Chapter 1

Introduction

The permanent magnet (PM) machines have gained popularity as an alternative to induction and switched reluctance motors due to high power density, high efficiency and ease of control. Since last few decades, the advancement of power electronics and PM technology have further expedited the use of PM machines. Nowadays, the PM machines are used in numerous applications such as servo drives [1], fan [2]- [4], blower [5], compressor [6], [7], pump motor [8]- [13], washing machine [14]- [16], wind power generation [17] - [29], electric vehicle/traction [30]- [44], linear actuators [45]- [48], wave energy generation [8], hard disk, tooling, robotics, and aerospace [49] - [55]. The accurate design of the electric machine drives requires the knowledge of machine performance and load profile. The machine performance evaluation primarily needs the information of field distribution in the machine, which is used for the determining of machine performance. Furthermore, the knowledge of field distribution is required for design optimization, as it involves either the improvement of average torque, linkage flux, induced voltage, winding inductances, back EMF and field weakening capability or reduction of torque ripple, cogging torque, unbalanced magnetic pull and even acoustic noise and mechanical vibration.

Basically, the design parameters such as winding arrangements viz., (1) integral slot winding (overlapping winding) and fractional slot concentric winding [56] (2) single layer, and multilayer winding [57]- [59], pole slot combinations selection [60]- [63], magnet pitch to pole pitch ratio [60], magnet shaping [64]- [66] and rotor types viz., surface mounted PM machine, surface inset PM rotor, interior PM, which influences the machine performance, ultimately modify the field distribution in the machine. In view of this, in the foregoing section, the methods of electromagnetic analysis for PM machine are briefly discussed.

1.1 Methods of Electromagnetic Analysis

The electromagnetic analysis of the machine involves the solution of the governing field equations in and around the region of interest. The governing field equations may be either Laplacian, Poissonian or Helmholtz 's equations depending on the nature of the source. The solution of the governing field equations are obtained considering the boundary conditions which account for the interaction of regions associated with them. Broadly, the electromagnetic field analysis of electric machine are classified as either numerical analysis or analytical analysis.

1.1.1 Numerical Method

The Finite Difference Method (FDM) reduces the governing field equations to a set of finite difference equations using either Taylor's series expansion, integration method or Rayleigh-Ritz mehto (variational method). This approach converts governing field equations to a set of simultaneous linear equations and iterative solution of these equations result in the final solution of actual governing field equations. However, FDM considers the regularly distributed nodes in the Cartesian coordinate system. It is more useful when the geometry of the problem exactly fits into the Cartesian coordinate system. The FDM approximate the governing field equations to finite difference equations, which results in inaccuracy in the solution. To obtain the accuracy within acceptable limits, the entire region of interest is discretized into several small sized elements [67].

The other numerical method named as Finite Element Method (FEM) solves the boundary valued problem using the calculus of variation. It involves the formulation of potential functions/ cost functional using the governing field equations and their optimization within subjected boundary conditions. The process of minimization/ maximization of the cost functional involves the following steps: 1) discretizing the area of interest into several elements; 2) assignment of potential to each element; 3) calculation of cost function for each element, and hence cost function calculation for the entire area of interest; 4) the cost function optimization under the subjected boundary conditions. The aforementioned process converts governing field equation to linear simultaneous equations and the process is well described in [68], [69]. Among both numerical methods, FEM is highly acceptable as it is comparatively more accurate. Moreover, it is also useful for analyzing irregular geometry problems. Though, it requires larger computing disk space, memory and computational time.

1.1.2 Analytical Method

In spite of undistinguished features of the numerical method viz., the capability of accounting the magnetic saturation, irregular shapes of the machine and high accuracy, it is the second choice for machine designers. The analytical method is quick as compared to FDM and FEM, and suitable for the iterative design process. Moreover, the parametric information of the machine performance is beneficial for design optimization. Hence, the designers primarily prefer analytical method for the electromagnetic analysis and subsequently, numerical techniques for the validation of the analytically obtained results.

1.2 Literature Review of Analytical Analysis

The foregoing section describes the literature review on the analytical analysis of the PM machine. The reported analytical methods are categorized into two groups in the thesis: (1) Magnetic equivalent circuit and (2) other methods. The methods of electromagnetic analysis of PM machines reported in the research literature are highlighted in the Figure-1.1.

