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Characterization of Axial Flux Permanent Magnet Generator Under Various Geometric Parameters for Improved Performance

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ABSTRACT

An improved design of an axial flux permanent magnet machine is obtained using finite element method and sensitivity analyses. A 9-phase axial flux permanent magnet machine with one-rotor-two-stators configuration equipped with concentrated winding is investigated and condition for minimum cogging torque and voltage harmonics is deduced. Owing to three dimensional structure of axial flux permanent magnet machines, 3-D finite element model is used to model and analysis of the generator performance characteristics. Sensitivity of the machine is evaluated respect to variation of its geometric parameters.

Keywords: Axial flux, FEM, Cogging torque

1. INTRODUCTION

Greater availability and remarkably improved properties of high energy permanent magnet (PM) materials such as NdFeB, make these materials very suitable to be used in electric motor and generators, especially for wind energy conversion systems [1-3]. In most applications direct drive wind turbines are preferred to wind turbines equipped with gearbox [4]. This is due to the fact that, the reduced size of the overall system can be achieved by the elimination of the intermediate gearbox. Consequently, lower installation and maintenance costs, lower noise and faster response to the wind fluctuations and load variation can be obtained. However, a direct drive system must operate at low speeds and the generator must be designed with high number of poles. Owing to disk structure of surface mounted AFPM machines, it is relatively simple to design and manufacture of the machine with high number of poles [5].

A comparison between various PM generator topologies shows that the highest torque density can be achieved with double-sided AFPM machines, especially if the machine is designed with high number of poles [6]-[8]. Optimizing the machine structure to achieve the desired requirements is one of the main focuses for several studies over the last few decades [9],[10]. In several studies, the ratio of inner diameter to the outer diameter is the major design parameter [11]-[12]. In [12], the influence of stator structure on the electromechanical parameters of TORUS-type brushless dc motors has been studied. Optimal design of direct-driven PM wind generator for maximum annual energy production has been proposed in [13]. Rostami *et al.* [14] have proposed a computer-aided design procedure based on Genetic algorithm to achieve minimum

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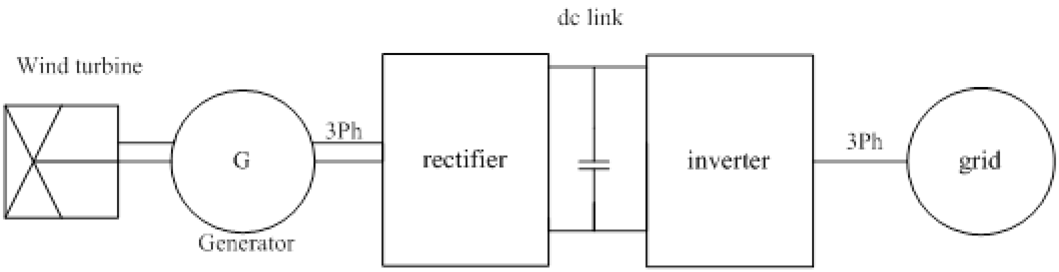


Fig.1 general schematic of wind system

active material cost for a variable speed AFPM generator with electromagnetic and mechanical constraints taken into account. A parametric analysis with reduced number of free design parameters for an AFPM machine with concentrated winding have been presented in [15].

Recently, several studies have concentrated their interest to design the AFPM machines with concentrated winding especially, at low speed direct drive applications [16]-[18]. Considering the power losses, it must be noted that the effect of iron losses is moderate as the pole pairs number increases. Therefore, at low speed AFPM machines, the copper losses are the dominating part of the losses which is mainly dependent on the length of the end-windings [5]. Compared to normal overlapping winding, shorter end-windings in the radial direction can be obtained on both the inner radius and outer radius of the stator core with concentrated winding.

