Introduction

1.1 Introduction

Many countries are facing the problem of energy management [1], due to poor economy [2]. This problem gets aggravated with the hike in fuel prices, and degradation in the coal store and natural reserves, on which the generating stations depend for fulfilling the energy demand [3], [4]. These energy sources are not only affecting the economy but also raise the climate issue [5], [6] and environmental problems [7], [8]. Therefore, the world is shifting its focus toward renewable energy resources [9], [10]. These energy resources are safe, reliable, clean, sustainable and cost-effective alternative to conventional energy resources [11], [12]. The renewable energy resources like biomass, solar energy, wind, hydro and geothermal are locally available in many areas [13], [14]. Among all the renewable energy resources wind energy is rapidly growing energy sources [15], [16], [17]. This energy source is quite popular because of cheap, clean, carbon emission-free and eco-friendly energy resource [18], [19], [20]. Unlike solar energy, wind energy is available during both day and night [21]. The wind turbines are normally installed on coastal areas, hilly areas and sometimes on the seabed/ offshore [22].

The world has realized the potential of wind energy that is why many countries are heavily investing in wind farms development projects across the globe. According to the global wind statics 2017 report [23], from the year 2001 to 2017 the global cumulative wind capacity installed has increased by 2157.66%. At the end of 2016, the global cumulative wind capacity has reached 487.657 Gigawatts (GW). Almost 55 GW of wind power capacity was added in 2016 alone. Half of the added capacity was from Asia which is seeing tremendous growth in the wind power development, with capacity addition totaling just over 27.7 GW. In terms of annual installations, China maintained its leadership position, although annual grid-connected capacity in China dropped by almost 24 percent. China added 23.4 GW of wind power capacity, highest by any country which accounted for one-third of total global capacity by year's end.At the end of 2017, the global wind cumulative capacity has reached 539.581 GW. The worldwide growth in wind power installation capacity from 2016 to 2017 is 51.924 GW. The major contributing countries in the wind power installed capacity in 2016-2017 are China, USA, Germany, U.K., India, Brazil and France. The wind power installed capacities of major contributing countries have increased in China by 19.5 GW, the USA by 7.017 GW, Germany by 6.581 GW, U.K. by 42.70 GW, India by 4.148 GW, Brazil by 2.022 GW and France by 1.694 GW. Outlook projected the worldwide capacity will reach over to 1.7 Terawatts (TW) by 2050 [24]. According to MNRE expert group report, India has set a target to generate 60GW power through the wind energy by 2022 [25].

Due to the fast growth and high expectations from the wind energy, the components of the wind turbine system have undergone numerous technological developments. The main components of installed wind power conversion systems are wind turbine, generating system, gearbox, power electronics converters, transformer, monitoring units, and controller. The technological advancement in aerodynamics, structural dynamics, and micrometeorology has led to 5% excess energy generation from wind turbines annually [26]. The tower of the wind turbine supports the two parts namely rotor and nacelle. The nacelle is occupied by the generator, converters, transformer, monitoring units and control devices. The wind turbines are categorized into two parts namely the vertical axis and horizontal axis. The aerodynamic performance of horizontal wind turbines is found better than the vertical wind turbine due to which horizontal axis wind turbine are widely adopted in large-scale power generation [27], [28]. These wind turbines may be of roof-top type, standalone type and grid connected. The components of the typical wind power system are shown in Fig. 1.1 [29]. In the wind power system, wind rotates the blades of the turbine which are connected to the low-speed shaft of the gearbox. The gearbox transfers the mechanical energy to the generator and the generated electrical energy from the generator passes through the power electronic converter which provides the constant voltage and frequency to the input terminal of the transformer and then the voltage is step-up by a transformer to feed the power into the grid.

