Design and Analysis of Novel Dual Stator Hybrid Operational Six-Phase Permanent Magnet Synchronous Machine for Wind Power Application

Raja Ram Kumar, Chandan Chetri, Priyanka Devi, and R.K. Saket*

Abstract— *This paper investigates the design and analysis of a novel dual stator hybrid operational six-phase permanent magnet synchronous machine (NDSHOSP-PMSM) for wind power applications. This machine serves two purposes namely, motor and generator. The inner stator-rotor system operates as a yaw motor for the directional change of nacelle of the wind turbine system whereas the outer stator-rotor system operates as a high-power density and more reliable generating system. To further enhance the power density, reliability, and fault tolerance capability six-phase has been considered in both the stators. For the design and analysis of the proposed machine, the finite element method (FEM) has been opted as it is a more accurate method. The magnetostatic mode of analysis is taken for optimal design modeling, whereas for the performance analysis, the transient mode of analysis is chosen. The back electromotive force (EMF), %THD, torque-current, power-current, and torque-time characteristics are investigated for the inner stator-rotor system as a motor. Similarly, generated EMF, %THD, generated voltage-speed, terminal voltage-current, torque-time characteristic are investigated for the outer stator-rotor system as a generator.*

Keywords— **Dual stator, finite element method, permanent magnet synchronous generator, six-phase, wind power.**

1. INTRODUCTION

Since the advent of the industrial age, the capability to harness and use diverse sources of energy has changed the living conditions of people. Most of these energies are obtained from fossil fuels which are unsustainable. Due to the growing dependencies on fossil fuels, it has changed the atmosphere to such an extent which may have significant implications in our environment. Hence, for the long-term future, renewable energy is the best suited option [1-3].

Due to various innovations in technologies and low operational cost, the generation of electricity has become more preferable from renewable energy sources [4]. Among the non-conventional sources, wind has an important and crucial role. Wind energy is available intermittently. But it was still the fastest growing energy technology in 20th century in terms of yearly growth of installed capacity per technology source [5].

For commercial purposes, most of the productivity has been achieved through large scale wind system, those producing more than 100 KW [6]. This system is more effective and produces more energy. However, building such a large system requires great investment of money and resources. Also, it requires a large space of windy area [7]. The distributed wind energy generation has emerged as a solution to this issue.

The distributed wind energy generation includes wind energy systems, either off-grid or grid-connected, for energy supply at homes, farms, local industries, etc. [8]. It has the significant role in improving power generation, reducing transmission losses, providing better voltage stability and improving power quality. Small wind system, which involves turbines that have small generating capacities, is the technology used in the distributed wind applications. This small-scale wind power system is used to provide clean renewable energy to homes, farms and business [9-10].

A very high-power density, robust and effective generation system is needed in order to utilize wind power efficiently [11]. To harness the wind power, permanent magnet synchronous machine (PMSM) are more popular as no external excitation is required to drive the rotor, light in weight, more reliable, requires less active material and therefore, it is less bulky [12]. Also, there is no need of gearbox or slip rings in PMSM which make the system more reliable and efficient [13-14].

To enhance the power density, in comparison with single stator, the dual stator PMSM is more effective [15]. Dual stator has two air gaps, which leads to the addition of the magnetomotive force (mmf) produced by inner and outer set of magnets of the rotor. Hence, more electromotive force (EMF) is generated from the machine. Due to the two sets of stator winding, it can operate either as a large rating or individual load separately [16-18].

To further increase the power density, multiphase (more than 3-phase) system can be considered. It offers high fault tolerant capability i.e. it can operate continuously, even if there are one or two phases faulty [19-20].

