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Comprehensive Parametric Study for Design Improvement of a Low-Speed AFPMSG for Small Scale Wind-Turbine

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Abstract- *In this paper, comprehensive parametric analyses are performed to improve the design parameters of an axial-flux permanent magnet synchronous generator (AFPMSG) used in a small-scale wind-power applications. The sensitivity analysis provides the condition for maximum efficiency, minimum weight and minimum cost. Based on the results of parametric study, a computer-aided design (CAD) procedure is proposed to design of an AFPM machine. Matching between the generator side and turbine characteristics as well as the mechanical constraints is taken into account in the design algorithm. A 2.5 kW AFPMSG with two parallel connected stators and surface mounted permanent magnets on its rotor back-iron is designed using the developed program, and then three dimensional finite-element analyses are carried out to validate the design procedure.*

Keyword: Axial flux permanent magnet machines; Direct drive permanent magnet generators; Wind turbine; Finite element (FE) analysis.

1. INTRODUCTION

Recently, wind energy is playing a vital role in electric power generation, especially in rural and remote areas where electricity is not easily reachable in Ref. [1]. Apart from the environment benefits of wind power plants, the network connection cost can be eliminated and the transmission and distribution losses can be avoided. Therefore, the selection and design of an efficient wind generator is an important research topic nowadays.

Recent studies shows that axial flux (AF) machines are become attractive and competitive alternatives for Radial Flux (RF) machines especially for small scale wind turbines. Furthermore, high energy permanent magnet (PM) materials have resulted in rapid development of PM machines [2-6].

The elimination of the gearbox between the generator and turbine in low-speed direct-drive applications reduces the overall size of the system and improves the system reliability. However, to produce electricity within a frequency range of 10 to 60 Hz at low speeds, the generator must be designed with a large number of pole pairs.

Permanent magnet machines have been studied intensively for small-scale wind power applications at rated power below than 10 kW. In [7-8], a direct-drive low-speed permanent magnet generator with radial flux (RF) and axial flux (AF) structure was proposed, respectively. Various topologies of PM generators used in direct-drive wind turbines have been intensively investigated for performance comparison. The considered criteria for comparison include the torque density, the machine volume and weight, and the machine active material cost [9]-[11]. Accordingly, double sided AFPM machine offer the high level of torque density, especially with high number of pole pairs. This structure also gives the advantages of adjustable air-gap and balanced rotor-stator normal attractive forces. However, these studies lack the theoretical information about different practical requirements and there is no attempt to improving the aforementioned criteria.

The diameter ratio (λ) has a significant influence on the machine characteristics and has been defined as the major design parameter in several studies. Most of AFPM designers have selected an optimal value of 0.58 to maximize the output power [12, 13]. In Ref. [14], λ=0.63 have been chosen to maximize the torque-to-weight ratio. Hung et al. [15, 16] have introduced different optimal λ for some machine topologies with various electrical and magnetic loading, material properties, and frequency based on general sizing approach. In Ref. [17], a detailed parametric analysis with reduced free design parameters has been carried

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out for an AFPM wind generator. However, the machine manufacturing cost was not taken into account.

In almost all of the aforementioned studies reported on the topic, practical and mechanical constraints have not been considered in the design process. Therefore, the design parameters may not be reliable or feasible in practice. A detailed design approach for low-speed AFPM machines has been proposed by Parviainen in Ref. [18] where the mechanical constraints were taken into account. However, the design was not optimized. Genetic Algorithm (GA) approach has been implemented in Ref. [19] to optimize a variable speed AFPM machine. Even though, the practical restrictions are considered in the design process, only active material cost was considered as the optimization objective.

In this paper, suitable parametric analyses are performed to obtain the proper values for major design parameters. The most proper values obtained from sensitivity analysis are used in a computer-aided design program. The design validity is verified by 3-D finite element analysis.