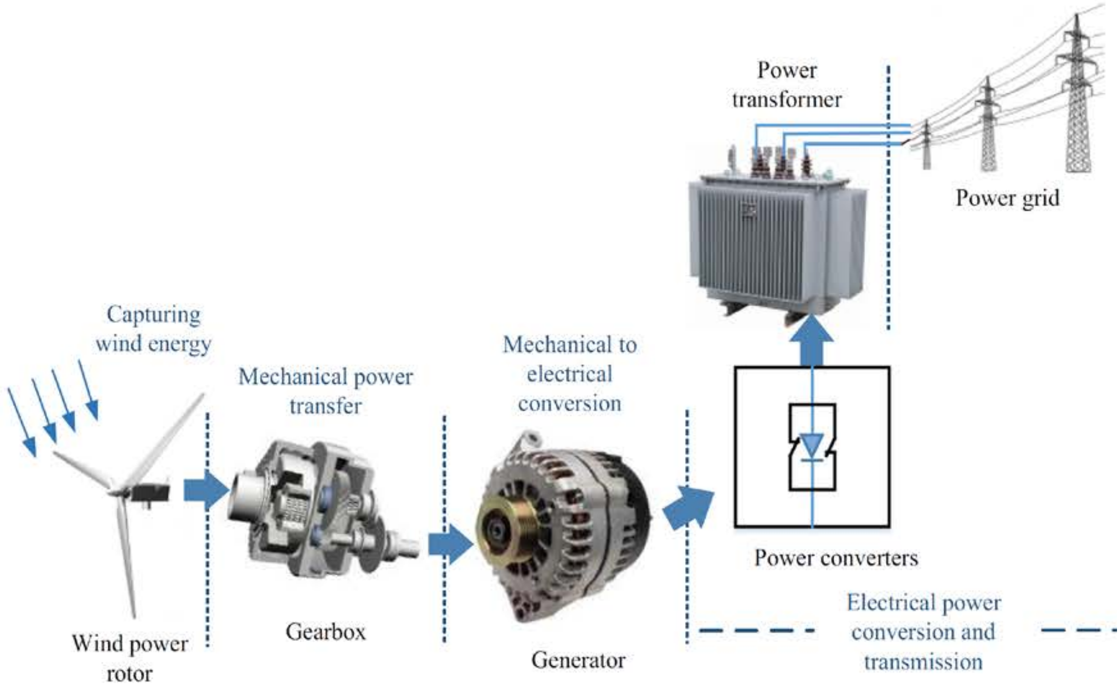


Fig. 1.1. Components of typical wind power system [29]

1.2 Different wind Turbine Generators

Broadly there are five types of wind power generator namely- SCIG, WRIG, DFIG, EESG and PMSG [30], [31]. The squirrel cage induction generator is directly connected to the standalone system as shown in Fig. 1.2. It can generate power within 1% of speed near to synchronous speed for a large rating of the generator. To achieve the speed near to synchronous speed, the generator shaft is to be connected with the gearbox which increases the generator speed. The power-generating range of rotor speed is very narrow so this type of generator is known as fixed speed generator. The required reactive power for generating electrical power can be provided by the grid or a capacitor bank. This type of generating units was popular in 1980s because of its ruggedness, low price and relative ease of mass production [32-35].

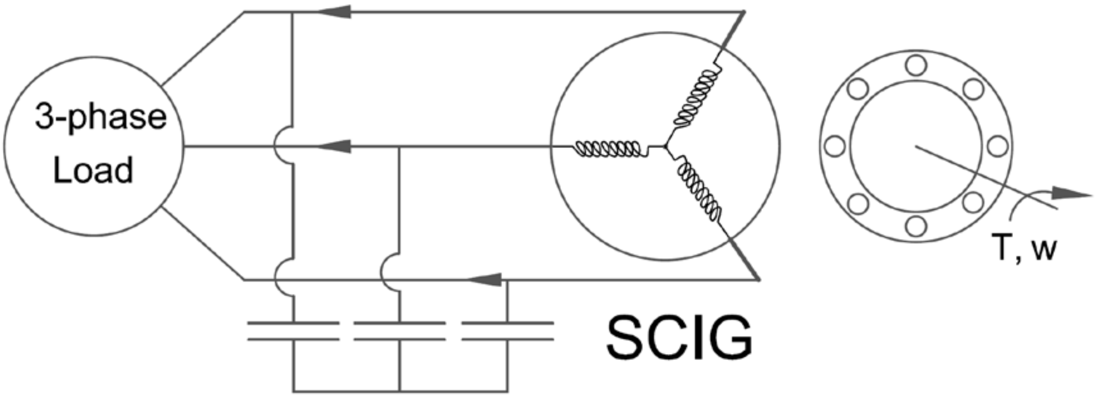


Fig. 1.2. Squirrel cage induction generator

The generating speed range can be enhanced by adopting resistance controlled wound rotor induction generator as shown in Fig. 1.3. In this arrangement, the stator is directly connected to the grid or standalone and a large rating of resistor is connected in the rotor winding [36] which allows varying the rotor speed within 10% range of the synchronous speed. The heat loss in the resistor makes the generator inefficient and slip rings require frequent maintenance of the system [37], [38].

The rotor resistor in a WRIG is replaced by a power converter to provide separate excitation. Since the power is fed to the 3-phase load by both the stator and rotor so it is known as doubly fed induction generator (DFIG) as shown in Fig. 1.4 [39], [40]. The power electronic converter enables the induction generator to generate electrical power up to 30% speed range near to the synchronous speed [41], [42].