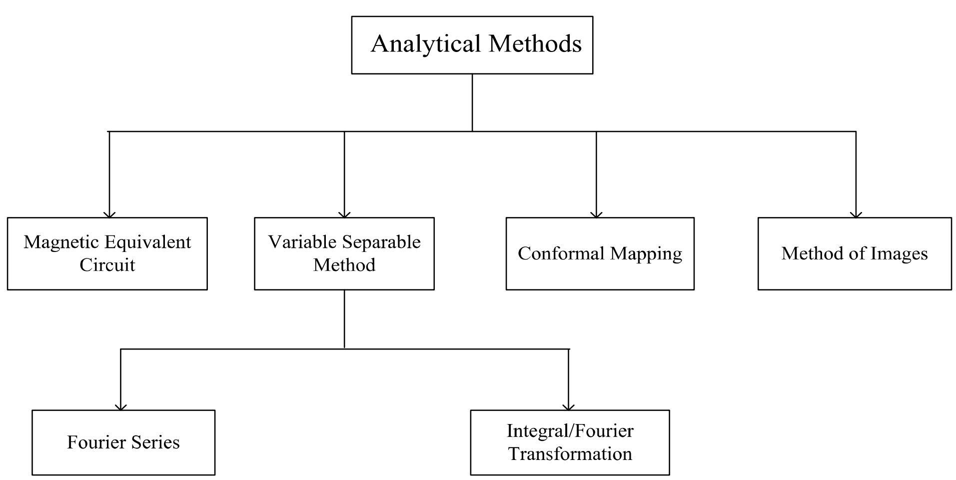

Figure 1.1: Methods of Analytical Analysis of PM Machines

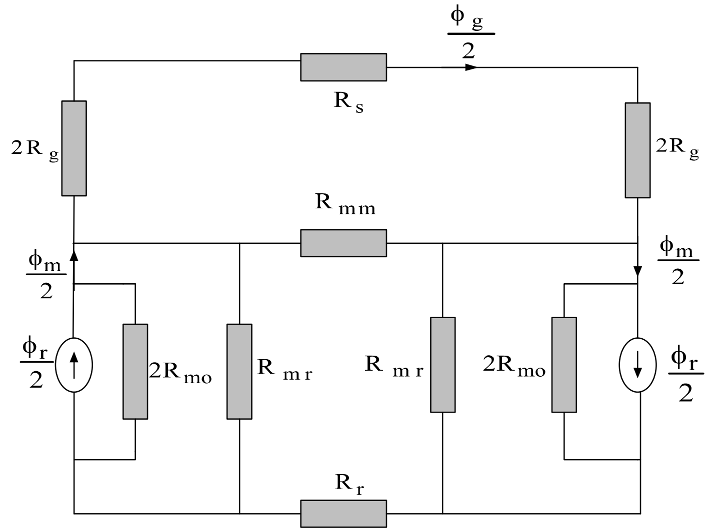

Figure 1.2: Generalized Magnetic Equivalent Circuit

1.2.1 Magnetic Equivalent Circuit Method

The most common analytical approach is the magnetic equivalent circuit model. This is useful for machine design and performance investigation as it establishes a parametric relationship between critical design parameters and machine performance [70] - [76]. A typical magnetic equivalent circuit for the analysis of PM machine is shown in Figure-1.2 [76]. However, this analysis suffers from the model inaccuracy, especially in case of complex machine topologies and magnetic saturation. The complex machine topologies, and magnetic saturation increase leakage flux and the flux path complexity, which requires high level of expertise for the analysis using lumped magnetic equivalent circuit model [77].

1.2.2 Chronicle Development of Field Analysis

To overcome the aforementioned shortcomings of numerical analysis and magnetic equivalent circuit analysis, other analytical models based on either the concept of charge (method of image), variable separable methods (using Fourier series, and integral transforms), conformal mapping or subdomain modelling etc. have been investigated extensively in literature.