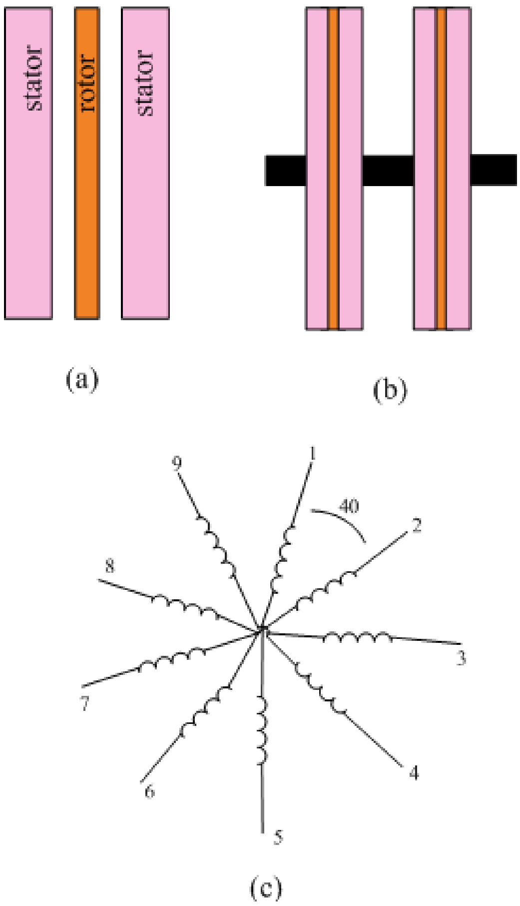


Fig.2 (a) generator structure. (b) multi-stack structure, (c) winding configuration.

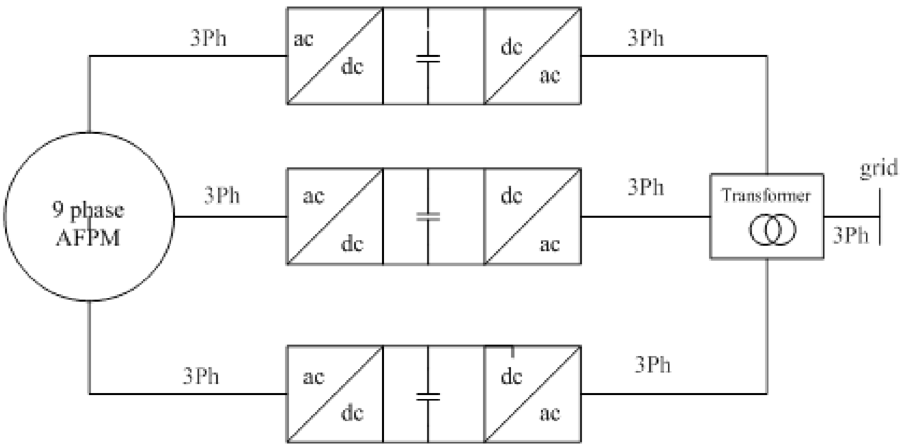


Fig.3 nine phase system configuration

Therefore, the machine efficiency and torque density are improved. Furthermore, with using concentrated winding enough free space between the shaft and the stator core can be obtained. Thus, end windings can be properly arranged even in the case of low diameter ratio which in practice, it may be very difficult or even impossible, especially in small scale AF machines with normal lap winding [5]. Besides, concentrated winding gives other advantages such as an easier design and manufacturing of the machine with high number of poles witch may not be feasible using the distributed windings [15]. The drawback, however, is the lower output torque due to a lower winding factor in concentrated coil machines. Recent studies, however, show that concentrated coil PM machines with high pole numbers can have high winding factors and good output torque [19]-[21].

In this paper a 9-phase AFPM machine with concentrated stator winding to operate in small scale wind power application as a generator is investigated. Although concentrated winding has low-order harmonics, but these harmonics can not affect on machines with more than 6 phases. Also poly phased machines have the advantage of modularity, with quick result for the fabrication process, transportation and maintenance [23]. The effects of the geometric parameters on the performance characteristics of the machine are studied using 3-D FEM and sensitivity analyses.

2. GENERAL DESIGN CONSIDERATION

2.1. 9-phase AFPM machine

General schematic of wind system is illustrated in Fig. 1. Wind turbine is connected to a generator and the generator is connected to grid through a back-to-back converter. As it can be seen from Fig. 2, the studied machine is a 9-phase double-sided AFPM machine with two parallel connected stators and one rotor disk.