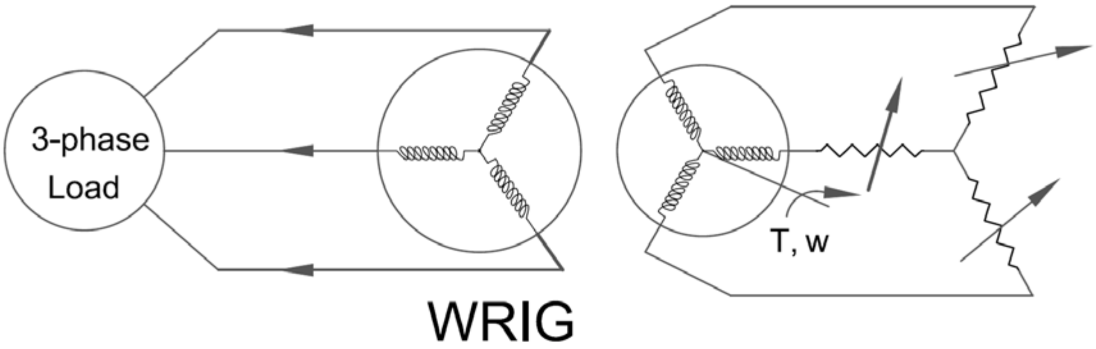


Fig. 1.3 Wound Rotor Induction Generator

In this arrangement, stator winding is directly connected to the grid and the rotor is also connected to the grid with the help of fractional rated power electronic converter. The rating of the converter required is 30% of the rating of the generator to buck or boost the rotor generated voltage and frequency, to regulate the load terminal voltage and frequency requirements [43], [44], [45].

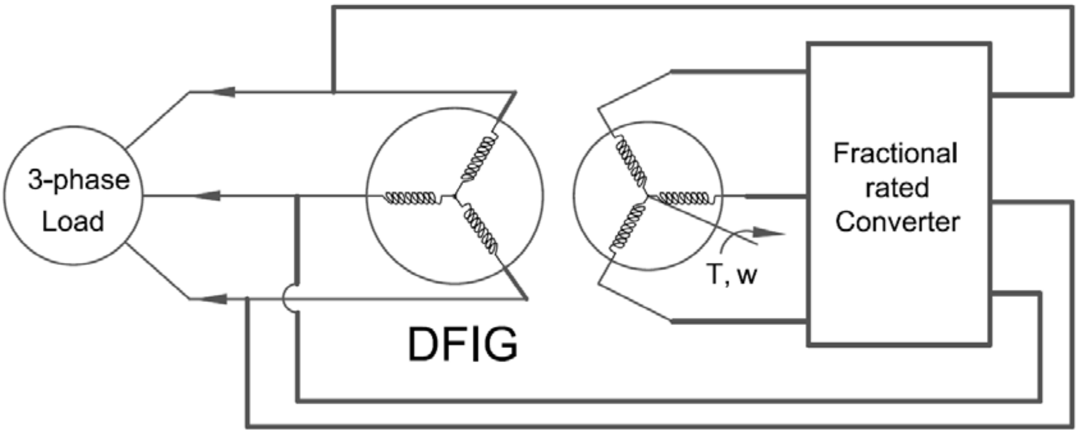


Fig. 1.4 Doubly Fed Induction Generator

There are mainly two types of synchronous wind generator namely electrically excited and permanent magnet (PM) excited synchronous generator as shown in Fig. 1.5 and Fig. 1.6, respectively. The stators for both the types of generator are same but the rotor periphery of the electrically excited generator is housed by direct current (DC) winding. The rotor winding is excited by the DC power using slip rings and connected to the load via power electronic converter [46], [47]. The other kind of generator is the PM excited synchronous generator. The rotor of the permanent magnet generators is directly connected to the rotor of the wind turbine, so there is no requirement of gearbox system which makes the system reliable and lighter [48], [49] and requires less space in the nacelle of the tower. Since the rotor is directly connected to the rotor of the turbine, so this is also known as a direct drive system [50], [51]. This wind turbine generating system is able to generate the electricity at full-scale of the speed of the generator. The stator of this generator is connected to the grid via power electronic converter having the same rating as the generator. The rotor of consist of permanent magnets which provide the magnetic flux in the air-gap. Since there is no requirement of winding and slip rings on the rotor so system becomes lighter and reliable [52], [53]. The main drawbacks of this type of generating systems are the cost of the permanent magnet and demagnetization of low-grade PM due to armature reaction, during short-circuit faults [54], [55].