In early 1900, the author [78], [79] determined the electromagnetic field in the cylindrical geometry due to currents using 2-D analytical solution of Poisson's equation. In 1977, Hughes et al [80] extended the work for the field and inductance calculation in both air cored and iron cored synchronous machines. While formulating the governing field equation, the entire machine is divided into five regions with assumption of constant rotor and stator's permeability. The solution incorporates the effects of iron and air cored machine and informative enough for both the fields (as by changing the winding location, the results may be produced for either field or armature windings). However, the analysis is limited to slotless machines targeted which for turbogenerator topology due to current windings.

In the early stage of analytical model development for PM machines, Boules [81], [82] represented the PMs with equivalent current density and using [78] evaluated the field distribution and the performance of radial flux machine which is used for design and optimization [83]. On the other hand, Bumby et.al used the same technique for the analysis of slotless axial flux permanent magnet machine [84].

Alternatively, Nasar and Xiong developed the concept of magnetic charge and established an analogy between magnetostatic potential and electrostatic potential. Hence, similar to electrostatic field problems, the authors applied method of image to account the boundary conditions and succeeded in analysing the field distribution in disk type and linear synchronous motor [85], [86]. Except for the paper [81], which accounted the slot effect of the stator using Carter's coefficient, all the reported analysis have focused on the slotless machine geometry. The Carter's coefficient modifies the airgap length, however, fails to account the flux fringing at the stator slot. Hence, this technique is not applicable to cogging torque calculation.

In a series of papers [87]- [90], Z.Q.Zhu and D.Howe developed an analytical technique for the investigation of permanent magnet brushless dc motor. In [87], the authors analysed radially magnetized slotless PM machine as two regions(PM region and airgap region). In order to obtain the field distribution, Fourier series expansion is used to model PMs magnetization vectors and to formulate the governing field equations, while the variable separable method is applied for the solution in polar coordinate. In [88], the armature field has been determined with the same philosophy. The paper [89] discussed conformal mapping, which transforms slotted PM machine to slotless PM machine. Consequently, the authors determined relative permeance function for taking into account the stator slotting effects in the PM machine. The authors in the last paper of this series used the field distribution [87], [88], and relative permeance function [89], and applied the superposition technique to evaluate the performance of radial flux brushless DC motor [90].

While applying the superposition technique, the authors considered the relative position of both the fields in time and space. The analysis is reported for both internal and external rotor machines, but limited to the radially magnetized machine with integral slot winding. From the analysis, the cogging torque is calculated using the prediction of the forces acting on the lateral edges of the slots [91]. This technique has also been extended for the field distribution analysis in PM motors with rotor eccentricity [92]- [95]. The authors studied the influences of rotor eccentricity on magnetic force imbalance, cogging torque and associated vibration [94].

Since the development of analytical techniques [87]- [90], several works have been carried out to improve the analytical analysis of PM machine. For instance, the author in [96] developed analytical model for the no load field prediction of parallel magnetized PM machine. This is improved by Zhu et.al [97], as the authors considered the radial/parallel magnetized magnet machine with both types of windings(overlapping and non overlapping winding). Moreover, analytical analysis of the Halbach magnetized magnet machine is reported in [98]. The Halbach magnetized magnet machine has been a preferable choice for high speed application as it posses several advantages such as sinusoidal airgap flux density, low cogging torque, sinusoidal back EMF and lesser torque ripples [99]. Besides this, absence of the rotor ferromagnetic rotor due to the flux shielding property of Halbach magnets makes it lighter. Hence, the analysis used three regions viz., airgap, magnet and rotor core to analyse the machine [98]. Consequently, the authors investigated the effects of the pole numbers on the airgap flux density and obtained relation between magnet thickness and pole number for optimal airgap flux density in a slotless PM machine with both air-cored and iron-cored stator. In [100] and [101], the authors have extended the analysis of slotless PM machine for eight regions: rotor backiron, retaining sleeves, airgap, winding region, stator back iron and external region. Subsequently, the papers evaluated self inductance, mutual inductance, eddy current in magnets, back iron and retaining sleeves of the machine. These papers also discussed the effect of winding unsymmetry, unsymmetrical magnetization.