High power machines can be designed with multi-stack structures. 9-phases are arranged as a triple-star configuration where the windings are uniformly distributed. Each star is supplied via a 3-phase back-to-back converter and the converters are parallel connected via the dc-bus or via the primary circuit of the transformer, as it is clear in Fig. 3. Compared to normally used 3-phase systems, less voltage ripple can be achieved in 9-phase system and consequently, a smaller capacitor is required which is very important especially, in high power applications. Required dc-link voltage level can be decreased and the reliability of the system is strongly increased using smaller dc capacitors.

As it is illustrated in Fig. 4, the investigated AFPM machine is a 9-phase, two-stator-one-rotor configuration with nine slots on each stator stack and 10 PMs on both sides of the rotor. The main parameters of the consideration machine is according to the machine of reference [10]. These parameters are listed in Table I. Concentrated winding is used and each coil is wound around a tooth. A layout of such a winding is illustrated in Fig. 5. By using open slots, the coils can be manufactured beforehand and just installed around the teeth, which will result in low price in realizing the winding. However, it must be cared the fixing of the coil around the tooth because of the lack of the tooth tip. Since short end-winding decreases the overall external diameter of the Rotor disk, the overall space required by the machine reduces [1]. material is construction steel S232JR and trapezoidal shape NdFeB permanent magnets are mounted on the surface of the rotor disk.

Table.1 main parameters of the nine phase axial flux machine

Nominal torque [N.m]	40
Nominal speed [rpm]	200
Number of phases	9
Number of poles	10
Outer diameter [mm]	250
Inner diameter [mm]	150
Stator thickness [mm]	35
Slots height [mm]	35
Rotor thickness [mm]	30
Number of turns per coil	747
Air-gap thickness [mm]	4
Magnet thickness [mm]	10

