Chapter 7

Conclusion and Future Work

7.1 Conclusion

PM machine drives are widely accepted for various applications such as HEV, wind power generation and electric aircraft applications. The critical applications demand precise and accurate design and control of the machines. Therefore, it is imperative to have accurate analytical analysis of the various topologies of PM machines. Though several analytical model have been developed, but they are limited to analysis of unsaturated PM machines. In this thesis, an analytical model for analysis of saturated PM machine has been developed in a simplified manner. Firstly, an analytical method was developed for the radial flux PM machine, and results are validated using FEM results obtained from ANSYS MAXWELL 18.0 simulations. The verification of the analytical model has been done for four different cases of machine teeth permeability. The analytical modeling methodology has been extended for the analysis of AFPM machine with saturated teeth. The obtained analytical results are further verified with the FEM results. In both the aforementioned cases, the resemblance of results are within the acceptable limit.

For the safety critical application, modular PM machine is an attractive solution. In the modular PM machine, to limit the mutual inductance of the machine, a magnetic flux gap between adjacent E cored stator segments is provided. However, the additional magnetic flux gap influences machine performance and regular machine design equation does not account for the influence of the magnetic flux gap. Therefore, an analytical model is also developed for analysis of E-cored segmented stator machine (commonly known as PM modular machine). Both variants of E-cored stator viz. E-cored stator without tooth

tips and with tooth tips are considered for analysis. The developed analytical model is verified with FEM analysis and further investigations has been carried out to improve the performance of these machine with modification in stator E-core teeth and teeth tips shaping.

Low cogging torque and high power density are required in critical applications such as actuators in aircraft applications. To address this issue, a PM machine with skewed slot opening is proposed and investigated comprehensively. For the performance study of the proposed machine, an analytical model has been developed and performances are evaluated. The obtained analytical results are compared with FEM results. Comparative study between existing machine and proposed machine is carried out which indicates that proposed machine has better performance in terms of cogging torque.

Lastly, analytical modeling for the axial flux machine with skewed magnet is developed. The analysis adopted the multislice technique to convert 3D problem into 2D. The developed analytical model is compared with the results obtained from FEM. The advantages of multislice technique has been used for the investigation of stator slot shapes on the cogging torque developed in machine. It is demonstrated with the help of the analytical modeling that the cogging torque in the machine mainly influenced due to slot opening rather than slot. Hence, the AFPM with parallel slot opening and trapezoidal magnets is reported to achieve least cogging torque.

7.2 Contribution of the Thesis

The major and minor contributions of the thesis are summarized below

7.2.1 Major Contribution

- The analytical modeling method is developed for the analysis of saturated PM machines. The magnetic saturation in the machine contributes to the increment in the flux leakage and torque ripple. The developed analytical model takes account of the finite teeth permeability and accurate prediction of the cogging torque.

- The analytical modeling is developed for the analysis of the modular machine. This analysis is advantageous for the design and optimization of the machine.

7.2.2 Minor Contribution

- For the estimation of the machine performance, the analytical model for the skewed AFPM machine is developed. The analysis contributes to the estimation of the reduction of cogging torque in terms of skewed angle and other design parameters.

- The methods available for the cogging reduction, alters either the magnetic location of the coils or reduces airgap magnetic flux density. Therefore, the technique reduces the machine power density along with cogging torque. An alternative method of cogging torque reduction is introduced with minimal reduction in power density.

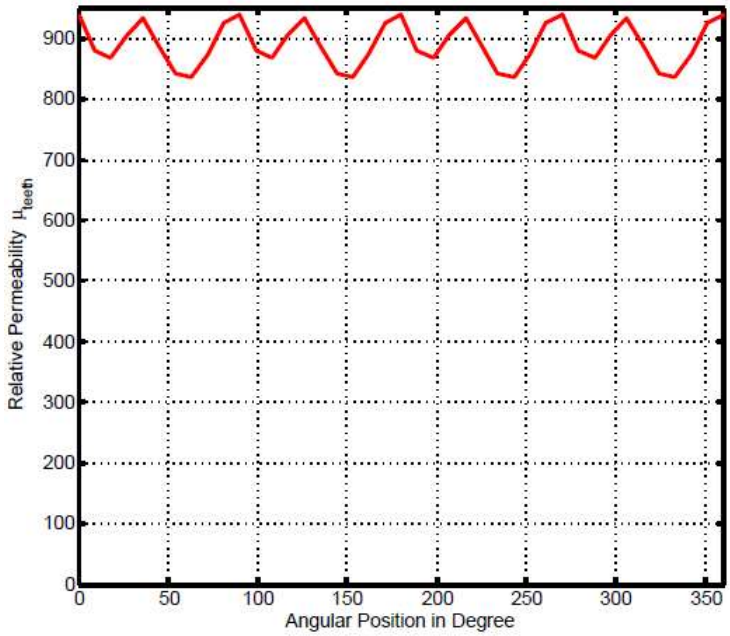

Figure 7.1: Relative Permeability of the Teeth

7.3 Future work

In PM machine drives, the local saturation of the stator core influences machine performance drastically. Hence, the machine design for critical applications needs to account for the local magnetic saturation during design process. The analytical model developed in Chapter 2, and Chapter 3 can be used for the evaluation of machine performance under magnetic saturation. The developed models have taken account of finite permeable teeth. However, the individual teeth would have been at different level of magnetic saturation.

The model can be extended using FEM to extract the relative permeability information as a function of time/position. For example, the teeth magnetic saturation as a function of position/time for the model developed given Figure-(2.2) can be evaluated using the formula given below

$$\mu_{teeth} = \frac{\iint_{s} \mu_{rt} ds}{S} \tag{7.1}$$

where, $\mu_{rt} = \frac{B}{\mu_o H}$ is the relative permeability of each elements of the FEM model, and S is the teeth area. The plot of the average teeth permeability of the teeth as a function is determined using FEM model and given shown in the Figure-7.1.

Based on the developed analytical model following future works are suggested

- The developed analytical model for the saturated PM machine can be extended for the analysis of machines to take account of the both stator teeth and yoke finite permeability. This analysis can be further used for the optimization of machine design to match the recent trend for improving the power density and lowering the machine size.

- E-cored PM machines are fault tolerant as their phases are magnetically isolated. However, the magnetic flux gap decreases the airgap flux density, but this can also be used as the cooling duct of the machine. Therefore, the decreased machine performance due to lowered magnetic flux can be compensated with the increased electrical loading. Hence, to estimate the influence of magnetic flux gap on the thermal circuit, a thermal modeling of this machine is suggested. The developed analytical model for electromagnetic analysis and thermal modelling can be used for the design optimization of high power-fault tolerant machines.