2. SIZING EQUATIONS OF AFPM MACHINES

The main dimensions of an AFPM machine for a given output power P_{out} can be determined as:

$$P_{\mathrm{out}} = \frac{\pi}{2}\eta k_{\mathrm{p}} k_{\mathrm{i}} k_{\mathrm{e}} \hat{B}_{\mathrm{agap}} A \frac{\omega}{p}(1-\lambda^2)(1+\lambda)D_{\mathrm{out}}^3 \tag{1}$$

where A and $\hat{B}_{\mathrm{agap}}$ are the electrical loading and the maximum air-gap flux density produced by the permanent magnets, respectively. η is the machine efficiency. ω, p and D_{out} are the angular frequency, the number of pole pairs and the stator external diameter, respectively. The quantities k_{p}, k_{e}, and k_{i}, are the electrical power waveform factor, the EMF factor, and the current waveform factor, respectively [17-18]. The details on how to design an AFPM machine is not the key concern of this study and it can be found in [19-20] which have been published by author *et al.* previously. The main focus of this study is to provide the condition to improve the design of an AFPM machine from the efficiency, cost, and weight point of views. This comprehensive parametric study would be very useful for machine designers to define the design parameters regarding their own design objectives.

The total active material mas and total cost of active material can be defined by:

$$m_{\mathrm{act,total}} = m_{\mathrm{cu}} + m_{\mathrm{fe}} + m_{\mathrm{pm}} \tag{2}$$

$$\wp_{\mathrm{act,total}} = \wp_{\mathrm{cu}} m_{\mathrm{cu}} + \wp_{\mathrm{fe}} m_{\mathrm{fe}} + \wp_{\mathrm{pm}} m_{\mathrm{pm}} \tag{3}$$

where m_{cu}, $\wp_{\mathrm{cu}}$, m_{fe}, $\wp_{\mathrm{fe}}$, m_{pm}, $\wp_{\mathrm{pm}}$ are the mas and price of copper wires, electrical steel (scraps are not included) and permanent magnet materials, respectively.

3. GENERAL DESIGN CONSIDERATIONS

3.1. Electromagnetic Design Considerations

Comprehensive knowledge of machine design and theory, modelling approaches and experience are required to accurate design of an electrical machine. Proper selection of general parameters necessitates some considerations in design process of AFPM machines. The number of pole pairs should be determined based on operating speed and acceptable frequency range. For direct-drive low-speed applications, the machine should be designed with high number of poles. It must be noted that the practical and mechanical restrictions should be taken into account. For example, high number of poles leads to narrow and thereby deep slots. Consequently, slot leakage is increased and slot fill factor is decreased. Besides, the machine performance is deteriorated if the number of slots per pole per phase is reduced.

Allowable level of flux density at different parts of the machine has the main role in determination of the specific magnetic loading. It should be determined in such a way that the saturation in narrow parts of the machine especially in the slot openings is avoided. Since the copper loss is the dominating loss component of the machine in low-speed applications, high enough air-gap flux density is preferred to decrease the needed copper and thereby size and weight of the machine. This can be realized by modern NdFeB magnets. However, expensive magnets lead to increased cost.

In contrast to specific magnetic loading, the lower value of specific electric loading as well as current density is preferred to achieve a desired efficiency. Higher values can be used with better cooling system. Generally, specific electric loading below than 50 kA/m and current density between (3-5) mm2 can be chosen for small-scale totally enclosed machines.

3.2. Practical Restrictions and Mechanical Constraints

In addition to electromagnetic design of an AFPMSG, the special constrains given by the wind turbine manufacturer must be taken into account. Matching between axial flux machine and wind turbine characteristics requires some general information. In addition to information about rated wind speed and rated turbine power, the wind Weibull curve of the site is needed to select the machine operating speed range to maximize the annual electric power generation. Then, turbine radius can be determined for optimized operation in the rated condition. For a given turbine power rating and its radius, the maximum diameter of the generator can be estimated.

