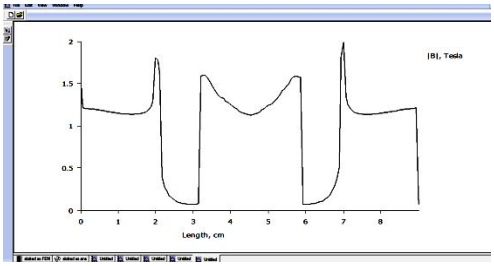


Fig. 9. The magnitude of magnetic flux density plot for one pole pairs

Fig. 9 shows the magnitude of magnetic flux density plot for one pole pairs of AFPMSG by using FEA software. In this figure, the flux density in the magnet will be higher than the air gap flux density and flux density in the stator section.

V. COMPARISON OF LOSSES AND EFFICIENCY

Table V shows the comparison of losses and efficiency between sizing equation based output and finite element analysis results for slotted stator of double-sided AFPMSG. According to the comparison results, it can be seen that the air-gap flux density is over estimated than the actual value in the sizing method and this leads to a higher losses in the machine. By applying the FEA method, the exact data of air-gap flux density is obtained and machine efficiency is recalculated by means of corrected data. Here, the efficiency of machine is higher than the theoretical sizing equation values. Finite element analysis leads to much more accurate magnetic fields solutions. Compare to the results i.e., the analytical result of copper losses, iron losses and the machine efficiency which is based on the initial assumed flux density data to the result getting from the FEA software.

Table V. Comparison of Losses and Efficiency between Sizing Equation and FEA Software

Specifications	Sizing Equation (AFPMSG)	2D FEA (AFPMSG)
Peak value of air gap flux density, T	1.37	1.238
The peak value of flux density for yoke, T	1.903	1.5
The peak value of flux density for teeth, T	1.85	1.55
Inductance, mH	0.49	0.00735
Resistance, Ω	0.109	0.088
Copper losses, W	64.09	51.744
Eddy current losses, W	93.14	60.21
Efficiency, %	89	91.3

CONCLUSION

The design and performance of double-sided axial-flux permanent magnet synchronous generator with slotted stator is mainly emphasized in this paper. Moreover, the finite element method was used to evaluate the accurate flux density in the generator components. The copper losses, iron losses and the efficiency values for AFPMSG are compared between analytical sizing equation and FEA software. In this paper, the air gap flux density from FEA software is lower than that of the initial assumed value. The yoke and teeth flux density values are lower that of the initial sizing equation. According to the FEA software the peak value of air gap flux density and the resistance are lower than the analytical sizing data. When the phase resistance is decreased for AFPMSG, it causes the copper losses also decrease. By reducing the yoke and teeth flux density are produced the iron losses also reduced. Because of the comparison results, the machine efficiency is higher than that of the analytical sizing equation. Therefore, it can be concluded that application of FEA can perform a great effort to get a more accurate machine designing process than using sizing equations only.

ACKNOWLEDGMENT

First of all, the author would like to express deep gratitude to Dr. Yan Aung Oo, Associate Processor, Electrical Power Engineering Department, Mandalay Technological University, for his close guidance, accomplished supervision, help, support and sharing ideas and experience during the research of paper.
Finally, the author would like to express her deepest great thank to her father and mother for noble support to her all times and their unique loving kindness to attain her destination without any trouble.

REFERENCES

[1] F. Libert, "Design, optimization and comparison of permanent magnet motors for a low-speed direct-driven mixer," Licentiate Thesis, Royal Institute of Technology, TRITA-ETS-2004-12, ISSN-1650-674x, Stockholm, 2004

[2] B.J. Chalmers, W.Wu and E. Spooner, "An axial-flux permanent-magnet generator for a gearless wind energy system", IEEE Trans. Energy Convers., Vol. 14, No. 2, pp. 251-257, 1999.

[3] Hanselman, D. C., 2003. Brushless Permanent Magnet Motor Design. New York: Elsevier Scientific Publishing Company, p. 330.

[4] P. Acarnly, J. Mecrow, J. S. Burdess, J. N. Fawchett, J. G. Kelly and P. G. Dicinson, "Design Principles for a Flywheel Energy Store for Road Vehicles", IEEE Trans. on Ind. Appl., vol. 32, no.6, pp. 1402-1407, Nov. 1996.

[5] K. Yamazaki, M. Shina, Y. Kanou, M. Miwa, and J. Hagiwara, "Effect of eddy current loss reduction by segmentation of magnets in synchronous motors; Difference

between interior and surface types," Magnetics, IEEE Transactions on, vol. 45, no. 10, pp. 4756–4759, 2009.

[6] A. Mahmoudi, H.W. Ping and N.A. Rahim, "A comparison between the TORUS and AFIR axial-flux PM machine using finite element analysis", Proc. IEEE Int. Electr. Mach. Drives Conf. – IEMDC 2011, pp. 242-247.

[7] Magnussen, et al., "Performance Evaluation of Permanent Magnet Synchronous Machines with Concentrated and Distributed Windings Including the Effect of Field Weakening," in International Conference on Power Electronic, Machines and Drives (PEMD 2004), 2004,pp. 679-685.

[8] Gieras, J.F., Wing, M., 1997. Permanent Magnet Motor Technology – Design and Applications. New York: Marcel Dekker Inc, p. 444.

[9] Ardresen EC, Keller R. Squrriel cage Induction Motor and Permanent Magnet Synchronous Motor. Symp on Power Electronic s, Electric Drives Conf. IEMDC'2001, Cambridge , MA, U.S.A., 2001, pp. 115-121.

[10] Caricchi, F., Crescimbini, F., Di Napoli, A., Santini, E., 1992. Optimum CAD-CAE Design Axial-flux Permanent Magnet Motors. In Proceedings of International Conference on Electrical Machines, ICEM'92, pp. 637-641.

★★★