Review in Transverse Flux Permanent Magnet Generator Design

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Abstract: Recently, Transverse Flux Permanent Magnet Generators (TFPMGs) have been proposed as a possible generator in direct drive variable speed wind turbines due to their unique merits. Generally, the quality of output power in these systems is lower than multi stage fixed speed systems, because of removing the gears, so it's important to design these kinds of generators with low ripple and lowest harmful harmonics and cogging torque that is one of the most important terms in increasing the quality of output power of generator. The objective of this paper is introducing a simple design method and optimization of high power TFPMG applied in vertical axis direct drive wind turbine system by lowest possible amplitude of cogging torque and highest possible power factor, efficiency and power density. In order to extract the output values of generator and sensitivity analysis for design and optimization, 3D-Finite element model, has been used. This method has high accuracy and gives us a better insight of generator performance and presents back EMF, cogging torque, flux density and FFT of this TFPMG. This study can help designers in design approach of such motors.

Keywords: Transverse Flux Permanent Magnet Generator, Direct Drive Wind Turbine, Cogging Torque, Vertical Axis Wind Turbine, TFPM.

1. Introduction

Using renewable energy resources specially wind power during last two decades has increased as worldwide, there are now over two hundred thousand wind turbines operating, with a total nameplate capacity of 282,482 MW as of end 2012 [1].

During this time, several wind turbine concepts have been proposed. There are three major topologies of wind turbine systems: fixed-speed wind generators with multistage gearbox, variable speed wind generators (with single-stage or multi-stage gearbox) and direct-drive wind generators [2,3].

Because of several advantages such as removing the gearbox, drive simplification, longevity, high reliability, weight reduction, maintenance cost reduction, higher aggregate efficiency, low level of vibration and noise of the drive train, simplified SCADA structure and better utilization of the available wind power, direct drive variable speed structures in wind power turbines are in attention. [3,4]

Vertical axis turbine systems have save several advantages such as: Insensitivity to wind direction and turbulence, Proper operation in unfavorable wind speeds and storms, facility in maintenance, noise reduction and high output power quality and removing the necklace box [5].

The most important part of these kinds of systems are permanent magnet type generators that have less weight and volume and less cooper and iron losses, more TPC, power factor and efficiency, less mechanical problems and more longevity than their rivals. [4,6,7]

Fig. 1 shows the topology of vertical axis wind turbine connected to a PM generator without gearbox [5,8,9].

Among all kinds of permanent magnet synchronous generator types, Transverse Flux Permanent Magnet Generators are the most top options for low speed systems and vertical axis gearless high power turbines because of low rotational speed and having low length and large diameter because of these merits [3, 4, 10-12]:

- Better cooling condition because of better heat distribution in stator
- Removing the armature reaction effect
- Low copper loss because of having lower end winding in concentrated winding
- Facility in maintenance
- Possibility to make with a very small pole pitch in

comparison with the radial and axial permanent magnet machine. So it can be design by low machine diameter

- High power and torque density (smaller active mass than the other machines to produce the same torque) and low weight because of having hollow rotor core
- Flexibility in geometry design with several kinds of structure
- Increasing the windings space without reducing the available space for the main flux
- Ability to provide a significant cost advantage in active material in comparison with Radial or Axial Flux Permanent magnet machines for small air-gap

Because of removing the gears, it's important to design these kinds of generators with low ripple and lowest harmful harmonics and cogging torque that is one of the most important terms in increasing the quality of output power of generator [5,13,14].

This paper has classified the TFPMGs structures, and introduced a simple design method and optimization of high power TFPMG applied in vertical axis direct drive wind turbine system by lowest possible amplitude of cogging torque and highest possible power factor, efficiency and power density.

For this purpose, a 3D-finite element model is implemented in order to simulate TFPM generator, (as these machines can be modeled and analyzed just in 3 dimension because of their topologies). This method has high level of accuracy and gives a better insight of generator performance.

Cogging torque in these machines is quite dependent to the geometry and volume of 2 I-Shaped PMs in each pole, the geometry of legs in U-Shaped core and airgap length. TFPMs can be designed by low airgap length for having

low leakage flux and high efficiency and power factor but the amplitude of cogging torque and its scheme can be variable and unsuitable.

Also this paper shows the diagram of cogging torque in different airgap lengths.

2. Structure and Configuration

TFPM machines can be classified in the categories below:

- U-shaped core, C-shaped core, E-shaped core and Z-shaped core. (Fig. 2) [3, 4, 12, 15,16]
- Single side, double side or multiple side core. (Fig. 3) [4,10]
- Inner PM or surface mounted PM structures. (Fig. 4) [4,10]
- Rayleigh or planar rotor structure. (Fig. 5) [4, 10, 17]
- Double or single piece stator structure. (Fig. 6) [4, 10, 12]
- Active or passive stator structure. (Fig. 7) [3, 4, 12]
- Axial or radial airgap structure. (Fig. 8) [4,10]
- Inner rotor or outer rotor topologies. (Fig. 9) [4, 16]
- Single turn or double turn winding per phase. (Fig. 10) [4, 16, 17]
- Single or triple structure. (Fig. 11) [4, 17, 18]

In addition to these classifications, compound structures with reluctance machines and flux switching can be considered as TFPM machines.