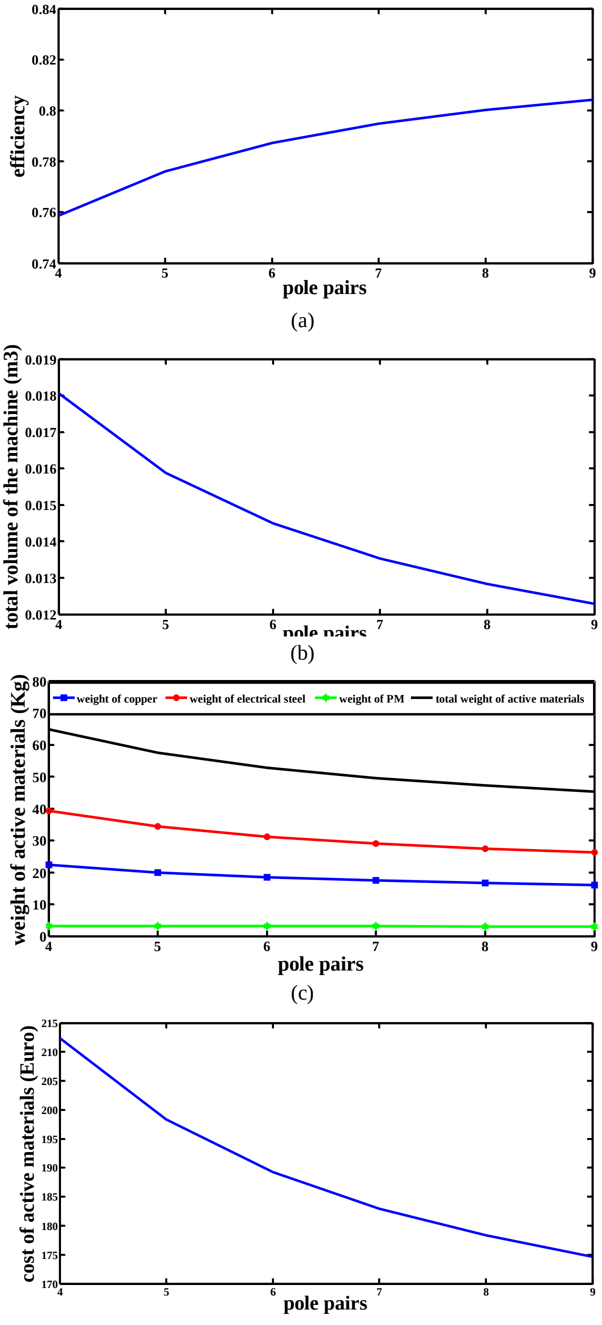
In addition to practical requirements, much attention should be paid to mechanical constraints. For example, stator yoke thickness as well as width of the stator teeth in inner radius of the stator stack may be very thin if they are determined only according allowable magnetic loading of the machine. From the mechanical point of view, a minimum thickness of the stator yoke and a certain value for teeth width is required especially for small-scale AFPM machines. This consequently influences the determination of pole and slots numbers. Besides, the thickness of the rotor back iron should be determined to be able to resist in front of the attractive forces between the stator and rotor without excessive deflection and vibration.

4. PARAMETRIC ANALYSIS

Suitable parametric analyses are carried out in this section to improve the design of AFPM machines taking the general design considerations into account. The results of these studies may be very useful for manufacturer to be able to optimize the machine design for high performance characteristics and minimum size and cost.

A 2.5-kW, 150-rpm AFPMSG is considered and a study is provided to find out the effect of the design variables on the desired criteria. The considered design variables are the pole numbers, diameter ratio, specific electric loading and current density where the criteria are the machine efficiency, the total volume and weight of the machine and as well as the cost of the active materials.

Fig. 1 shows the variation of the mentioned criteria as a function of pole pair numbers. As it can be seen from Fig. 1a, the efficiency of the machine is increased with the pole numbers. For higher number of poles, the length of the end turns becomes shorter. Therefore, winding resistance is reduced which consequently leads to efficiency increase. Other mentioned criteria exhibit the similar variation with increasing the pole numbers. As it is clear from Figs. 1b, 1c and 1d, minimum volume, weight and cost for the AFPM machine is achieved by using a large number of poles. This is mainly due to the reduction of stator yoke thickness and the length of coil overhangs, as the number of poles increases.