In this paper, design and analysis of a novel dual stator hybrid operational six-phase PMSM is presented. The two rotors in the model are decoupled in nature, as there is no flux linkage between the two rotors and thus loading effect of one does not affect the other. This machine is considered as novel because the outer stator-rotor system can be operated as a generator and the inner stator-rotor system as a motor. This system is advantageous, when both motor and generator are used simultaneously. For small-scale wind energy generating system, this machine is the most suited one. In addition to high-power generation, it also operates

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as a yaw motor for the rotation of nacelle of the wind turbine for maximum power tracking under normal conditions. As per author's information, this machine is reported for the first time. The six-phase winding arrangement both on the inner and outer stator provides a higher degree of fault tolerance capability and freedom of multitasking. The prime objective is the designing and performance evaluation of the above-mentioned model having both generator and motor in it. For the fulfilment of this purpose, the authors opted for the finite element method (FEM) for accurate modelling and evaluation of electromagnetic performance.

The paper has been organized in the following manner- Section 2 introduces the structure and specification of the Proposed Model. The Finite Element Method analysis is covered in Section 3 and the optimal design and performance analysis are reported in Section 4. Finally, the paper has been concluded in Section 5.

2. PROPOSED TOPOLOGY

The various parts of the proposed novel dual stator hybrid operational six-phase permanent magnet synchronous machine (NDSHOSP-PMSM) is shown in Fig. 1. It consists of two stators and two rotors. The outer stator has 60 slots, 10-pole 6-phase winding arrangement while the inner stator has 18 slots, 10-pole 6-phase winding. Both the inner and outer rotors have 10 poles surface mounted permanent magnet arrangement. The green and blue colour shows the north and south facing magnet of the Nd-FeB grade forming ten poles. A flux barrier is provided between the inner and outer rotor so that no flux linkage takes place between the rotors which allows both the rotor to act independently.

The specification of the proposed dual stator machine is enlisted in Table 1 whereas the design parameters are in Table II.

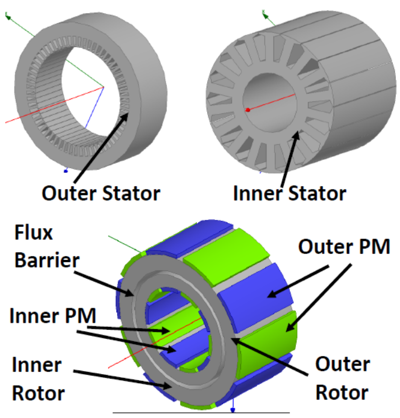

Fig. 1. Various parts of the proposed NDSHOSP-PMSM.

Table 1. Specification of Machine

Parameter	Ratings
Outer stator Power	4.945 KW
Power developed in inner rotor	1.3886 KW
Outer stator voltage	153 Volts
Inner stator voltage	60 Volts
Stator phase current	6 Amps.
No. of phases	6
Speed	600 rpm

Table 2. Design Parameters of Machine

Parameter	Ratings
Outer radius of outer stator	145 mm
Inner radius of outer stator	100 mm
Outer radius of inner stator	47.2 mm
Inner Radius of Inner Stator	20 mm
Width of magnet	3 mm
Air gap length	1 mm
Radius of shaft	20 mm

Operating Principle

The NDSHOSP-PMSM has two stator and two de-coupled rotors. Both the decoupled rotors have the ability to rotate in different speeds, but in our case both of them are moving in the same speed but in an opposite direction at 600 rpm. This feature of the rotor enables the proposed machine to function, partly as a motor and partly as a generator. The inner rotor and inner stator functions as a motor supplying mechanical power (Pm) to load whereas the outer stator and outer rotor functions as a generator supplying electrical power (Pe) to the load as shown in Fig. 2.

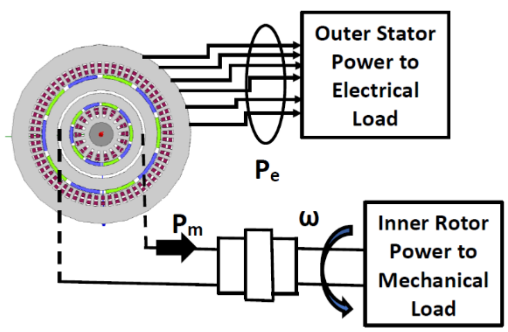

Fig. 2. Principle of operation of proposed NDSHOSP-PMSM.