Transverse Flux Permanent Magnet Machines are generally single phase, so for building the 3-phase machine, three separated parts should be connected together, but it's possible for Z and E Shaped core topologies and the topologies with double winding per phase to build the 3 or more phases in just one part.
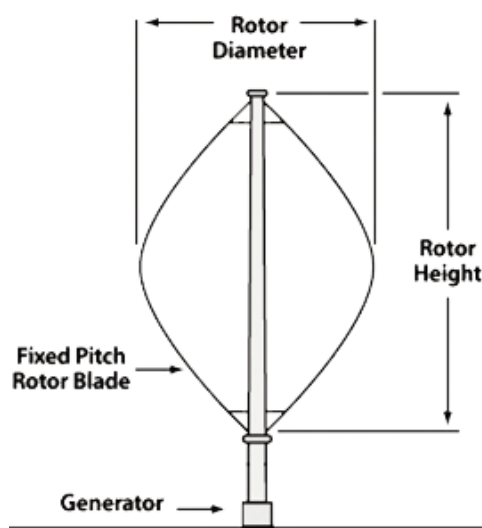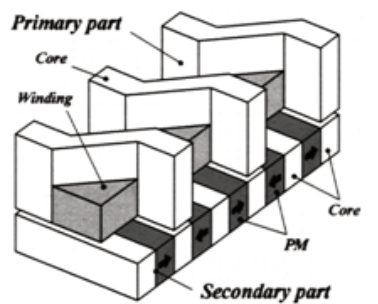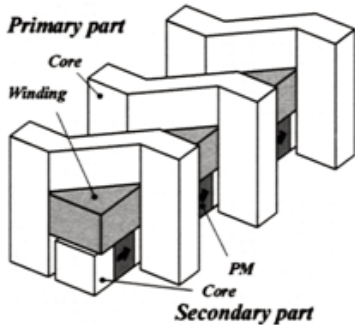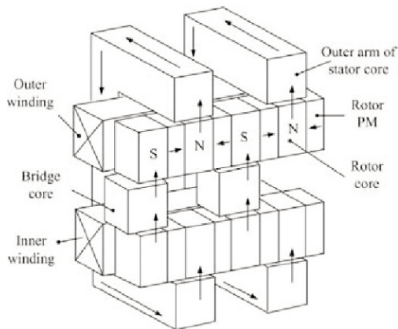

Fig. 1. Vertical axis direct drive wind turbine
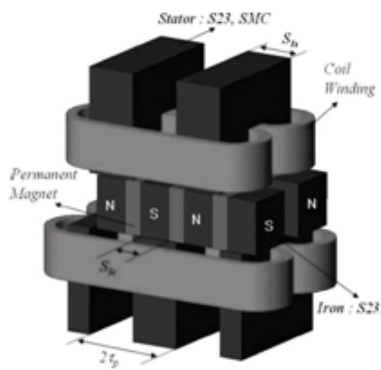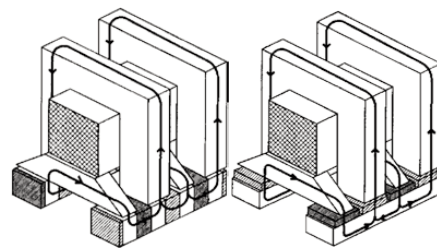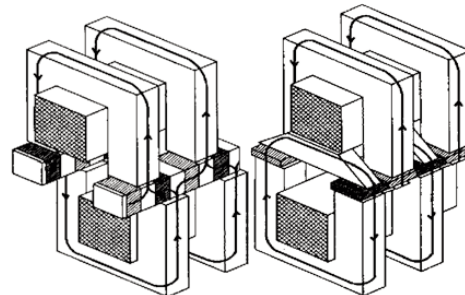
(a)

(b)

(c)

(d)

Fig. 2. Transverse Flux Permanent Magnet Machine Classification: (a) U-Shaped Core (stator structure is on the rotor structure) (b) C-Shaped Core (I-Shaped rotor structure is surrounded by Stator Structure) (c) E-Shaped core (d) Z-Shaped core. E and Z shaped cores are high cost and generally complicated to build.
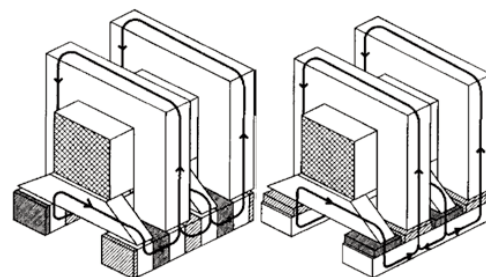

(a)

(b)

Fig. 3. Transverse Flux Permanent Magnet Machine (1 phase, 2 poles) (a) Single side structures (b) Double side structures.

(a)   (b)

Fig. 4. Transverse Flux Permanent Magnet Machine (1 phase, 2 poles), Difference between Inner PM or surface mounted PM structures. (a) Inner PM used in rotor structure (If the stator is simple these topologies need a bridge in stator structure but if the stator is claw shaped, no need to this additional structure). (b) Surface Mounted PM used in rotor structure (these topologies need a bridge in stator)
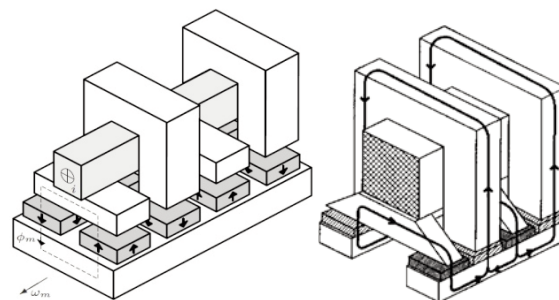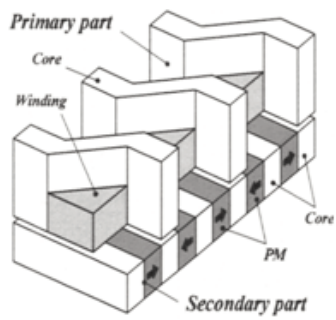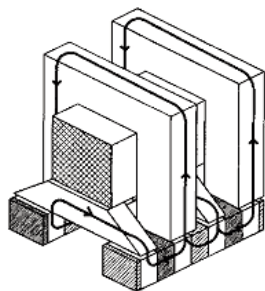