(a)

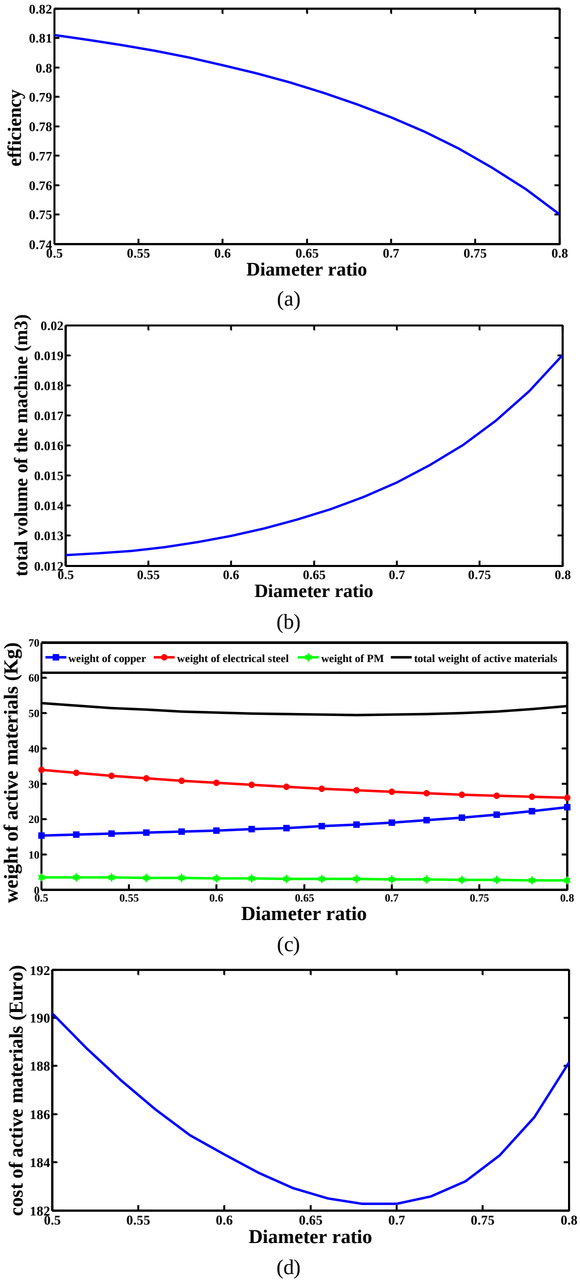
(b)

(c)

(d)

Fig. 1. Effect of AFPMSG pole numbers on (a): efficiency; (b) volume of the machine; (c) weight of active materials and (d) cost of active materials.

Fig. 2 shows the variation of mentioned criteria as a function of diameter ratio (λ). As it is clear, the efficiency of the machine decreases with an increase in diameter ratio. This is due to an increase in length of the end turns and thereby copper losses which is the dominating loss component for low-speed machines. The total volume of the machine increases as the diameter ratio and therefore outer diameter of the machine increase. Although the weight of PM materials and iron core decrease with increasing λ due to a reduction on the length of the stator stack, but the weight of copper increases with diameter ratio. In fact, any increase in λ results in an increase of the outer diameter, and thereby increasing the length of end turns. Therefore, there exists an optimal value for λ with minimum weight of the machine. Cost of active materials exhibit the same behavior as a function of λ.



(a)