All the literatures discussed so far are confined to the slotless surface mounted PM machines. However, surface inset PM machine has several advantages such as high torque density, high flux weakening capability and high demagnetization tolerance [1]. The presence of iron inter-poles between the magnets in a surface inset PM motor increases inter-pole flux leakage and flux focusing capability. The authors [102] developed analytical model for the slotless surface inset radially magnetized PM machine which included the effect of inter-pole flux leakage and flux focusing capability both. Rahideh et al. [103] extended this analysis for different magnetization vector viz., radial, parallel and Halbach. The authors used the developed model for further investigation of the effects of iron inter-pole on the no load magnetic flux density and back-EMF. Furthermore, in [104], the analytical analysis is developed for armature reaction investigation in slotless surface inset PM machine and influence of iron inter-poles on the armature reaction field investigated comprehensively. In a subsequent paper [105], an analytical model using both excitation is developed and the effect of iron inter-pole on machine parameters such as inductances, back EMF, reluctance torque and electromagnetic torque is discussed. The analysis considered different magnetization vectors (radial, parallel, and Halbach) and different armature current waveforms (sinusoidal waveform, ideal rectangular waveform, and six step rectangular waveform) and also discussed the influence of pole arc to pole pitch on the machine performance.

In high speed industrial drives, the torque pulsation due to cogging is mitigated due to system inertia. In case of low speed drives such as fuel pump of aircraft and radar drive system, cogging toque produces distorted performance. Moreover, in case of high speed drives used in gyroscopes, the tilt angle of shaft generates a vibration signal which is proportional to the angle of tilt. When such drive is having its own motor toque pulsation and its vibration, the vibrations are superimposed. The noise vibration due to cogging torque need to be separated for instrumentation. Such drive demands low cogging toque. Therefore, the analysis of slotted PM machine is essential so as to evaluate the cogging torque in the machine. The interaction of magnet MMF and stator slot develops cogging torque. Hence, for the prediction of cogging torque, it is essential to estimate the magnetic field of slotted permanent magnet machine. In early development [89] and [90], the air flux density distribution in slotted machine is determined by multiplying the slotless machine airgap flux density with the relative permeance function. Because of the ease of relative permeance function calculation and clear parametric demonstration of the modulation effect due to the slotting, this technique has been extensively used. Though this technique predicts radial flux density fairly well, fails to forecast the tangential flux density accurately. For relative permeance calculation, the shape of relative permeance function waveform is predetermined and conformal mapping is used to calculate the relative permeance function corresponding to only one point on the curve in the center of the slot opening which results in high discrepancy for tangential flux density between analytical and FEM analysis. To overcome this shortcoming, Zarko [106] used conformal mapping to predict every point of the slotted machine and introduced complex relative permeance function. The authors [107], [108] extended the work for evaluation of cogging torque and electromagnetic torque. The imaginary part of the proposed complex relative permeance function takes account the mutual interaction of tangential and radial flux density due to slotting and hence this technique is more accurate than the relative permeance function. However, the calculation of complex relative permeance function for each point is quite cumbersome and time consuming as the numerical technique is required for its calculation. Even though, because of high accuracy, several authors have used conformal mapping for different machine topologies analysis. Several other machines such as surface mounted PM machine with tangentially magnetized magnets [109], Halbach magnetized magnets [110], external rotor machines [111], semiclosed slot machine for high speed [112], spoke types rotor [113] have been analyzed using conformal mapping.

