Conclusion and Recommendation for the future work

6.1 Introduction

This Chapter is mainly focused to highlight the contributions and summarizes the results of the thesis together with the recommendations future work. Section 6.2 highlights the contribution of thesis and section 6.3 summarizes the results. Finally, Section 6.4 presents the recommendation for future work.

6.2 Contribution of Thesis

This thesis started with the design, modelling and analysis for SSFP-PMSG and MCDSFP-PMSG and ends with the thermal modelling of the generators. A number of analytical methods are reported, but because of being fast and simple, the magnetic circuit approach has been adopted. For the field distribution and electromagnetic characteristics, the electromagnetic analysis is carried out. To enhance the design with a proper selection of temperature sensitive materials the thermal modelling of the proposed generator has been conducted. Finally, to validate the electromagnetic performances of both the generators, their prototypes have been developed. The contribution of the thesis is listed in the Table 6.1.

Table 6.1: Prominent contributions of the Thesis

Sl. No.	Contributions	SSFP-PMSG	MCDSFP-PMSG
1	Identification of high power density generator	Highlighted the various PM arrangements on rotor for identification of high power density generator.	Highlighted the different topologies like dual stator dual rotor, dual stator single rotor and single stator dual rotor. Furthermore identified the

			MCDSFP-PMSG generator as a potential candidate.
2	Magnetic circuit model	Reported Improved magnetic circuit model to achieve the optimised design parameters.	Reported Improved magnetic circuit model to achieve higher airgap magnetic coupled flux.
3	Fabrication challenges	Presented the challenges faced during pasting the magnets and installation of PM rotor and stator.	Presented the challenges faced during the fabrication of novel segmented rotor, PM arrangement on the rotor surface and installation of rotor between two stators.
4	Identification of critical design parameters	Identified the critical value of PM height beyond which the performance started to decreased.	Identified the critical value of segmentation angle of rotor beyond which the harmonic injection in the airgap flux density increased. This would decrease the performance of the proposed machine.
5	Identification of suitable rotor PM sleeve	Reported the porous metallic (Al) rotor PM sleeve which reduces the eddy current and develop loss in it.	Reported the porous metallic (brass) rotor PM sleeve in which generated eddy current and developed loss is less compared to Al due to its higher resistivity.

6	Lumped parameter thermal model	Reported simplified lumped parameter thermal model (with restricted convective and no radiation thermal parameters) to predict the temperature distribution in the generator and to identify the appropriate winding insulation, insulation between core laminations, and grade of PM material.	Reported a more accurate generalised lumped parameter thermal model including all possible (convective and radiation) thermal parameters for accurate prediction of the temperature distribution in the generator. Also to identify the appropriate winding insulation, insulation between core laminations, grade of PM material.

6.3 Summary of results

Chapter 1 has discussed the necessity, advantage, and present and future trends of wind power generation. The detailed literature survey has been covered for different topologies of PMSG, multi-phase systems and analytical techniques for the electromagnetic performance analysis. The necessity of thermal analysis has also been reported. Different topologies and design analysis techniques is presented based on their advantages and disadvantages.

Chapter 2 is based on design aspect of the machine. To select the appropriate PM generator for wind power application, a comparison with conventional dual stator is done to develop a novel structure of the dual stator. The advantages and disadvantages of the proposed generator are discussed. An improved magnetic circuit for the design analysis has been proposed and the electromagnetic performances are investigated. To get the optimal design various design parameters have been tuned comprehensively. For SSFP-PMSG, It is found that as the height of magnet increases from 3.5 mm to 4.5 mm the airgap flux density started to decrease from 0.6585 Tesla to 0.6151 Tesla due to saturation of iron core material. This in turn reduces the performance of the generator. Various types of rotor PM sleeve have been discussed and it was found that carbon fibre is most suitable for this purpose. Similarly, the flux barriers in the local leakage path of the rotor of MCDSFP-PMSG have been optimized. Due to the flux barriers in the local leakage flux path, the flux in the local path decreases from 1 milli webers to 0.4 milli webers, due to which the main airgap flux enhances in the MCDSFP-PMSG.

The other electromagnetic performances like cogging torque, generated voltage, and electromagnetic torque for both the generators have also been discussed. Furthermore, it is found that the predicted analytical results are in close agreement with the FEM results.

Chapter 3, discussed the development and fabrication of prototype of both SSFP-PMSG and MCDSFP-PMSG for validation of the electromagnetic performance. The difficulties in the winding arrangement for unconventional double layer fractional slot five-phase stator windings for both the inner and outer stator winding has been discussed. The magnet pasting process, selection of rotor sleeve and the concept of the hollow shaft have also been discussed. The possibilities of the two stator winding namely series and anti-series connection are also presented.

In Chapter 4, electromagnetic performance of SSFP-PMSG and MCDSFP-PMSG have been carried out experimentally and validated with the predicted results. The validated results have confirmed the effectiveness of the proposed analytical technique. The open circuit fault analysis for no-load and load is done and the severe faults during the operations for both the five-phase PMSGs have been identified

In Chapter 5, the thermal modelling has been discussed for SSFP-PMSG and MCDSFP-PMSG. The lumped parameter model has been adopted for this purpose. For SSFP-PMSG simple thermal model has been discussed which do not consider the radiation and axial flow of heat. On the other hand, the radiation and axial heat flow is included in the thermal model of MCDSFP-PMSG. The thermal analysis is used to identify the requirement of suitable grade of PM material, winding insulation, and insulation of iron core laminations. The FEM is used to identify the effectiveness of the lumped parameter model. The predicted temperature distribution for SSFP-PMSG is found within 5% error with the FEM results. Likewise, the temperature distribution for the MCDSFP-PMSG is found within 3.3% error with the FEM results.

So broadly in this Thesis the author has targeted for designing and developing high power density generator. To achieve this at first concept of five phase and fault tolerant capability was analytically and experimentally validated using a single stator Five phase PMSG. This was followed by the concept of dual stator arrangement which gives the freedom of regulating the output voltage by utilizing the interconnection of inner and outer stator windings. This would permit the enhanced speed range of the generator particularly towards the lower speed range. Interestingly in author opinion the concept of magnetic coupling between the outer and inner magnets is somewhat being reported for the first time.

6.4 Recommendations for the Future work

Due to distinct features of proposed MCDSFP-PMSG, the application of this machine can be extended from wind generator to the other applications like navel ship, aerospace space vessels and transportation. Though the author has performed rigorous work in this thesis, certain aspect of the proposed machine is yet to be explored as future work.

Optimization of the proposed machine is the first and the immediate task to bring down the size and cost of the proposed dual stator machines. Before fabricating the machines, optimization would assist in setting the benchmark for comparison of the proposed machines with the other wind generators.

To form the magnetic pole small pieces of magnets are pasted on rotor in this work which is a very cumbersome job. So, for smaller rating of proposed machine single arc magnet should be preferred which will reduce the complexity and save the time and labour cost.

Both the PMSGs are tested for open loop control by using diode uncontrolled rectifier. In future for improved and stable operation of the machine proper arrangement of AC to AC converter or controlled converter in close loop could be used to fulfill the load power demand.

The analytical method adopted for the electromagnetic performance analysis does not consider the temperature effect during the load test operation, so this analytical method can be extended to take into account the magnet temperature rise for performance during loading.

The thermal analysis validation is done on the basis of FEM simulation. In future actual measurement could be done using temperature thermal sensors installed in the proposed machine. It would also help for the performance evaluation and reliable operation of the machine during heavy loading and fault conditions.