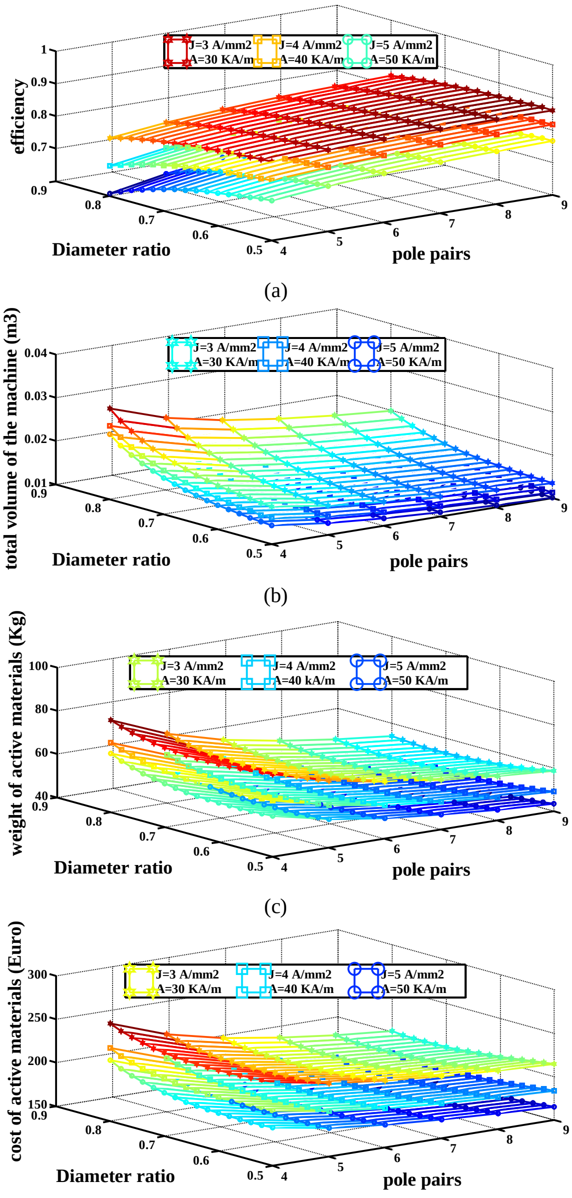
(b)

(c)

(d)

Fig. 2. Effect of the diameter ratio of AFPMSG on (a): efficiency; (b) volume of the machine; (c) weight of active materials and (d) cost of active materials.

Finally, as demonstrated in Fig. 3, higher value of specific electric loading and current density lead to decrease in total volume, weight and cost of the machine. On the other hand, because of increase in the copper requirements with high value of A and J, it gives low efficiency.



(a)

(b)

(c)

(d)

Fig. 3. Effect of the electric loading and current density of AFPMSG on (a): efficiency; (b) volume of the machine; (c) weight of active materials and (d) cost of active materials.

As a summary, the following remarks and statements may be done:

- The high number of poles is preferred for all mentioned criteria especially at low-speed applications.
- There is an optimum value for λ to achieve the minimum weight and cost with acceptable volume and efficiency.
- An average value of specific electric loading and current density is advisable for small machine with acceptable efficiency and at the same time allowable weight, size and cost.

In addition, the geometric restrictions of the small-scale AFPM machines in turn raise a restriction on the selection of the pole numbers. In the case of small-scale

AFPM machines, particularly with low diameter ratio, a high number of poles lead to a week and impractical tooth width at the inner radii.

Using the results of parametric analysis and considering the mechanical constraints, the following parameters are selected as a good tradeoff between the mentioned criteria and mechanical requirements.

$$p = 7, \quad \lambda = 0.67, \quad J = 4\frac{\mathrm{A}}{\mathrm{mm}^2}, \; A = 40\,\mathrm{kA/m}$$

5. IMPROVED DESIGN AND FE ANALYSIS OF AFPMSG

5.1. Improved CAD Program of the Machine

A computer-aided design program using the results of parametric analysis, defined in previous sections, is utilized to design improvement of an AFPMSG. Design procedure is illustrated as a flowchart in Fig. 4. As can be seen from the flowchart, firstly the electromagnetic design is obtained using the sizing equations described in section 2 and the results of the parametric analysis. Then, the matching between wind turbine and generator geometry as well as mechanical restrictions is checked. While both electromagnetic and practical requirements are not fulfilled, the design is renewed with a less amount of flux density. The machine efficiency is computed after losses calculations.