3. FINITE ELEMENT METHOD

The proposed machine consists of a dual stator and dual de-coupled rotors. The outer stator consists of 60 slots, 10-pole balanced 6-phase windings whereas the inner stator consists of 18 slots, 10-pole balanced 6-phase windings. The inner and outer rotors have a set of 10-pole surface mounted magnets. This machine has been designed and analyzed using FEM, because it is the most accurate method of analysis. To fulfil this purpose, two methods of analysis namely, magnetostatics and transient have been opted. The flux lines and flux density distribution have been evaluated using magnetostatics mode of analysis and the performance evaluation of the machine has been carried out by transient mode of analysis.

For the design and analysis, the following steps need to be carried out: modeling, assigning material properties and boundaries, providing excitation, meshing, providing analysis set-up and finally the results are obtained. Fig. 3 shows the mesh plot for the machine having 120040 numbers of triangular meshes.

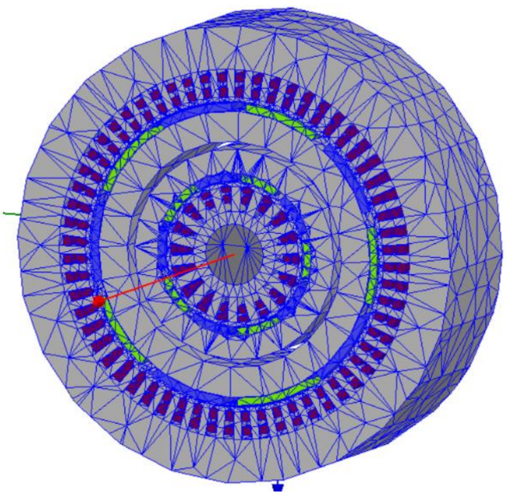

Fig. 3. Mesh plot of proposed NDSHOSP-PMSM.

The magnetostatic analysis has been done for the distribution of flux and flux density. The Fig. 4 shows the flux distribution of the lines conforming 10 poles of the magnet mounted on the surface of both the rotors. From the figure, it can be observed that due to the presence of a flux barrier in between the rotors, there is no flux linkage in between the rotors, thus facilitating the independent operation of the rotors. This allows the inner stator-inner rotor to operate as a motor and the outer stator-outer rotor as a generator.

Fig. 5 shows the flux density distribution of NDSHOSP-PMSM. From the rainbow colour representation of magnitude of flux density plot it clear that the flux density at different portions namely, outer stator yoke, outer stator tooth, outer rotor yoke, flux barrier, inner stator yoke, inner stator tooth and inner rotor yoke are 0.7175 T, 1.55 T, 0.956 T, 0.0 T, 0.837 T, 1.6742 T, 1.0762T respectively. From the above values of flux density distribution, it is clear that the flux density in the model is less than 2 T, which proves the optimal designing of the model.