There are several PM materials which can be used in the PM generator. The most common PM materials are ferrites, AlNiCo, Samarium Cobalt (SmCo) and neodymium iron boron (NdFeB). However, the ferrite material has a very low value of $(BH)_{max}$, this was the most promising material in 1950s before the development of AlNiCo in 1960s. The SmCo became very popular in the 1970s owing to the high value of $(BH)_{max}$ and high value of temperature demagnetization value upto 350^{o}C [56]. Nevertheless, SmCo was quite expensive. Since the 1980s the NdFeB become commercially available which has a very high value of $(BH)_{max}$ [57] and is cheaper than SmCo. Due to this, NdFeB is very popular in permanent magnet machine, although the demagnetization temperature range of NdFeB is around 180^{o}C which is lesser than the SmCo [58], [59], [60].

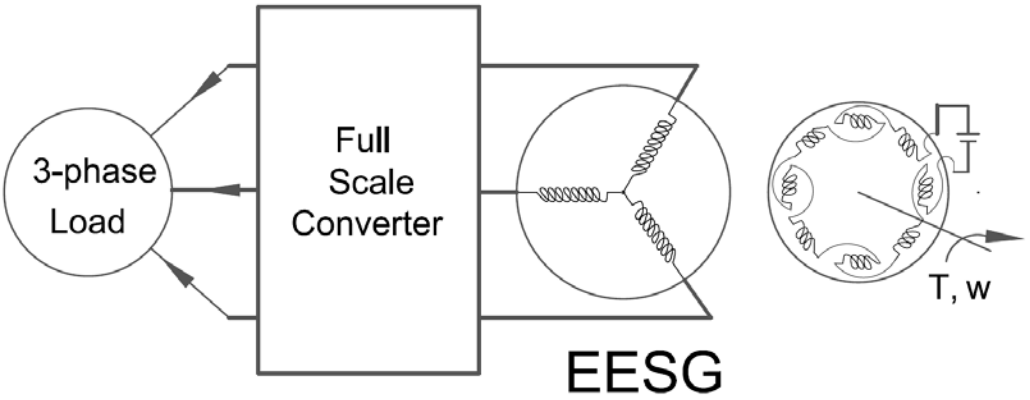


Fig. 1.5 Electrically Excited Synchronous Generator

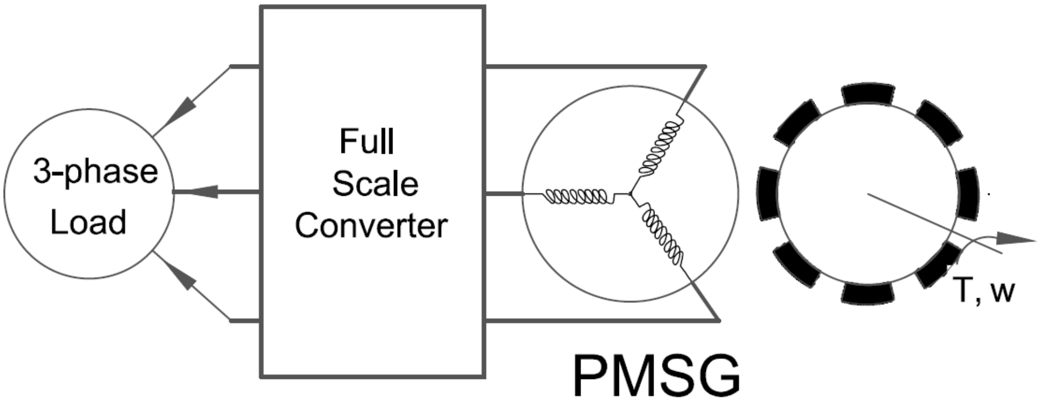


Fig. 1.6 PM excited synchronous generator

1.3 Permanent Magnet Synchronous Generator

The PMSGs has several advantages as discussed above, due to which it is a favorable choice for the direct drive wind power application. On the basis of flux path orientation, PMSGs are divided into three categories namely radial flux, axial flux, and transverse flux PMSG. They can be further divided on the basis of the number of rotor and stator structures. There are four such structures possible namely single stator single rotor PMSG, dual stator single rotor PMSG, single stator dual rotor, and dual stator dual rotor PMSG.

1.3.1 Radial Flux PMSG

Radial flux machine is the most common configuration of the AC machine in which magnetic fluxes are oriented in the radial direction [61] as shown in Fig. 1.7. This machine has a smaller diameter and larger axial length [62]. There are several structures of permanent magnet rotors which are surface mounted, surface inset type, buried type, V-shape buried type and permanent magnet assisted reluctance machine [63], [64], [65].