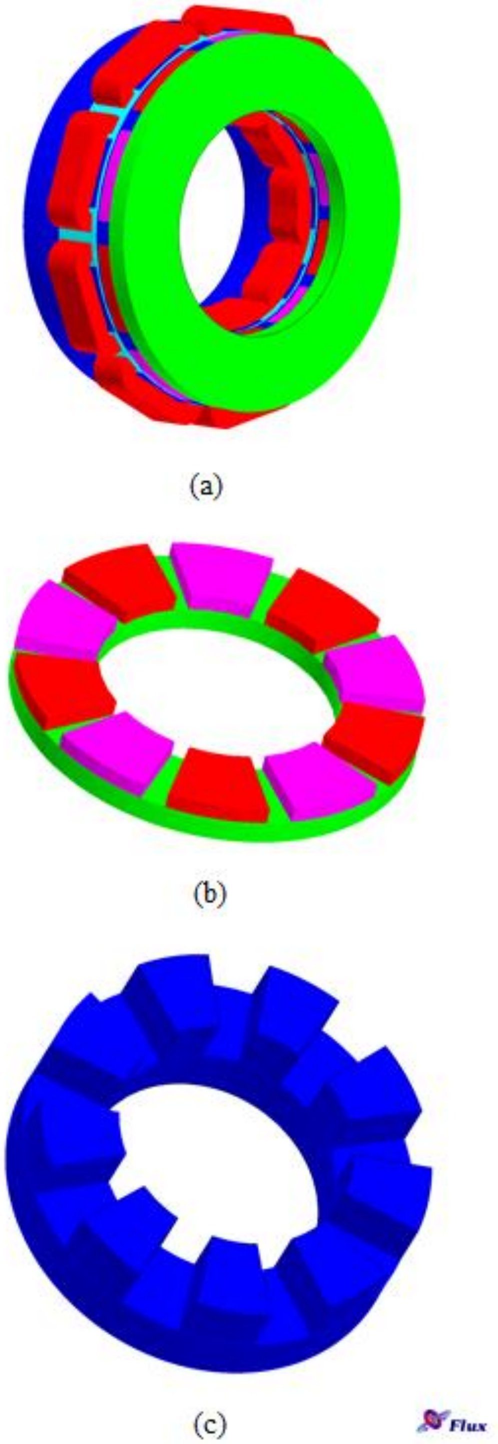


Fig.4 (a) half generator. (b) half rotor. (c) one stator

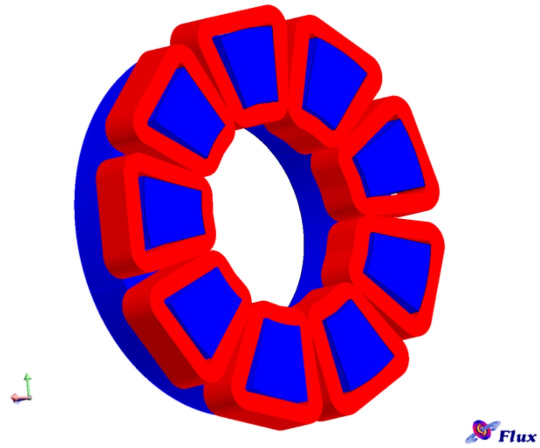


Fig.5 9-phase concentrated winding

The stator core material is a fully processed electrical steel sheet M600-50A and is designed with nine rectangular open slots. The winding of the same phase placed on different stators can be connected in series or in parallel.

2.2. Electromagnetic Design Considerations

For accurate design of a machine, the electromagnetic as well as the practical criteria must be considered which requires the use of the machine principles, the design knowledge as well as the experience. In AFPM machines the number of pole pairs should be determined based on the operating rotational speed of the machine and acceptable range of the frequency. High number of poles is preferred in direct drive wind turbine applications. However, the practical and also economical limitations must be taken into account.

Specific magnetic loading and allowable flux density in different parts of the machine must be determined regarding the material properties used in the machine structure.
To reduce the amount of needed copper as well as the size and the mass of the machine, the air-gap flux density must be high enough in direct drive applications in order to reach high efficiency and less wind turbine tower size and cost.

Modern NdFeB magnets are technically the best choice due to their high energy product and remanent flux density. The ratio between the PM height and air gap physical length (h_m/g) mainly influences the PM working efficiency [22]. It should be chosen to be high enough in order to ensure a desirable air gap magnetization level and to limit the load reaction influence and the related p.u reactance [5]. However, due to relatively high PM cost, h_m should be limited as much as possible.

Finally, the amount of specific electric loading as well as current density of the machine depends on the employed cooling system and desired efficiency.

2.3. Practical Design Considerations

Obtained parameters from analytical and numerical design methods of electric machines may not be feasible and reliable without sufficient consideration of mechanical constraints. Some practical limitations for design and manufacture of an AFPM machine must be taken into account [5], [14]. If the number of poles is high in AFPM machines, the required thickness of stator yoke, rotor disk and width of the stator teeth are often determined by the mechanical aspects. This is due to the fact that, in AFPM machine with high number of poles, the stator yoke may be very thin if its thickness is calculated according to the allowed magnetic loading. Moreover, for AF machines the width of the teeth is a function of the stator radius so, the slots and teeth structure has to be designed such that a certain thickness for the teeth remains on the inner radius of the stator. Furthermore, due to electromagnetic forces acting in the axial direction of the machine, rotor disk thickness of an AF machine must be determine such that it can resist these forces without excessive deflection. The air gap physical length is determined based on required magnetic flux density level at the air gap and the tolerances allowed for the manufacturing of stators and rotors.

3. FINITE ELEMENT METHOD

3.1. FEM Model of 9-phase AFPM Machine With Concentrated Winding

From the modeling point of view, an AFPM machine inherently is a 3-D structure. Therefore, it is necessary the use of 3-D FEM software to take into account the actual 3D structure of the machine and achieve an acceptable accuracy. Actual electromagnetic behavior, leakage fluxes as well as the end-winding inductances of the machine can be evaluated using the 3D model, which may be very difficult to be considered otherwise. Considering the accuracy of computation, proper mesh size must be applied to different parts of the model. A dense mesh pattern is required in air gap region. However, for AFPM machines with concentrated winding the number of the volume elements tends to be large which in turn increase the computation time. In most studies related to AFPM machines, the analytical design method or the 2-D FEM analysis is usually performed on the average radius of the machine to decrease the model creation and computation time at the expense of lower accuracy [5].