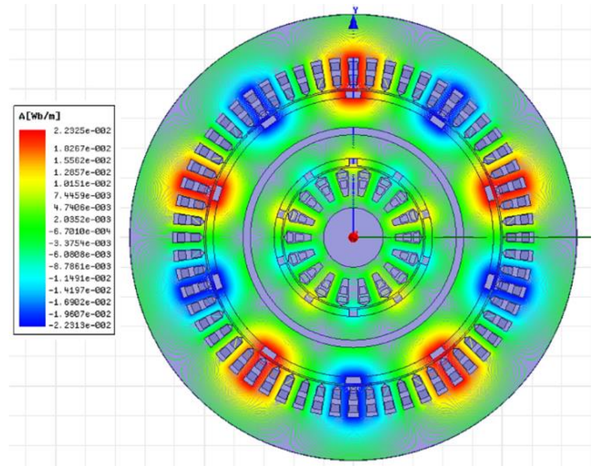

Fig. 4. Flux line distribution of proposed NDSHOSP-PMSM

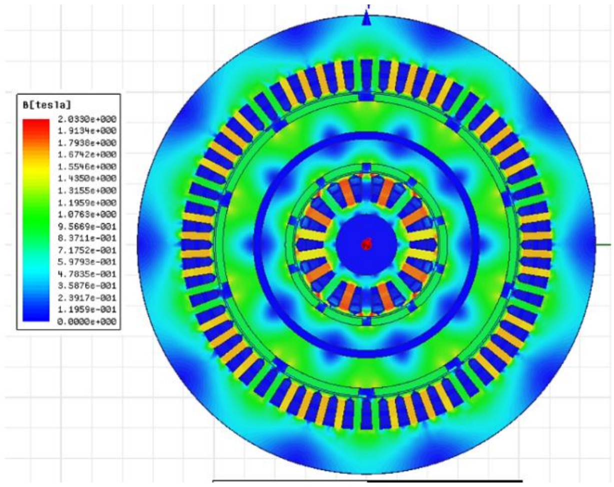

Fig. 5. Magnetic flux density distribution of proposed NDSHOSP-PMSM.

Fig. 6 shows the flux density plot in the inner airgap of the machine. The mean airgap flux density in the inner air-gap is found 0.865 T. There are two dip in the first half portion of the plot. It is found because of two slot faces opposite to the magnet whereas one dip in the second half portion of the plot because of one slot faces opposite to the magnet.

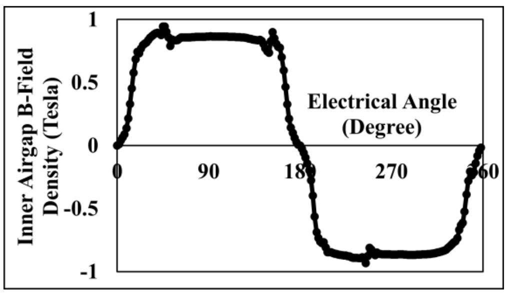

Fig. 6. Inner air-gap B-field density.

Similarly, Fig.7 shows the flux density plot in the outer airgap of the machine. The mean air-gap flux density in the outer airgap is 0.84 T. There are five dips in the both half portion of the plot because of slotting effect.

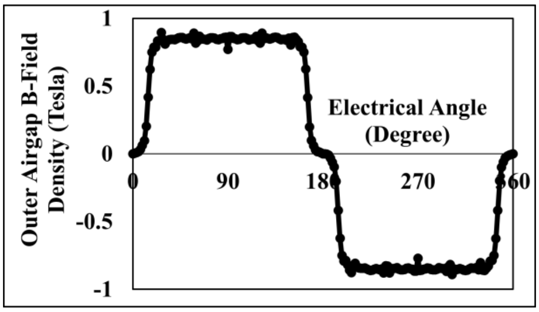

Fig. 7. Outer air-gap B-field density.

4. RESULTS

The electromagnetic analysis of the NDSHOSP-PMSM has been carried out by using transient mode of analysis. Here, the inner stator-rotor system operate as motor whereas the outer stator-rotor system operate as generator. Because of it, all the characteristic of inner stator-rotor system is shown as motor whereas the outer stator-rotor system is shown as generator.

Fig.8 shows the back electromotive force (EMF) developed in the inner stator winding which is trapezoidal in shape and the rms value of 60 volts at 50Hz.

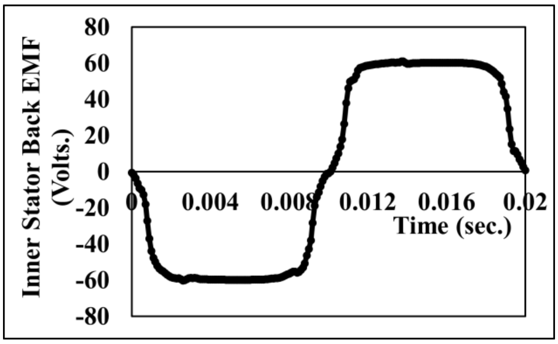

Fig. 8. Inner stator back EMF

Fig. 9 shows the FFT analysis of back EMF developed in the inner stator winding. It is found that the magnitude of %THD is 23.62% and the multiple of six order harmonics are found absent from the back EMF.

Fig. 10 shows the torque vs current characteristic of the inner stator-rotor system. It is found that from 1 to 3 ampere (amps.) the torque is linearly increasing and from 3 to 8 amps. it is creeping with the maximum torque of 23.171 N.m. at 8 amps.