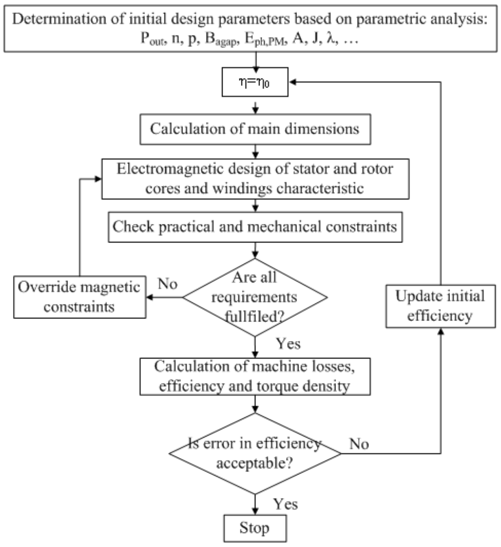


Fig. 4. Improved design procedure of small-scale direct-drive AFPMSG.

The machine losses include two main components: copper losses, and iron losses. It must be noted that, in low speed applications, copper losses are the most dominating part of the losses. Therefore, accurate estimation of the phase resistance is very important. Since the copper resistance depends on the wire temperature, the winding temperature should be known. Lumped parameter thermal model developed by author *et al.* in Ref. [21] is used to predict the temperature at windings. Afterwards, the phase resistance is calculated as follows:

$$R_{\mathrm{ph}} = k_{\mathrm{ac}}\frac{l_{\mathrm{cu}}\left(1+k_{\mathrm{cu}}\left(T-20\right)\right)}{\sigma_{\mathrm{cu}}S_{\mathrm{cu}}a} \tag{4}$$

where l_{cu} is the total length of phase coil. k_{ac} is a coefficient to take the skin and proximity effect into account [22]. T is the winding temperature in °C. k_{cu} is the temperature coefficient of copper resistivity ($k_{\mathrm{cu}} = 3.8\times10^{-3}$ 1/°C). σ_{cu} is the copper electric conductivity at 20 °C . S_{cu} is the cross-sectional area of the copper in one coil turn and a is the number of parallel branches. The copper losses of the machine is then calculated as

$$P_{\mathrm{cu}} = mR_{\mathrm{ph}}I_{\mathrm{ph}}^2 \tag{5}$$

where m is the number of phases and I_{ph} is the RMS value of the phase current.

An accurate estimation of the iron losses is a difficult task. It is affected by the material properties, the nature of the flux variation, and even by the manufacturing process of the laminations. Therefore, there are some uncertainties in the iron losses calculation. However, for low-speed machines in which the iron losses are considerably smaller than copper losses, this inaccuracy cannot cause a remarkable error. In this paper, the iron losses are subdivided into hysteresis losses, eddy current losses, and anomalous excess losses. Accordingly, the iron losses per unit volume are calculated as [23]

$$P_{\mathrm{Fe}} = k_{\mathrm{hys}}\hat{B}^2 f + \pi^2\frac{\sigma_{Fe}d^2}{6}\hat{B}^2 f^2 + 8.67k_{\mathrm{ex}}\hat{B}^{1.5}f^{1.5} \tag{6}$$

where d and σ_{Fe} are the thickness and electric conductivity of the laminations, respectively. $\hat{B}$ and f are the maximum flux density and frequency in the laminations. k_{hys} and k_{ex} are the hysteresis loss and excess loss coefficients, respectively which are determined based on the loss curves provided by the steel manufacturers. Mechanical losses and stay losses are also included in the machine efficiency calculation according to [24].

As shown in Fig. 5, the designed machine using the developed program is an AFPM machine with one rotor sandwiched between two parallel connected stators. The main geometrical dimensions of the machine are illustrated in Fig 6. The design parameters are given in table 1.

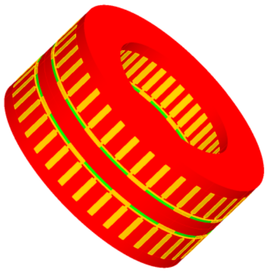
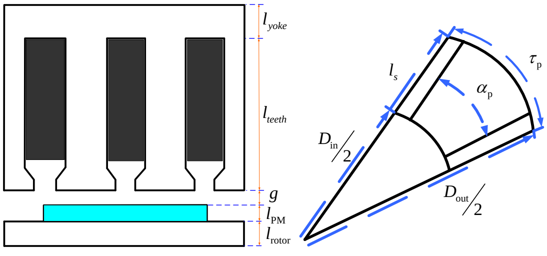


Fig. 5. Reference AFPM machine.