1.3.2 Axial Flux PMSG

Axial flux machine has the orientation of the magnetic fluxes in the axial direction as shown in Fig. 1.8 [66]. Generally, the diameter of the axial flux machine is larger than the axial length due to which it has the disc shape construction [67]. It can be used in the application where the length of space is limited. The axial flux machine has several advantages like high power density, high efficiency, high torque to volume ratio and less maintenance which enables it for several applications like wind generator, electric vehicles, aircraft and electric traction [68-72].

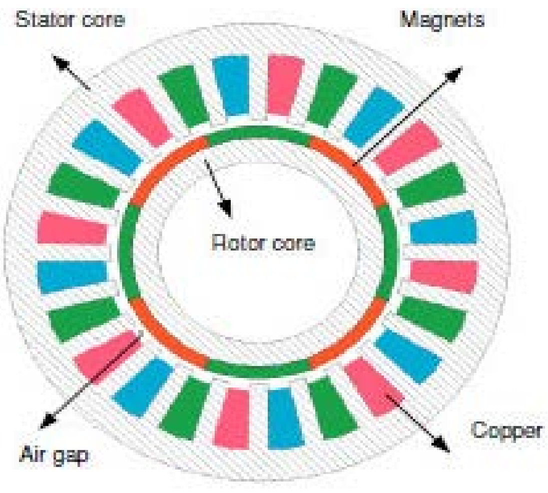


Fig. 1.7 Radial Flux PMSG

In comparison to the axial flux PMSG, radial flux PMSG is simple in construction, rugged, no attractive force, reliable and less requirement of permanent magnet materials [73], [74], [75]. Due to the magnetic pull in single-sided axial flux machine, it requires a strong construction to maintain the air-gap constant [69]. The problem of magnetic pulling can also be resolved by shifting the single-sided axial PMSG to the double-sided (either dual rotor or dual stator arrangement) axial PMSG as shown in Fig. 1.9 [76], [77], [78].

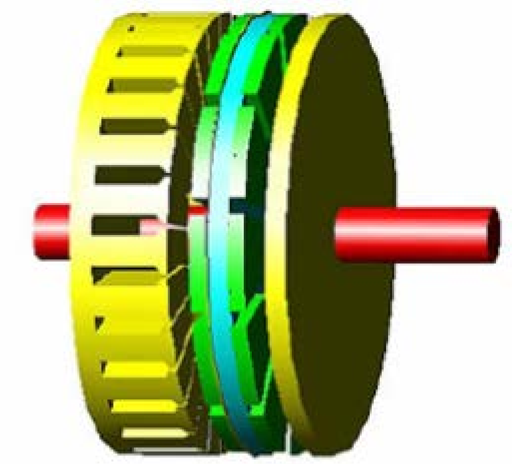


Fig. 1.8 Single Sided Axial flux PMSG [66]

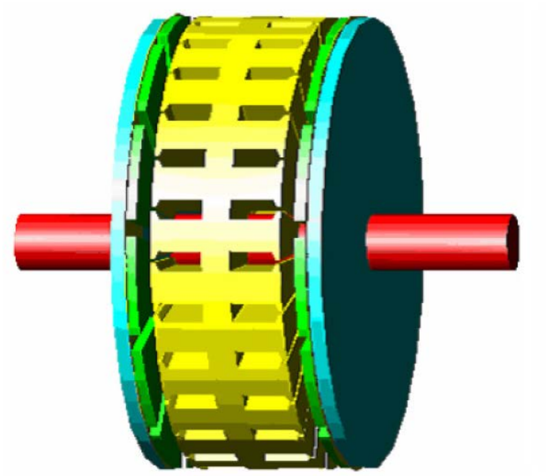


Fig. 1.9 Double Sided Axial flux PMSG [66]

1.3.3 Transverse flux PMSG

In a transverse flux machine, the plane of flux is perpendicular to the direction of rotor rotation as shown in Fig. 1.10. In this machine, the number of windings is equal to the number of phases and is independent of the number of poles. The most attractive feature of this machine is that both the current loading as well as the magnetic loading can be adjusted in dependently [79-82]. This machine has a high number of poles so having the advantage like high power density and high torque density and hence suitable for a low-speed application. It has a low winding loss and a high force density compared to axial and radial flux machine [83]. In [84], a light weight transverse flux direct-drive wind generator has been proposed by the reduction of the active material from the popular modules of transverse flux machine. The higher number of poles increases the leakage flux due to which the power factor becomes lower. The transverse flux machines have the drawback of high leakage flux, high cost, low power factor, mechanically not reliable and very difficult to construct using iron alloy steel. Because of which it is not used in small-scale power generation [85].