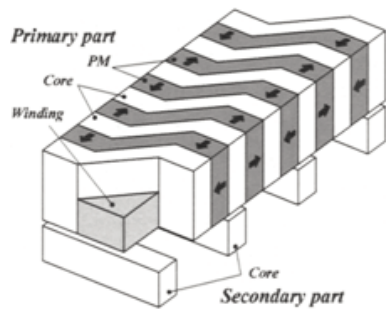**Fig. 5.** Transverse flux Permanent Magnet Machine, various rotor topologies: (a) Planar structure. (b) Rayleigh structure.

Fig. 6. Transverse flux Permanent Magnet Machine, various stator topologies: (a) Single piece stator structure (b) Double piece stator structure (with bridge).

Fig. 8. Transverse flux Permanent Magnet Machine, The difference between the direction of flux in airgap and the construction: (a) Radial airgap structure. (b) Axial or airgap structure.
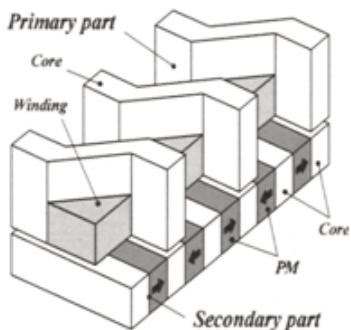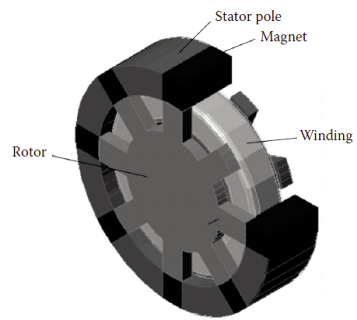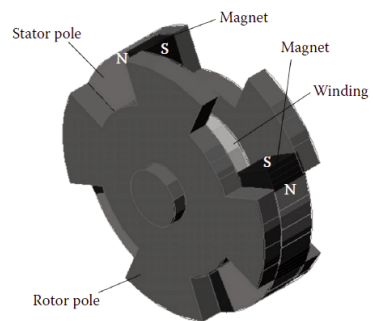

Fig. 7. Transverse flux Permanent Magnet Machine, various stator topologies: (a) Active stator structure. (b) Passive stator structure.
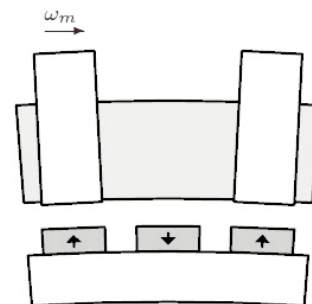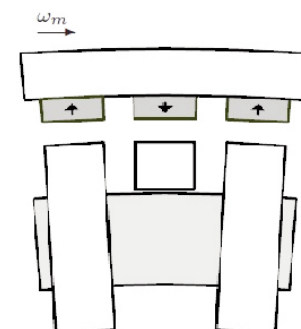

Fig. 9. Transverse flux Permanent Magnet Machine: (a) Inner rotor topology (b) Outer rotor topology.
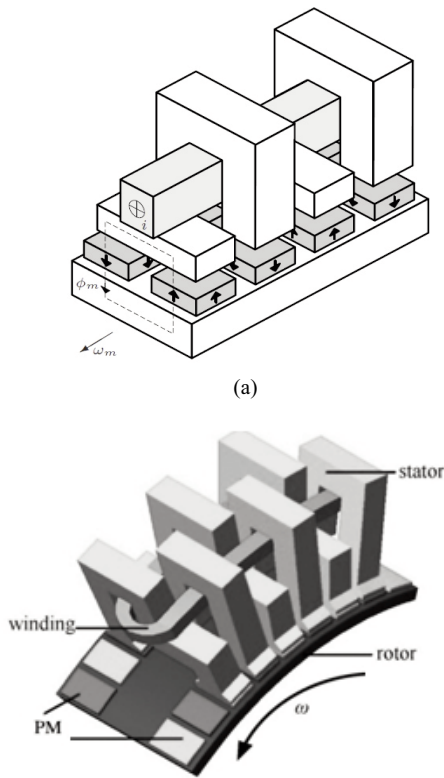
(a)

(a)

(b)