Due to the concentrated winding, it cannot be modeled only one pole pitch of the machine in the FEM model where, periodicity can be used in the case of lap winding. Therefore, whole machine poles must include to the FEM model. Due to symmetrical structure on the machine around z axis, it is just enough to model the half geometry (half of a rotor and one stator) of the machine. Fig.4 shows one stator and a half-rotor.

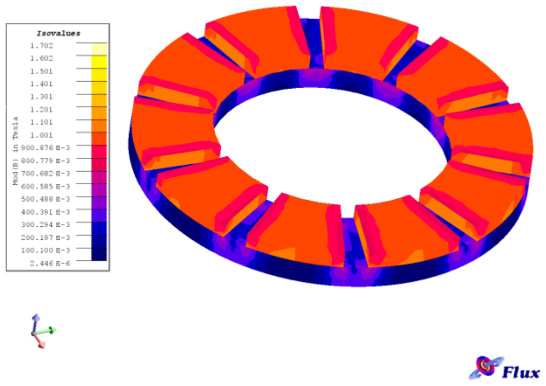
3.2. Analysis of the machine model using FEM

Using the electromagnetic and mechanical considerations given in previous sections an AFPM machine is considered and sensitivity analyses using the results of FEM are carried out to achieve better performance characteristics. Machine 3-D model is generated and solved in scalar model that is a general model proposed for 3-D applications.

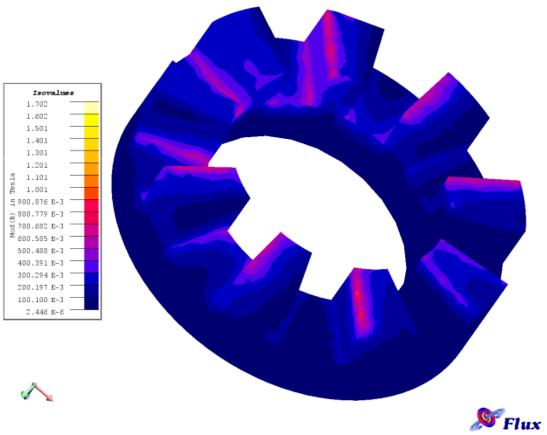
In order to evaluate the air gap flux density distribution and the cogging torque produced by the considered machine, a set of magneto-static problems are solved at different electrical angles. Furthermore, the machine is solved as a 3-D transient magnetic problem at no-load condition to determine the no-load induced EMF. The magnet pole-arc-to-pole-pitch (magnet pitch) is chosen as 0.7 and the slot pitch is 0.55.

Flux density distribution at different parts of the machine structure as well as the air gap flux density waveform is illustrated in Fig. 6 and fig.7.

The cogging torque of the machine is shown in Fig. 8. As it is can be seen, the produced cogging torque amplitude is about %3.14 of rated torque value.



(a)



(b)

Fig.6 flux density distribution at different parts of the machine. (a) rotor (b) stator