Above mentioned techniques do not consider stator slots explicitly, while formulating governing governing field equations. So, researchers focused on the development of the analytical method to include the slot effect and named this technique as subdomain method. This method formulates the governing field equations in all subdomain of the slotted PM machine and obtain the field distribution using separable variable method. In 1968, for prediction of end-effect, Gu et al. [114] axially expanded a surface mounted PM machine into a linear PM machine and developed subdomain method in Cartesian coordinates. The author [115] applied this technique and analysed a 2 poles, 12 slots PM machine in polar coordinate. A more general subdomain technique was reported in [116] for the investigation of cogging toque in PM machine. However, all these analyses assumed the relative permeability of the magnet as unity and focused on open slots machines. In other analysis, Liu et al. focused on the study of slot opening and pole transition interaction [117]- [119]. Consequently, the authors obtained the magnetic scalar potential distribution along each slot opening using one slot machine model and extended it to determine the airgap flux density in multi slot machine. The field solution was obtained by solving governing field equations with new boundary conditions. The newly imposed boundary condition was the scalar potential distribution (obtained from single slot machine model) along all slots at the stator bore and hence magnetic field, the force developed in the slot, force in PM machine including magnetic pull and cogging torque are evaluated. The scalar potential along the slot opening was initially derived in cartesian coordinate in [117], and [118], while the paper [119] used polar coordinate. The single slot analysis and its extension for the different slot pole combination do not account the mutual interaction of slots. Therefore, the accuracy of the analysis is sacrificed to a certain extent. For overcoming this limitation, Dubas and Espanet successfully developed exact subdomain analytical model for vector potential and magnetic field analysis at no-load for an integral slot winding PM machine by considering both magnetization vector : radial and parallel magnetized [120]. For the evaluation of the coefficients, the authors used the Fourier series expansion of slot tangential flux density over a pole pitch, which effectively restrict the analysis to one slot /pole model [121]. Hence, Zhu et al., [121] improved the analysis to obtain the exact solution for any slot pole combination of surface mounted permanent magnet machine. The authors evaluated the Back- EMF, electromagnetic torque, cogging torque and unbalanced magnetic force for both radial/ parallel magnetized magnets and internal/ external rotor topologies and have also considered the magnet relative permeability. Furthermore, the authors have included the comprehensive discussion of the performance parameters obtained from exact subdomain method and earlier reported conventional subdomain method. The exact subdomain method of calculation is time consuming as field needs to be evaluated at each rotor position for capturing the interaction of slot and rotor position. However, Ackermann et al. [116] discussed a two steps method to reduce the computational complexity for each rotor position: solution of the slotless machine first and then the prediction of the slotting effect based on the slotless field. Though slotting effect still needs to be evaluated for all rotor position, however the method is very quick. Nevertheless, the method is an approximate one. The paper [121] reduced the computation complexity by calculating the scalar potential distribution along the stator bore firstly instead of calculating the vector potential in magnet as done in [116].

All the subdomain analysis reported so far have been focused on the no load magnetic field distribution in open slot surface mounted PM machine. Lubin [122] extended the exact subdomain analytical model for the semicolsed slot PM machines with any pole and slot number combinations including fractional-slot machines with distributed or concentrated winding. The governing field equations are derived in all subdomain: Poisson's equation for PM region and slot regions, and Laplace's equation for airgap and slot opening regions. The authors evaluated the cogging torque, electromagnetic torque and analysed the effect of slot opening angle to slot angle ratio on them. Alternatively, Wu et al., [123]- [125] developed subdomain method to determine the influence of the tooth tips on the electromagnetic performance such as the cogging torque, back-EMF and electromagnetic torque and winding inductances have been calculated. The matrix equations involved in prediction of field reported in [122], [125] shows singularity in the ratio of slot opening angle to slot angle. Furthermore, these analysis are not applicable for one pole pair machine such as 3 slot, 2 poles machine. The authors in [126] addressed theses issues and proposed an analytical subdomain method for no load magnetic field distribution, back EMF and cogging torque determination. The authors comprehensively discussed the field results of the 3 slots, 2 poles, and 12 slots, 10 poles machines in all subdomain. Since the development of subdomain method, researchers have been using it for analysis of the machines with different topological variants, including surface inset permanent magnet [127], [128], and consequent pole machine [129]. Further field distribution in PM with rotor eccentricity has been analysed using this technique [130] and its effects on cogging torque have been comprehensively addressed in [131] and [132].