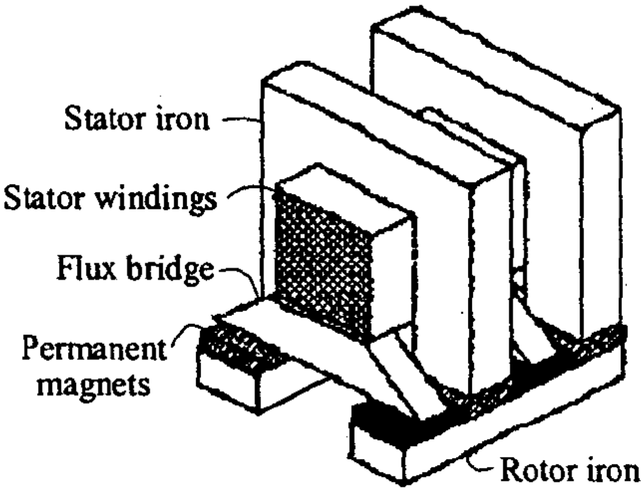


Fig. 1.10 Transverse flux machine [82]

1.4 Different Topologies of PMSG

The high power density, high efficiency and reliability are favorable features required for the wind turbine generator. The improvement in these features can be possible by the structural changes of rotor or stator arrangement. For the single stator single rotor PMSG topology, it can be achieved by the different arrangement of magnet either inside of rotor or on the surface of the rotor. The multi-layer arrangement of magnet provides the higher flux density in the air-gap which enhances the generator performance. The different layer of the magnet and V-shape of magnets arrangement of permanents are arranged in such a way that the magnetic fluxes can assist to each-other, as a result, a high value of air-gap flux can be achieved as shown in Fig. 1.11 [86] and Fig. 1.12 [87].

Topologies using dual stator single rotor or single stator dual-rotor or dual stator dual rotor have been reported to improve power and torque density [88–93], and cogging and ripple torque minimization [94], [95]. In the dual stator single rotor PMSG, the rotor consists of two sets of an equal number of magnets. These magnets are arranged such that the magnetic flux can assist each-other and setup a common flux in the air-gap as shown in Fig. 1.13. The common flux in both the air-gaps can also be achieved by dual rotor single arrangement as shown in Fig. 1.14.

Though the circumferential flux barrier for dual stator PM machine is reported in [96] as shown in Fig. 1.15, the machine behaves as two isolated single stator single rotor arrangement. For proper utilization of magnets, the mean flux densities in the two air-gaps for single stator-rotor system arrangement cannot be greater than 50% of the magnet remanence flux density (Br).

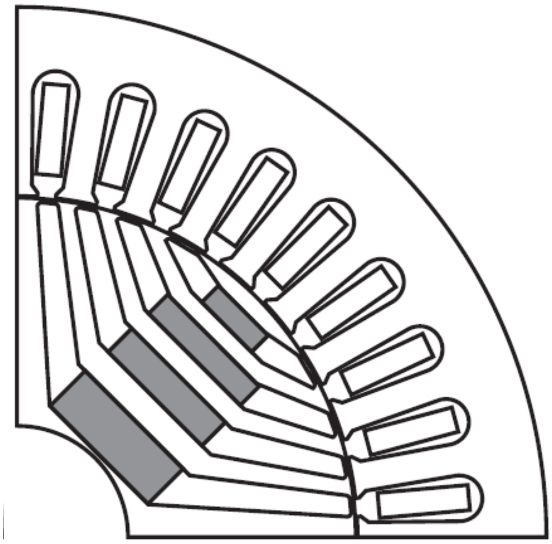


Fig. 1.11 Multi-layer PM rotor PMSG [86]

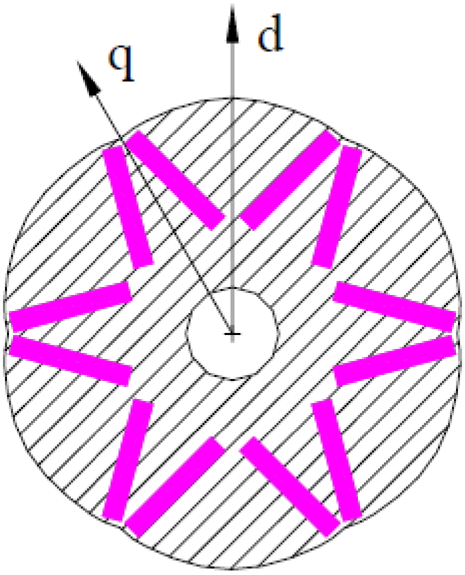
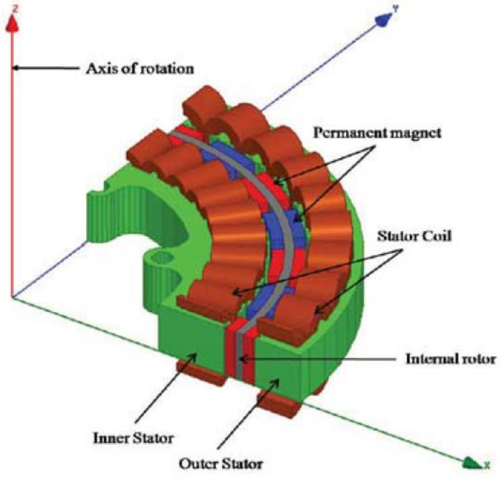