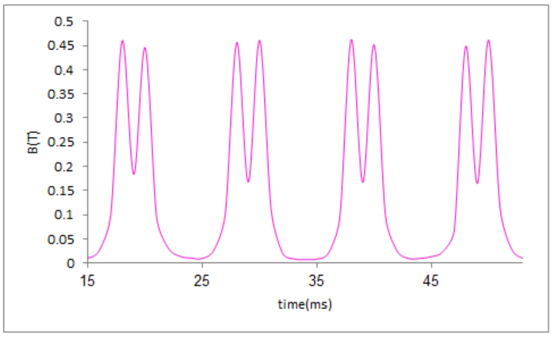


Fig.7 air gap flux density

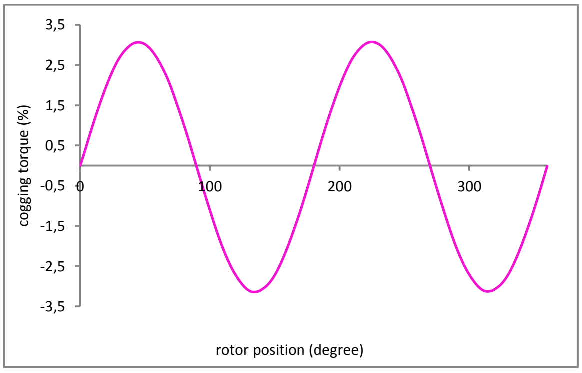


Fig.8 electromagnetic torque

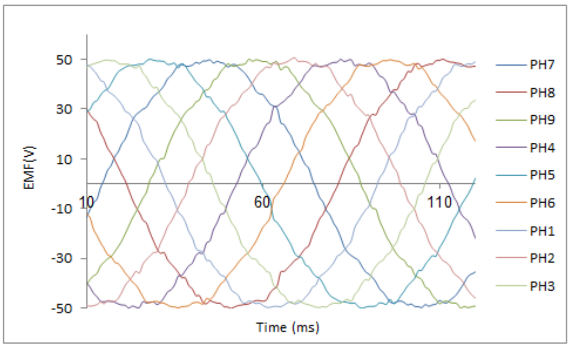


Fig.9 nine-phase no-load EMF

Furthermore, the induced phase voltage at no-load condition at nominal speed is illustrated in Fig. 9.
The windings of the same phase in two stators are connected in series. FFT analysis shows that the resulting no-load phase EMF has a 0.35% third harmonic.

4. SENSITIVITY ANALYSIS

4.1. Cogging Torque

Assessing the torque performance of electric machines is an important task during the design procedure. Not only the amount of the produced torque density, but also the torque ripple must be considered. The main sources of torque ripple in electric machines are : a) cogging; b) pulse width modulated (PWM) current harmonics; c) non ideal back-electromotive force (EMF) waveforms; d) phase commutation events; and e) dc-link voltage pulsation and inverter dead-time [12]. At high speeds, torque ripple is usually filtered out by the system inertia. However, at low speeds, torque ripple may result in an unacceptable speed variation and acoustic noise.

This paper is concerned only with the sensitivity analysis of the cogging torque using 3-D FEM results. In AFPM machines, the cogging torque occurs from the interaction between air gap permeance harmonics due to stator slotting and magneto motive force (MMF) harmonics due to the permanent magnets [5]. A variety of techniques have been proposed in order to reduce the cogging torque in radial flux PM machines [12], such as displacing and shaping the magnets [5], employing a fractional number of slots per pole [5], etc. Some of the aforementioned techniques can be applied directly to AFPM machines. In this paper, the influence of magnet pitch and slot pitch on the produced cogging torque by the machine is investigated. Since the cogging torque is produced by the interaction between the edges of the magnet poles and the stator slots, the magnitude of the cogging torque depends on the magnet pole arc. Fig. 10 shows the waveform of produced cogging torques at different magnet pitches and Fig. 11 represents its RMS values. It can be seen, when the magnet pitch is 0.9, the peak cogging torque is 5.6999, while when the magnet pitch is 0.65, the peak cogging torque is reduced to 0.9803. Fig.12 shows the RMS values of cogging torques for various slot pitches. As it can be seen, when the slot pitch is 0.4 , the peak cogging torque is minimum. The maximum cogging torque is happened when the slot pitch is 0.6.