Fig. 10. U-Shaped core Transverse flux Permanent Magnet Machine: (a) Single turn winding per phase. (b) Double turn winding per phase
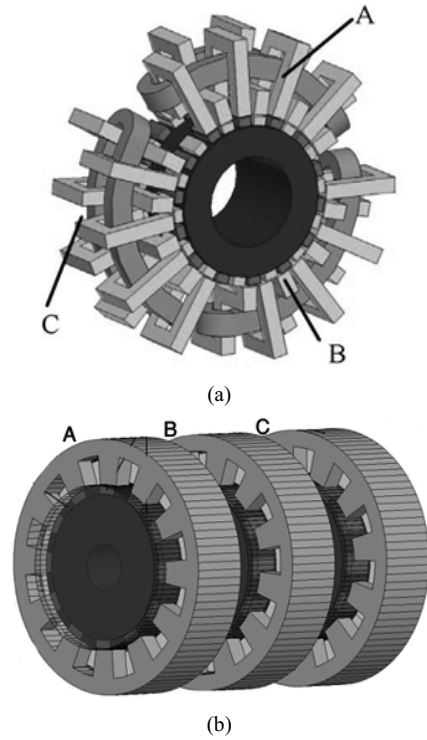
Fig. 11. The difference between single or regular triple topologies: (a) Single part for 3-Phase topology (b) Three parts for 3 phase (one part for each phase) structure.

Fig. 11 shows the difference between single or regular triple topologies. Also Fig. 12 shows two possible magnets and windings arrangement methods for connecting the 3 parts of machine (each phase) for building the 3 phase TFPM machine [4, 16, 18].

As it can be seen, the winding has a three times single phase structure. However, in the case when the flux paths are mixed (Fig. 12.c), the three-phase winding distribution is obtained naturally, as it is usual in the radial-flux machines with concentrated windings. These two possible windings will be referred to as separated and mixed windings, respectively [16].

3. Design Method

The aim of this paper is designing a 3-Phase, claw pole, U-Shaped, Passive Stator, Inner magnet TFPM generator shown in Fig.13. The generator features are: 13.5 MW (4.5 MW for each phase), 14.4 KV, 15 RPM, 75 pole pairs, 90 KN/m3 force density and 162000 ampere-turn.

Rated torque per phase:

$$T_n = \frac{P_n}{\Omega_n} = P_n \left/ \frac{2\pi n_n}{60} \right. = 2.865[MN] \quad (1)$$

By considering D/L ratio equal to 14 (Generator Dimension Ratio: k=14), the primary inner stator diameter is:

$$D_g = \sqrt[3]{\frac{2.T_n}{3.\pi.\dfrac{F_d}{k}.}} = 10.402[m] \quad (2)$$

So, Axial length of one phase is:

$$l_s = \frac{D_g}{k} = 0.746\ [m] \quad (3)$$

The pole pitch would be:

$$\tau_p = \frac{\pi.D_g}{p} = 0.218[m] \quad (4)$$

Also the primary airgap length is estimated by:

$$l_g = \frac{0.75D_g}{1000} = 7.8\ [mm] \quad (5)$$
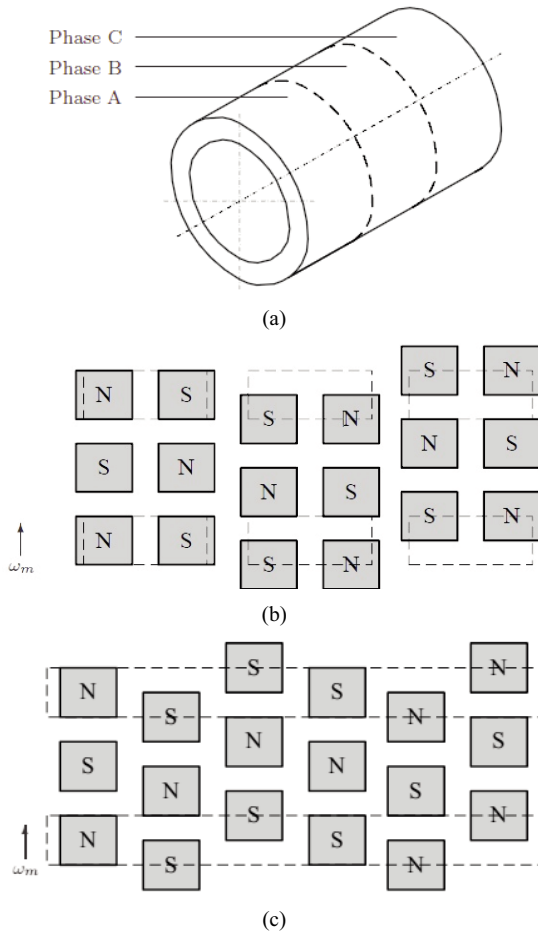
(a)

(b)

(c)

Fig. 12. Schematic representation of 3-Phase transverse flux permanent magnet machine, (Three parts for 3 phase structure, one part for each phase): (a) general view of the machine (b) Arrangement of winding in case of separated flux paths (c) Arrangement of windings in case of mixed flux paths.