Fig.11 shows the power vs speed characteristics. It is found that from 0 to 200 revolutions per minutes (rpm) the power is increasing nearly parabolically, from 200 to 1000 rpm nearly linearly and start creeping in between 1000 to 1500 rpm. The power is found maximum of 3.474 KW at 1500 rpm at rated current.

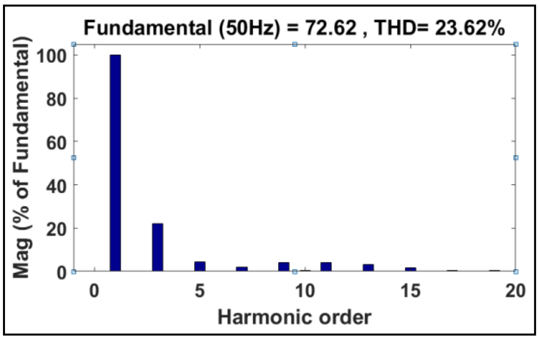

Fig. 9. FFT analysis of inner stator back EMF.

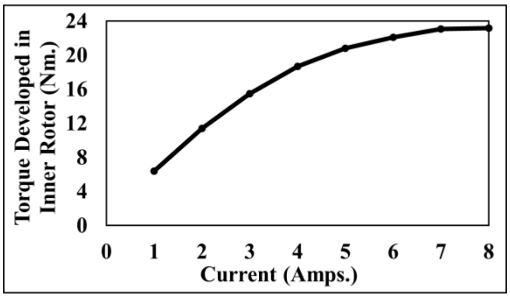

Fig. 10. Torque vs Current.

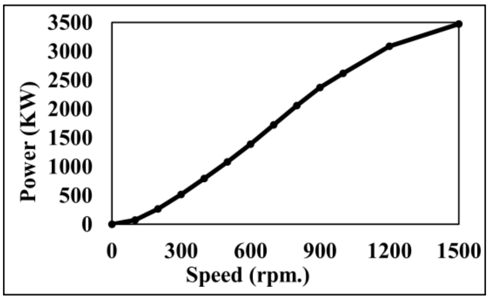

Fig. 11. Power vs Speed Characteristics.

Fig.12 shows the developed torque on the inner rotor and the average value of torque is found to be 22.112 Nm. It is also found that for a period of 20 milli-sec, the torque has 12 ripples and 8.045 % of the ripple factor.

The generated electromotive force (EMF) in the outer six phase 10-pole winding is also trapezoidal in shape with rms value of 153 volts at 50 Hz as shown in Fig. 13.

Fig. 14 show the FFT analysis of outer stator generated EMF developed in the outer stator winding. It is found that the magnitude of %THD is 27.33 % .and the multiple of six order harmonics are found absent from the generated EMF.

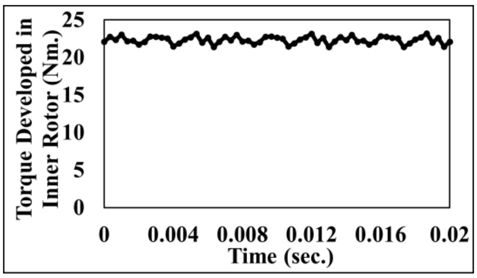

Fig. 12. Electromagnetic torque developed in inner rotor.

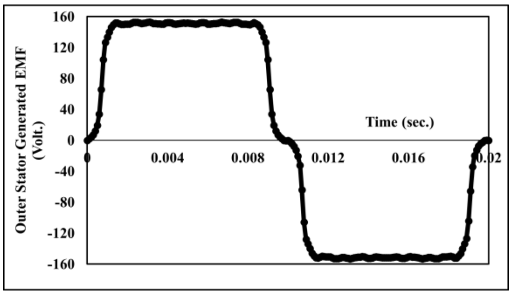

Fig. 13. Outer stator generated EMF.