1.3 Analysis of PM Machines Considering Magnetic Saturation

All the aforementioned techniques of analysis, assume that the stator and iron are infinitely permeable. Hence, the field problem of PM machines at most confined to four types of regions: magnet region, airgap region, slot opening region and slot region. However, [133] and [134] demonstrated the effect of the machine outer diameter on the machine sizing equation. To take the account of the stator and rotor magnetic properties on the airgap flux density and cogging torque, the authors [135] extended the analysis [87] to five region problems: rotor core region, PM region, airgap region, stator core region and stator outer region. Though analysis assumed finite permeability of stator and rotor cores, but it is capable to account the magnetic saturation using an adaptive analysis. Further improvement in the analysis of the PM machine with saturated stator core is obtained using the on load analytical model and FEM modeling [136]. The FEM modeling has used winding region at inner radius of the stator bore and extracted the ferromagnetic stator permeability. The average modeling of the stator core permeability results in discrepancy with the actual machine. Alternatively, Sprangers et al., [137] proposed an analysis based on the multi-layer models using the convolution theorem (i.e., Cauchys product theorem) which takes into account the iron core permeability parts. Subsequently, the work is extended by dividing the machine into an infinite number of homogeneous or non-homogeneous layers where the permeability in the stator and/or rotor slotting is represented as a complex Fourier series (CFS) along the direction of permeability [138]. Recently, papers [139], and [140] analysed various topologies of saturated PM machines.

Alternatively, the effects of saturation and electric loading on the electromagnetic performance of machine have been extensively analysed using numerical method [141]. Indeed, the torque ripple in PM machines are mainly contributed due to distortion of the back EMF waveforms, winding inductances, current waveforms and cogging torque. The numerical analysis of PM machines demonstrates that voltage waveform, back EMF and cogging torque of the machine depend on the electric loading, and magnetic saturation [142]- [144]. However, the analytical method of performance evaluation requires no load flux distribution, cogging torque and back EMF information. But the magnetic properties of the stator and rotor materials are significantly affected by electrical loading and magnetic saturation. Hence, the back EMF waveform and cogging torque actually influence the machine performance differently. The machine performance differs than the estimated using open circuit analysis of machine. The accurate analysis of saturated PM machine is possible with FEM method using the frozen permeability [141]- [150]. Figure-1.3 depicts the principle of frozen permeability method, and its comparison with conventional analysis method. In ferromagnetic stator core, the individual excitation of PMs (H_{PM}) and armature currents (H_{AR}) produce magnetic flux density B_{PM} and B_{AR}, respectively. On the other hand, when the machine is loaded (excited with PM and current simultaneously) i.e. $H_{all} = H_{PM} + H_{AR}$, the resultant flux density in stator becomes B_{all}, which is lower than $B_{PM} + B_{AR}$. Hence, the traditional method of superposition is invalid for machine analysis.

However, frozen permeability method can be used for machine performance evalua-

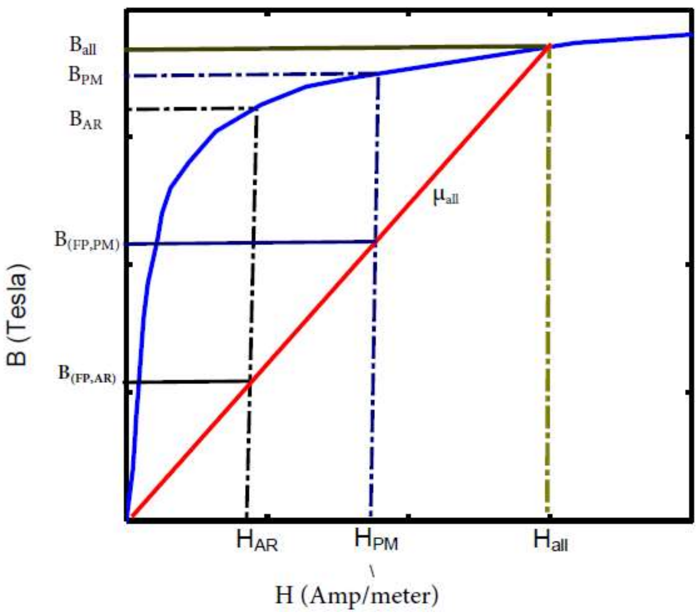

Figure 1.3: Principle of the Frozen Permeability Method

tion using superposition technique. In frozen permeable method, for each time step, the FEM model of the machine is simulated under loaded condition and magnetic permeability of every element is stored. Then, machine is again simulated with PMs (H_{PM}) and armature currents (H_{AR}) excitation independently but material permeability assigned for this simulation is the stored magnetic permeability. Hence, the flux density due to the magnets and armature are $B_{(FP,PM)}$ and $B_{(FP,AR)}$, respectively as shown in the Figure-1.3. As $B_{all} = B_{(FP,PM)} + B_{(FP,AR)}$ is the flux density corresponding to the excitation of both sources at a time, hence, the no load PM and armature field can be decoupled.