For calculating the dimensions of the rotor, the magnets dimensions should be found firstly. The PM length of each pole could be estimated by:

$$l_m = 0.3 . \frac{\tau_p}{2} = 32.65 \, [mm] \tag{6}$$

Then, stator width in each pole would be:

$$b_{sp} = 0.8 . \frac{\tau_p}{2} = 87.1 \, [mm] \tag{7}$$

Rotor width in each pole would be:

$$b_{rp} = \frac{\tau_p}{2} - l_m = 76.35 \, [mm] \tag{8}$$
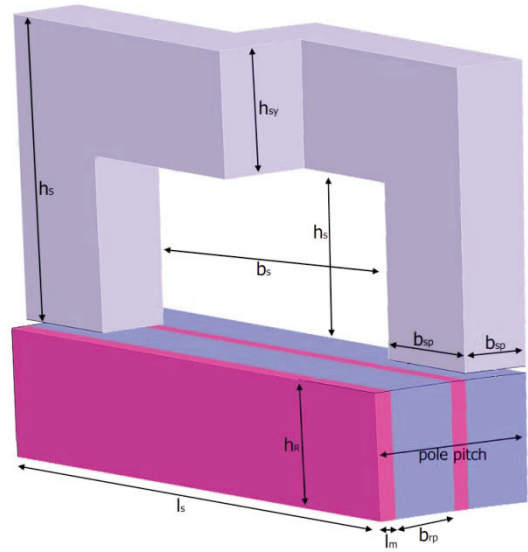
Fig. 13. Geometry dimension illustration 3-Phase, claw pole, U-Shaped, Passive Stator, Inner magnet TFPM generator.

By having 162000 ampere-turn and 8.33 kilo volt per phase and ideal power factor estimation for primary design, rated current would be:

$$I_n = \frac{P_n}{3.E} = 180 \, [A] \tag{9}$$

So, number of turns (conductors) per slot is:

$$N_{cs} = \frac{mmf}{I_n} = 900 \, [turns] \tag{10}$$

By considering 4 (Ampere/mm2) for current density, The cross section of all conductors per slot is:

$$A_{Cus} = \frac{N_{cs} \times I_n}{J_s} = 0.0405 \, [m^2] \tag{11}$$

The area of each slot by considering fill factor ratio = 0.5 would be:

$$A_s = \frac{A_{Cus}}{k_{sfill}} = 88200 \times 10^{-6} \, [m^2] \tag{12}$$

By considering stator slot height (hs) = 0.5*stator slot width (bs):

$$b_s = A_s / h_s = 420 \, [mm]$$
$$h_s = 210 \, [mm] \tag{13}$$

By considering maximum flux density equal to 0.8 Tesla (it can be considered up to 3 Tesla in regular U-Shaped core TFPMs with iron bridge, but it should be less than 1.5 in claw shaped inner PM topologies because of the direction of flux in their structures), the length of each pole in axial direction is:

$$l_{sp} = \frac{\sqrt{2} \times E}{(p/2).N_{cslot} \times B_{p\max} \times \dfrac{2 \times \pi \times n_n}{60} \times b_p} = 0.143 \, [m] \tag{14}$$

The stator and rotor yokes height would be:

$$h_R = h_{sy} \cong l_s = 0.143 \, [m] \tag{15}$$

It should be $h_s > h_{sy} + h_s$ in U-Shaped core TFPM generators [4,11], so the stator height would be 0.233 (m). So the average radius of winding is:

$$D_m = D_g + \frac{1}{2} h_s = l_{sp} = 5.306 \, [m] \tag{16}$$

The length of each conductor in circumferential direction would be:

$$L_{con} = 2\pi D_m = 33.34 \, [m] \tag{17}$$

By having 900 conductors, the cross section of each conductor is 45 mm². (rectangular conductor: 9*5 mm). The resistance of each phase by considering copper conductors (resistivity=1.7*10⁻⁸) is:

$$R = \rho \frac{L.N_{cs}}{A_{wire}} = 11.335 \, [\Omega] \tag{18}$$

Fig. 14 shows the magnetic characteristics diagram of soft magnetic material used in stator core: Initial Relative Permeability is equal to 6000, Saturation Magnetization is 1.6 Tesla and Knee Adjusting Coefficient is 0.3 [5,19]. Fig. 15 shows the magnetic characteristics diagram of PM used in rotor structure (Nd-Fe-B). For this reason a linear approximation has been used. Remanent Flux Density of
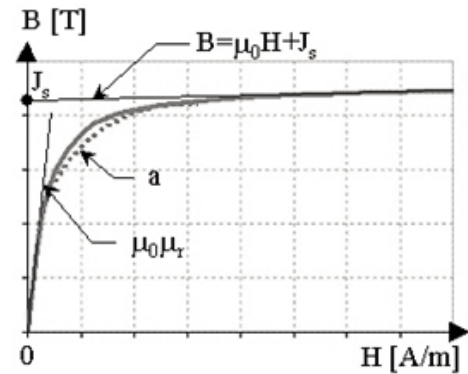

Fig. 14. Magnetic characteristics diagram of soft magnetic material used in stator core
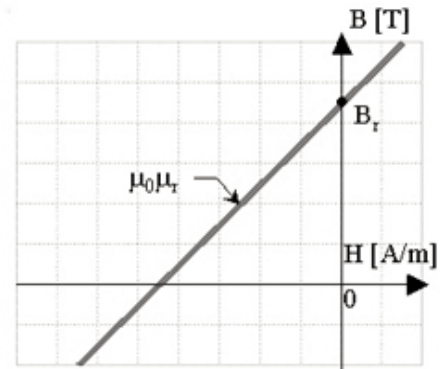
Fig. 15. Magnetic characteristics diagram of PM used in rotor structure

this PM is 1.1 Tesla and the Relative Permeability (μ_r) is 1.0446 [5,20].

After finding the primary dimension of the generator, by using Finite element simulation and analysis, the exact and optimum dimension of the generator could be found.

4. FEM Model

As it has been mentioned, a 3D-finite element model is implemented in order to simulate the proposed TFPM generator, These machines can be modeled and analyzed just in 3 dimension because of their topologies and the direction of flux in the structures [4,5]. This 3D model has high level of accuracy and gives a better insight of motor performance.