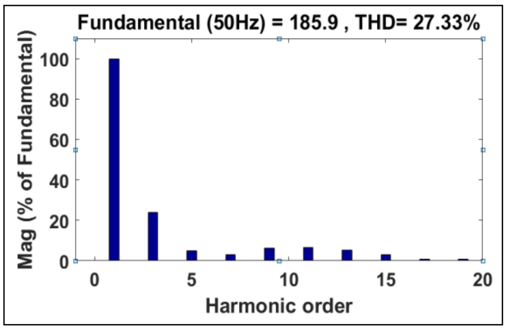

Fig. 14. FFT analysis of outer stator generated EMF.

Fig. 15 shows the plot of outer stator terminal voltage vs speed. It can be seen that as the speed of the outer rotor increases from 0-1000 rpm, the curve increases in a parabolic manner.

Fig. 16 shows the variation of outer stator terminal voltage with phase current. It is found that at no-load the terminal voltage is found 153 volts whereas the voltage regulation is found 11.378 % of the generator at the rated load current.

Fig. 17 shows the electromagnetic torque developed on the outer rotor and the average magnitude is found 87.3 N.m. It is also found that there are 12 ripples and 36.33% of ripple factor in the torque.

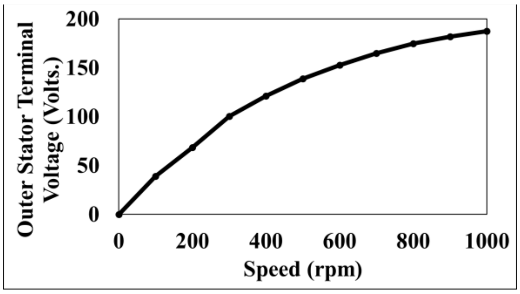

Fig. 15. Outer stator terminal voltage vs speed characteristics.

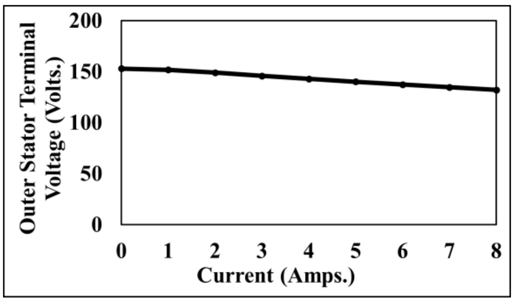

Fig. 16. Outer stator terminal voltage vs current characteristics.

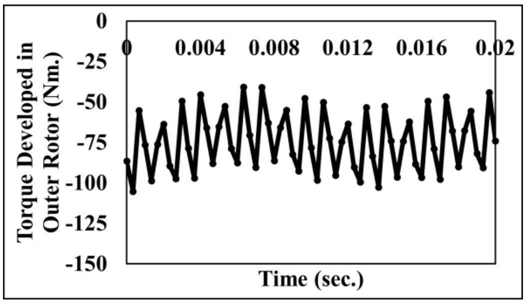

Fig.17. Electromagnetic torque developed in outer rotor.

5. CONCLUSION

This paper proposes the design and analysis of NDSHOSP-PMSM for small scale wind power application. For the optimal design, FEM has been opted. From the magnetostatic mode of analysis, the average inner airgap flux density is found to be 0.865T whereas the outer air gap flux density is found to be 0.84T. The maximum flux density of 1.674T is obtained in the inner stator tooth which is under the unsaturated condition of the core. This confirms the optimal design of the machine model. From the transient mode of analysis, it is found that the back EMF developed in the inner stator winding is trapezoidal in shape and its rms value is found to be 60 volts at 50 Hz with a THD of 23.62%. The outer stator generated voltage is found to be 153 volts at 50 Hz with a THD of 27.33%. The electromagnetic torque on the inner rotor is found to be 22.112 Nm with a ripple content of 8.045%. Similarly, the torque on the outer rotor is found to be 87.5 Nm with a ripple content of 36.33%. The power developed in the inner rotor is found to be 1.389 KW at 600 rpm at the rated current. Based on the performance evaluation, it can be said that the proposed NDSHOSP-PMSM is suitable for wind power applications.

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