Fig. 1.12 V-shape PM rotor-PMSG [87]



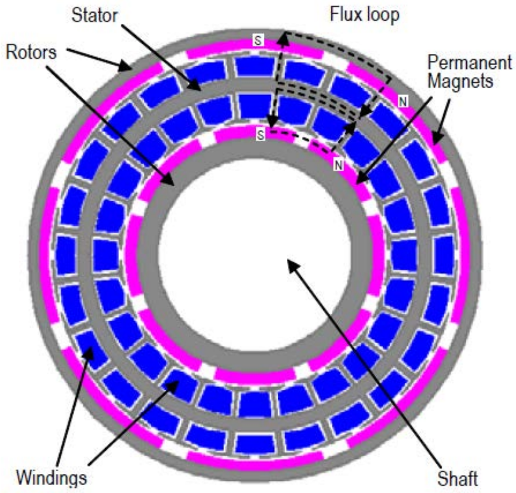


Fig. 1.13 Dual stator Single rotor PMSG [105]

Fig. 1.14 Dual rotor Single stator-PMSG [102]

The several researches have been reported for high power density and torque density. Ronghai Qu has reported a novel single stator dual rotor toroidal wound permanent magnet machines to improve the torque density and efficiency of the machine [97]. Xiping Liu has proposed a novel dual-stator hybrid excited synchronous wind generator as shown in Fig. 1.16 and carried out their electromagnetic performances using the magnetic circuit approach and validated with the FEM results and experimental results [98].

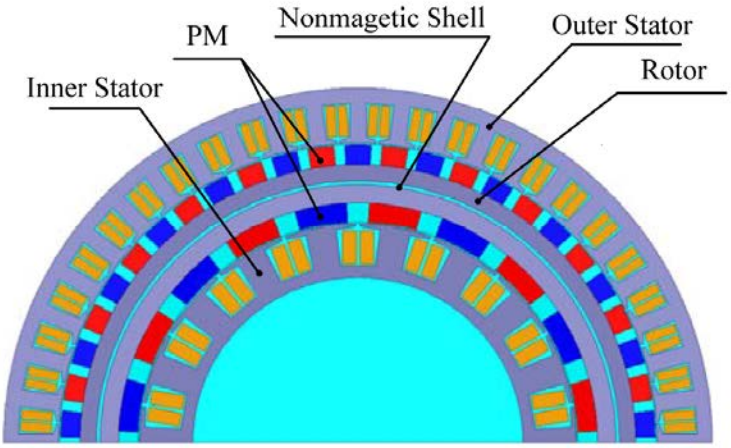


Fig. 1.15 Dual rotor single stator PMSG [96]

Alfredo has reported a new dual stator winding induction machine drive in which two sets of winding can produce two independent torque which can be controlled to produce at any desired combination of output torque [99]. A.S.O. Ogunjuyigbe has reported the modeling and analysis of dual stator-winding induction machine using complex vector approach [100]. Peterpisek has reported performance comparison of double rotor single stator and single rotor single stator permanent magnet machine and found that dual rotor has good performance but the system becomes more complex and dual-rotor is only preferable if it essential otherwise single rotor system should be preferable for hybrid electric vehicle application [101]. Ronghai Qu has reported a comparison of performance of dual-rotor radial-flux and axial-flux permanent-magnet BLDC machines and found both are having similar performance but the material cost of axial flux machine is higher than the radial flux machine [102]. Y. Kano has reported a Simple Non-Linear Magnetic circuit model analysis to maximize the torque of double-