In order to have high level of accuracy the mesh diagram is designed manually, in this simulation node congestion is higher around the air gap and center of poles. The total number of nodes is about 103000 per pole per phase, that lead to high level of accuracy, meanwhile, for boundary condi-

(a)

(b)

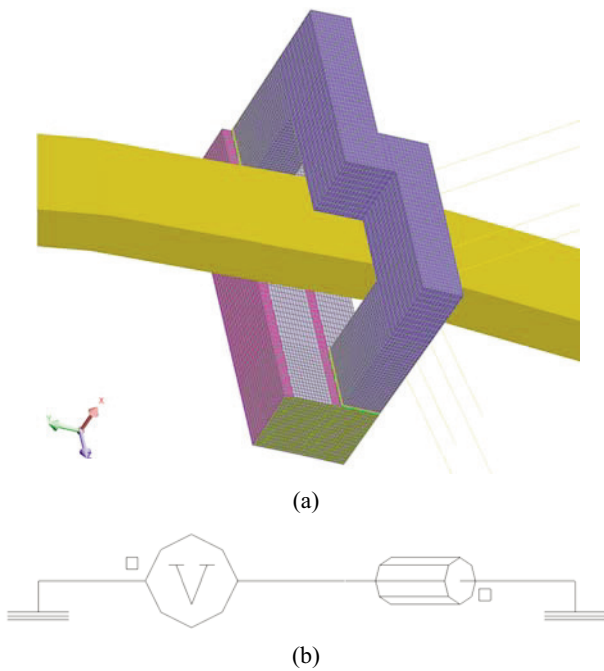**Fig. 16.** Circuit coupled model used in this study: (a) Meshed TFPM generator (one pole of one phase) and the its winding diagram (b) Circuit coupled model used in simulation for one phase.

Fig. 17. Mesh diagram of simulated machine (One pole of one phase).

tions, the homogenous dirichlet condition is adopted on the infinite box that encompasses the generator, according to this assumption on infinite box flux distribution is zero.

This simulation is based on circuit coupled model using the phase voltage as input quantity, Fig. 16 shows the circuit coupled model that is used in this study.

It must be noted that one pole of one phase is analyzed because of the magnetic periodicity of the machine. As seen in Fig. 17, nodes congestion becomes higher near the air gap in order to accurate simulation. Based on FEM model the simulation of the generator is done and output characteristics are extracted.

In order to choose an accurate volume of permanent magnet regarding to magnetic circuit that PM material is in, inner diameter of the stator and the airgap length an iteration method has been used which has illustrated with a flowchart in Fig. 18. From the finite element analysis, the cogging torque and back EMF waveform in each phase can be obtained and checked with amplitude of input voltage in each phase and this procedure continues until the convergence criterion will be satisfied.

The main achievements of this iteration method are:

• Finding the accurate volume of permanent magnet regarding to magnetic circuit that PM material is in, inner diameter of the stator and the airgap length.
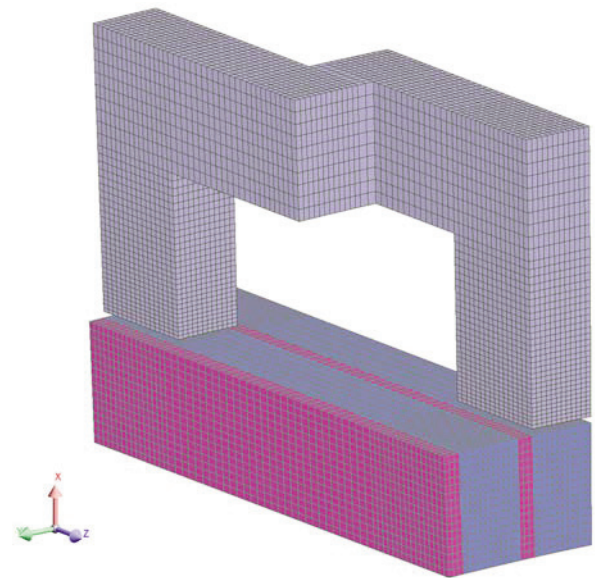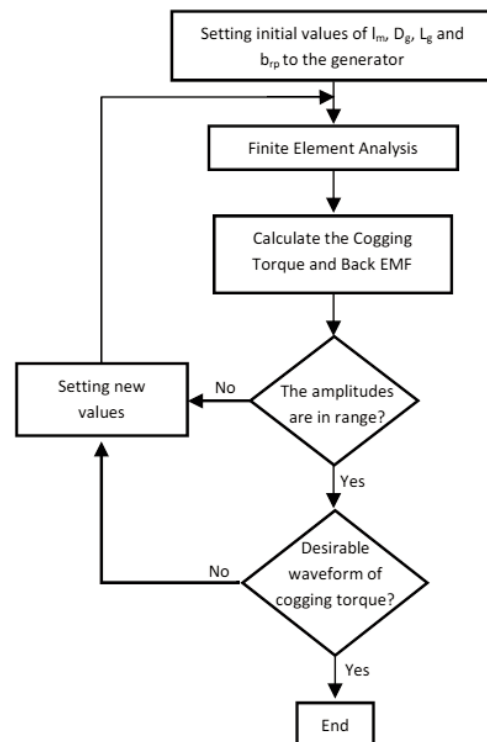

Fig. 18. Iteration method flowchart implemented to obtaining optimum dimension of TFPM generator.