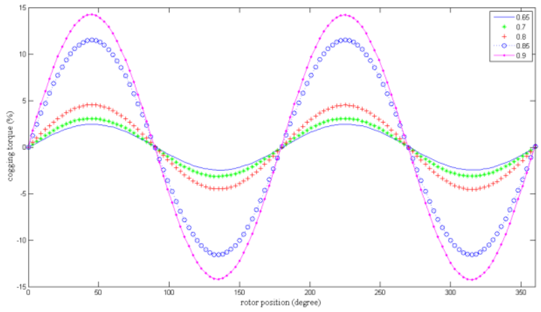


Fig.10. cogging torques at various magnet pole-arc to pole-pitch

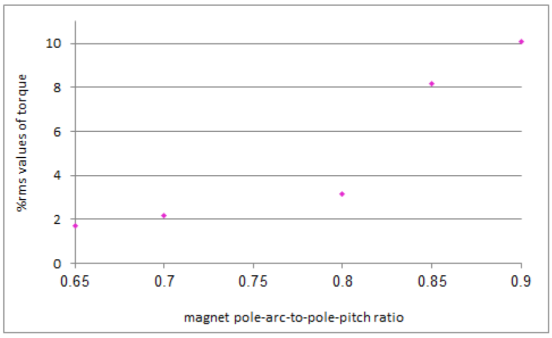


Fig.11 RMS values of cogging torque versus magnet pole-arc to pole-pitch ratio

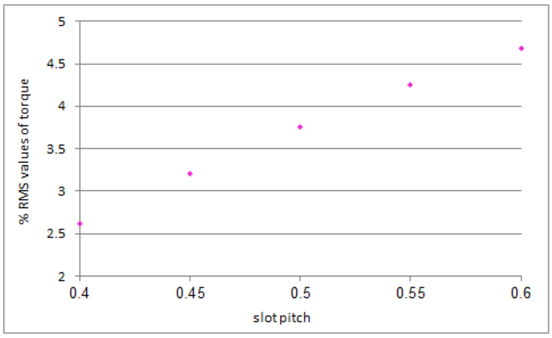


Fig.12 RMS values of cogging torque versus slot pitch

4.2. Induced Phase EMF

Voltage harmonics increase the losses of the generator, such as copper losses in the stator winding and iron losses in the stators and rotor cores (eddy current and hysteresis). These losses affected the overall performance and temperature rise of the machine. Therefore, it must be considered in design procedure to obtain an improved machine structure. Optimal magnet pitch and slot pitch can be chosen to reduce the amount of voltage harmonics. Fig. 13 and Fig. 14 show the harmonics of EMF versus the magnet pitch and slot pitch, respectively.

As it can be seen in Fig. 14, the third harmonic is minimum when the magnet pitch is chosen as 0.7 and fifth harmonic is minimum when pitch is chosen 0.75. With some approximation we can choose the optimal magnet pitch equal to 0.7.

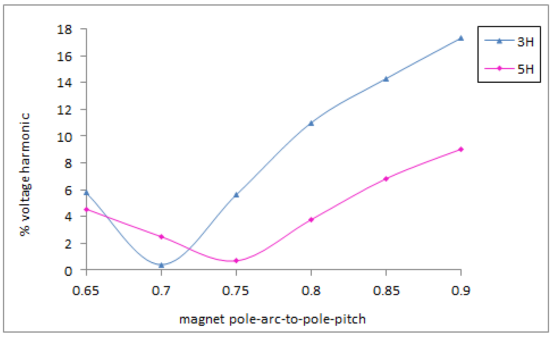


Fig.13 Harmonics of no-load EMF versus magnet pole-arc to pole-pitch ratio.

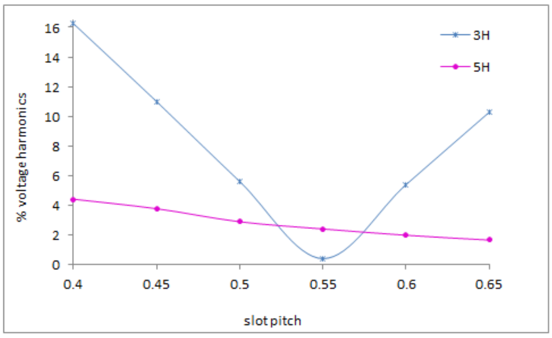


Fig.14 harmonics of no-load EMF versus slot pitch

Fig.14 shows that, the minimum third harmonic is occurred when the slot pitch is 0.55. But by increasing the slot-arc, 5th harmonic decreases.

5. CONCLUSION

A nine-phase axial flux permanent magnet generator was investigated in this paper. Generator has concentrated winding that it makes easy to design machine with multi poles. The machine was modeled by 3-D FEM. The no--load back EMF and electromagnetic torque were illustrated. Some parameters of the machine were varied and the variation of the machine characteristics versus these parameters were investigated. By increasing the magnet pole-arc to pole-pitch ratio and also the slot pitch, cogging torque increases. From the point of view EMF harmonics, it can choose the best operating point approximately when the magnet pole-arc to pole-pitch is equal to 0.7 and slot pitch is equal to 0.55. However by increasing the slot pitch 5th harmonic decreases.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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