The magnetic saturation of each elements of machine's FEM model is different. This changes with load current and load angle. For an accurate analysis, the magnetic properties of each element at every time stepping is required to be stored when machine is loaded, and to reassign the magnetic property while analysing the machine for single excitation. Hence, the analysis requires high storage, efficient computer memory and took longer time.

1.4 Challenges

Based on the literature survey for the PM machines analysis, following challenges are identified

- The concept of frozen permeability is considered for the accurate prediction of saturated PM machine performance. However, this is time consuming method, hence, not suitable for initial machine design.

- The E-Cored modular PM machines are inherently fault tolerant machine. Hence, these machines are suitable for safety critical applications such as fuel pump motor and actuators in aircraft applications. However, the magnetic flux gaps between two adjacent E-core, adversely influences airgap flux density and therefore, machine power density.

- Cogging torque in the PM is critical issue for the servo drives. The methods proposed in the literatures for the cogging reduction adversely affects the machine performance such as lowering the airgap flux density, linkage flux and power density.

1.5 Objective and Problem Statement

The objective of this thesis is to develop analytical model to take account of the magnetic saturation (in case of saturated PM machine), magnetic flux gap (in case of E-Cored PM machine), skewed AFPM machine (for cogging reduction) and skewed slot opening radial flux PM machine (for cogging reduction). The focus of the thesis are

- First analytical model is developed for the analysis of saturated PM machine. This work is focused to reduce the time consumption, while estimating the machine performance at the initial stage of the machine design. The analytical model mainly focused on the two variants of PM machines viz., radial flux PM machine and axial flux PM machine.

- In second analytical model, the focus is to analyse E-cored stator PM machine(modular PM machine). Two category of the machines i.e. modular PM machine with open slots and modular PM machine with semiclosed slots, are considered. The analysis aimed for the evaluation of machine performance and further used for the performance improvements.

- The third analytical modelling method is used for the reduction of cogging torque in the PM machine. Using analytical method of analysis, a new PM machine with reduced cogging torque is proposed and analysed.

- At last, an analytical model is developed for the analysis of skewed magnet axial flux machine. The analytical model development is focused on the reduction of cogging torque in AFPM machine, and comprehensively studies the influences of stator slot shapes and type on the cogging torque in the machine.

1.6 Structure of Thesis

This thesis is arranged into seven different chapters. A brief description of these chapters are as follows:

Chapter 2 develops simplified analytical model for analysis of saturated radial flux PM machine. The analytical model is developed using subdomain analytical technique, and focused on the consideration of machine teeth saturation. The derivation of all governing field equations in all regions and their analytical solution is proposed. The evaluation of machine performance using the proposed analysis is obtained and results are verified with FEM analysis. The analysis is validated at different level of teeth saturation.

Chapter 3 develops simplified analytical model for analysis of saturated AFPM machine. The magnetic field distribution in the machine is determined using Maxwell equations analytically. The development of model is comprehensibly described and machine performance is evaluated. The analytically obtained results are verified with FEM simulated results.

Chapter 4 develops analytical model for modular PM (E-cored stator) machines. The analytical modeling is proposed for two variants of the modular machine, and analytically obtained results are verified with FEM simulated results. Based on the analysis, and investigation, further modifications are carried out to improve the performance of the machine.

Chapter 5 proposes a new PM machine for cogging torque reduction. The machine stator slot opening is skewed over the slot angle. An analytical model is developed for the analysis of this machine. The performance is evaluated and compared with FEM results. Further, a comparative study of proposed machine and regular PM machine is carried out.

Chapter 6 proposes a semi-analytical modeling for investigation of skewed magnet

AFPM machine. The proposed analysis is described and results are validated with FEM analysis. Further, investigation is carried out to quantify the influence of stator slot shapes on performance of the AFPM machine.

Chapter 7 concludes the thesis and suggests the scope for the future work.