- Reaching to cogging torque less than 5% of rated torque and suitable waveform for cogging torque.

5. Simulation Results and Discussion

Based on the above respects, finite element simulation has been done for the 3-Phase, claw pole, U-Shaped, Passive Stator, Inner magnet TFPM generator. It must be noted that one pole of one phase is analyzed because of the magnetic periodicity of the motor.

Optimal dimension parameters of the TFPM generator and the output quantities of the machine are given in Table 1. As it can be observed from the simulation results, this procedure is so effective to find the optimal dimensions of PM, airgap length and the inner diameter of the stator.
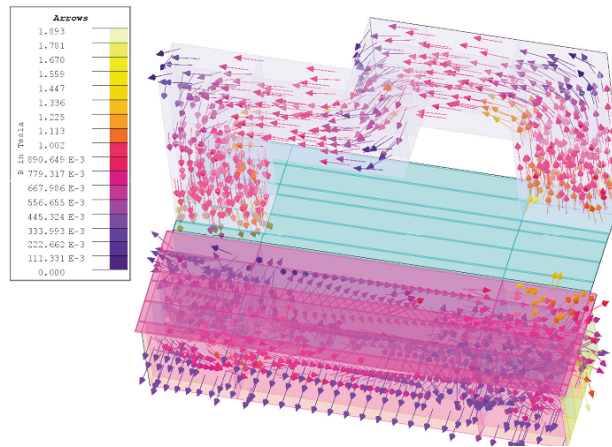
(a)
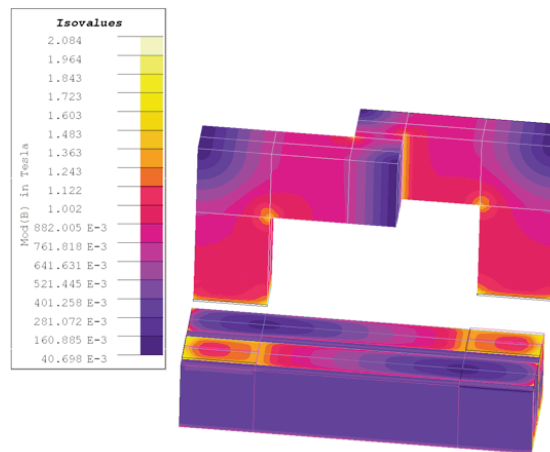
(b)

(c)

Fig. 19. Flux lines and flux density of one pole – one phase of TFPM generator (a) Distribution of flux and flux lines (b) Isovalues diagram of flux density (c) Isovalues diagram of flux density from another view.

Table 1. Optimal dimension parameters of the TFPM generator and the output quantities of machine Parameter

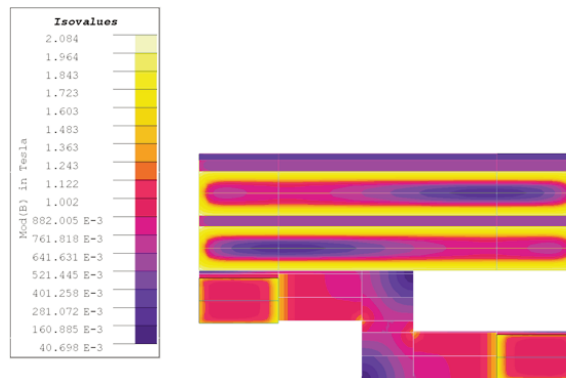| Parameter	Value	Parameter	Value
Angular velocity (Ω_n)	1.5708 [rad/s]	Rated current (I_n)	180 [A]
Ampere-Turn (AT)	162000	Number of conductors per slot (N_{cs})	900
Force density (F_d)	90 [KN/m3]	Current density (J_s)	4 [Ampere/mm2]
Number of poles (p)	150 (75 pole pairs)	Cross section of all conductors per slot (A_{cus})	0.0405 [m2]
Rated speed (n_n)	15 [R.P.M]	Slot fill factor ratio (K_{sfill})	0.5
Phase voltage (E)	8.33 [KV]	Slot area (A_s)	88200×10^{-6}
Line voltage (V_L)	14.4 [KV]	Slot height (h_s)	210 [mm]
Rated power per phase (P_n)	4.5 [MW]	Slot width (b_s)	420 [mm]
Rated torque per phase (T_n)	2.865 [MN]	Maximum flux density (B_{pmax})	1.5 [Tesla]
Generator Dimension Ratio k=(D/L)	14	Length of each pole in axial direction (l_{sp})	0.143 [m]
Inner rotor radius (R_g)	5.1728 [m]	Stator yokes height (h_{sy})	0.143 [m]
Axial length of one phase (l_s)	0.746 [m]	Rotor yokes height (h_{ry})	0.143 [m]
Pole pitch (τ_p)	0.108 [m]	Average radius of winding (D_m)	5.306 [m]
Airgap length (l_g)	28.2 [mm]	Length of each conductor in circumferential direction (L_{con})	33.34 [m]
PM length of each pole (l_m)	21.75 [mm]	Conductors dimension (each wire)	9*5 [mm]
Stator width in each pole (b_{sp})	87.1 [mm]	Resistivity of copper (ρ)	1.7×10^{-8}
Rotor width in each pole (b_{rp})	76.35 [mm]	Total resistance of each phase (R)	11.335 [Ω]
Torque ripple percent	≈5%	Cogging torque amplitude (T_{cog})	150 [KN]
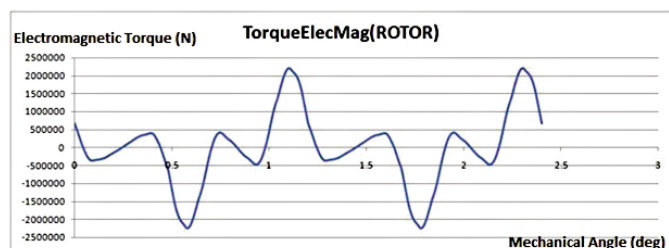
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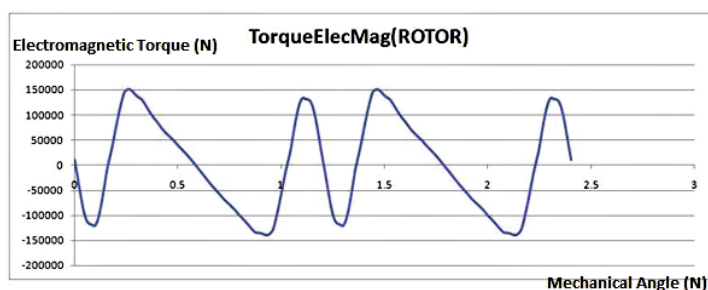
(b)