(a) (b)

Fig. 6. Definition of the main geometrical dimension of AFPM machine; a) axial view, b) radial view.

Table 1. Improved design results of AFPMSG obtained from developed program

Design data	Value
Rated output power at speed n=150 rpm, P_{out}	2.5 Kw
Rated voltage at speed n=150 rpm, n	211 V
Number of pole pairs, p	7
Number of stator slots, s	42
Physical air-gap length, g	1.5 mm
Number of coil turns in series per phase, N_{ph}	638
Stator outer diameter, D_{out}	337 mm
Diameter ratio, λ	0.67
Axial height of PM, l_{PM}	4 mm
Thickness of the stator yoke, l_{yoke}	15.3 mm
Height of the teeth, l_{teeth}	20.8 mm
Thickness of the rotor disk, l_{rotor}	19.6 mm
Total weight of active materials	49.43 Kg
Total volume of the machine	0.0141 m^3
Cost of active materials	182.35 Euros
Torque density	11308 N/m^2

5.2. Numerical Modelling of AFPMSG

3-D finite element analysis is required for accurate modelling of an axial flux generator regarding its inherently 3D geometry. Fig. 7 shows the FE model of the considered machine. Proper boundary conditions are defined to reduce the model size. Dirichlet boundary condition above the stator yoke and normal magnetic fields, tangent electric fields at bottom of the model is defined. Therefore, only one pole pitch and one stator and half of a rotor back iron is modelled considering the periodicity and axial symmetry in the machine structure.

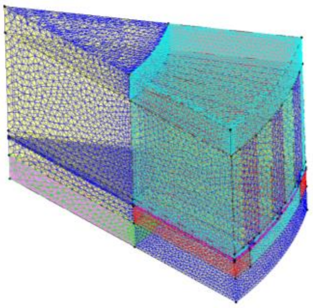


Fig.7. FE model of AFPMG

The magnetic vector potential *A* and electric potential *V* are employed in the conduction area and only *A* in the non-conduction area. From Maxwell equations, a system of equations for the vector and scalar potentials (*A*, *φ*) is obtained, which, for the region of conductors can be written as follows:

$$\vec{j} = -\frac{1}{\mu_0}\nabla^2\vec{A} = -\sigma\left(\nabla\varphi - \vec{v}\times\nabla\times\vec{A}\right) \tag{7}$$

$$\nabla\bullet\vec{j} = \nabla\bullet\left(\sigma\left(\nabla\varphi - \vec{v}\times\nabla\vec{A}\right)\right) = 0 \tag{8}$$

In the non-conducting area, where the current density $\vec{j} = 0$, equation (7) is expresses as:

$$\nabla^2\vec{A} = 0 \tag{9}$$

The results of FE analysis are given in table 2. As it is clear from data, there is a good agreement between design requirements and FE analysis.

Table 2. Results of FE method for studied AFPMSG

Parameters	CAD results	FE results
Maximum air-gap flux density (T)	0.817	0.808
Maximum flux density in stator teeth (T)	1.72	1.7
Maximum flux density in stator yoke (T)	1.38	1.32

6. CONCLUSION

A comprehensive parametric analysis was carried out to design of an axial flux permanent magnet generator used in low-speed small-scale wind turbine. Sensitivity analysis is performed to obtain the most appropriate design parameters from the machine efficiency, weight, volume and cost point of views. It can be concluded that, there exist an optimum value for λ to achieve the minimum weight and cost with acceptable volume and efficiency. Besides, the high number of poles is preferred for improved design of the machine, but the mechanical constraints restrict the selection of pole numbers. In addition to parametric study, a small-scale AFPM machine was designed with the developed CAD program using the results of the parametric study. Matching between the generator and turbine as well as the practical constraints was taken into account in the design algorithm. The analytical design was validated using the three dimensional finite element analyses.

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