Fig. 20. Cogging torque of simulated TFPM generator: (a) By primary values (b) By optimal values obtained from the flowchart.
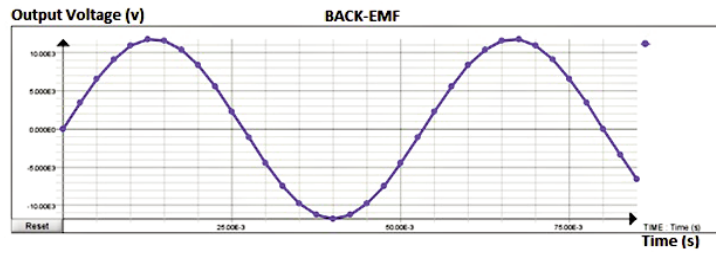
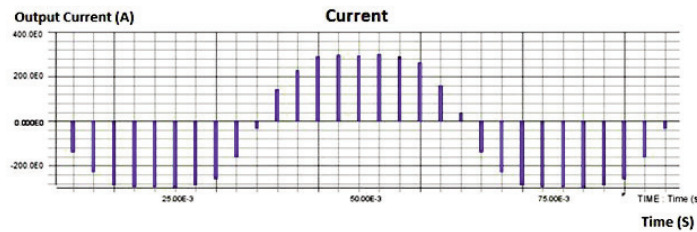**Fig. 21.** Extracted back EMF for one phase of simulated TFPM generator.

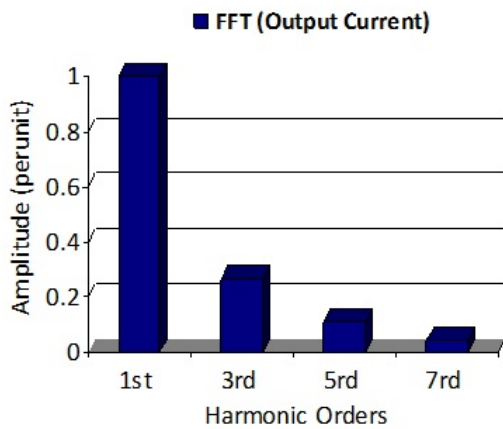**Fig. 22.** The output current per phase of simulated TFPM generator

Fig. 23. Harmonic Spectrum of generator's output current.

Fig. 19-a shows the distribution of flux at rated power. This figure shows the accuracy of assignment of PMs and the correctness of the simulation. Fig. 19-b and c show the isovalues diagram of flux density at rated power. As it can be seen from this figure, flux density at the airgap space and the iron core of the rotor under the stator legs are the highest amount.
Fig. 20 shows the cogging torque at 3 steps of flowchart process. Fig. 20-a shows the cogging torque by primary

values: l_g=7.8 [mm]; R_g=5193.2 [mm]; l_m=32.65 [mm]; b_{rp}=76.35 [mm].
Fig. 20-b shows the cogging torque by optimal values obtained from the flowchart: l_g=28.2 [mm]; R_g=5172.8 [mm]; l_m=21.75 [mm]; b_{rp}=87.1 [mm], as it can be observed from this figures, cogging torque is less than 5% of rated torque.
The extracted back EMF for one phase has been shown in Fig. 21. It's obvious that amplitude of back EMF per phase is equal to the amplitude of input voltage per phase. The output current per phase of simulated TFPM generator by considering the extracted back EMF has been shown is Fig. 22. Also, the harmonic behavior of the output current is shown in Fig. 23. The results show verity of the simulation and accuracy of the proposed method for TFPM generator design.

7. Conclusion

In this paper a simple design method and optimization was introduced for a high power TFPMG applied in vertical axis direct drive wind turbine system by lowest possible amplitude of cogging torque and highest possible power factor, efficiency and power density. In order to extract the output values of generator and sensitivity analysis for improvement of design and optimization, a 3D-Finite element model was used. This method has high accuracy and gives us a better insight of generator performance and presents back EMF, cogging torque, flux density and FFT of this TFPMG. This study can help designers in design

approach of such motors.

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