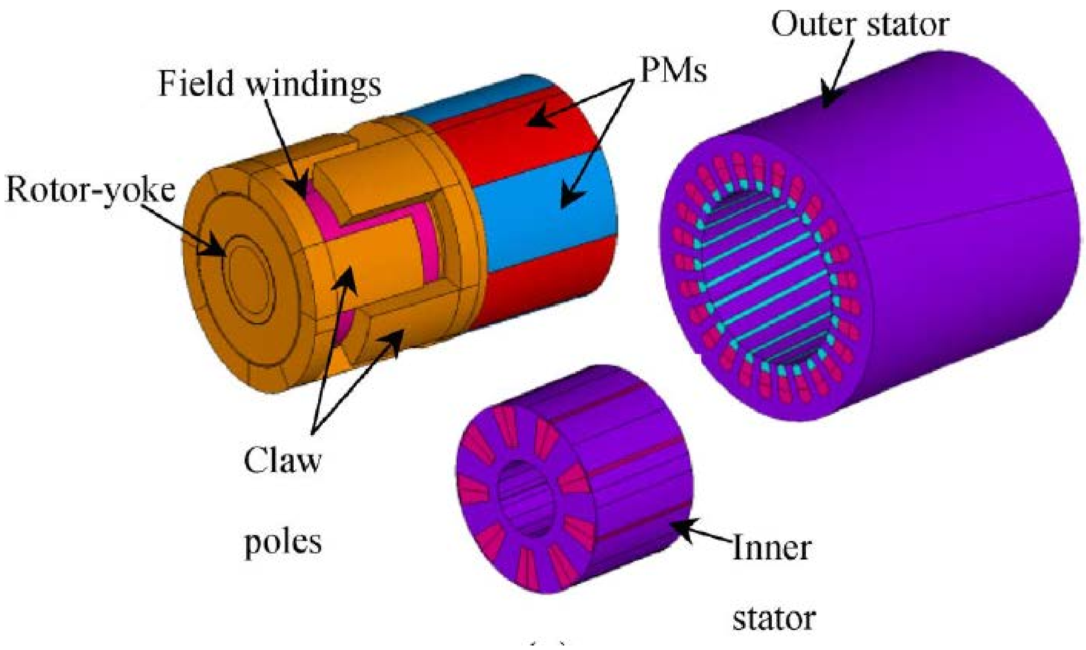


Fig. 1.16 Dual stator hybrid excited rotor PMSG [98]

Stator axial-flux PM machines [103]. A. M. Gazdac has reported a simple magnetic equivalent circuit approach to design and analysis of performance for dual-rotor Permanent Magnet Induction Machine [104]. Gyeong-Chan Lee has reported that the cogging torque can be reduced by the considering the optimal design for dual stator single rotor PMSG [105]. P. Sivachandran has reported the reduction in cogging torque by tuning the pole width and stator slot opening for the dual-rotor permanent magnet generator [106]. Lucian Nicolae Tutelea has reported a magnetic circuit approach to design analysis of performance and control of single stator dual PM rotors axial synchronous machine for hybrid electric vehicles [107]. Fengge Zhang has reported the design and analysis using magnetic circuit approach for a novel wind-power permanent magnet generator with opposite-rotation dual rotors [108].

1.5 Multi-Phase PMSG

The power density, fault tolerant capability, cost-efficient,and reliable operationare further enhanced by multi-phase system. Due to a higher number of phases, the phase current reduces without affecting the voltage for the same power rating. This reduces the peak-peak amplitude of ripple torque and increases its frequency, resulting in quiet operation. Furthermore, multi-phase reduces the DC link capacitor size [109], [110]. Though six phase machines have also been reported, the five-phase machine of similar volume and same slot per pole per phase (SPP) provides 6-8% higher current for similar output power. However, due to lesser number of phases, 5-phase offers 20% copper saving, enhancing the power density of the machine [111]. A comparative study of 3-phase, 5-phase and 6- phase is presented in Table 1.1. Fewmore advantages of five phase structure include the capability of continuous operation with one or two faulty phases, ability to allow smaller amplitude of currents, low torque ripple and smooth operation with less noise [112-114]. Multi-phase generator possesses fault tolerance capability since they can operate stably even when more than one phase is under fault, with acceptable output. It has inherent features of minimizing the space harmonics, torque ripples and suppressing the vibrations, due to which it is suitable for direct drive wind power applications [115-117]. With optimized design, the torque ripple and harmonics in the generated voltage could be further reduced.

Table 1.1: Comparison of performance of 3, 5 and 6 phases [111]

Parameter	**3-phase**	**5-phase**	**6-phase**
Ripple Torque	Highest	1/3 of 3-phase	Approximately 30% lower than the 5-phase
Output phase current	Less than 5-phase	6-8% Higher than 3-phase and 6-phase	Less than 5-phase
Maximum Power Density	Smaller than 5 and 6-phase	Highest	Less than 5-phase but higher than 3-phase
Line to line voltage	1.732 times of phase voltage	1.902 times of phase voltage	1.732 times of phase voltage

1.6 Design Analysis of Generator

The design analysis is required for the enhancement of the machine performance. The machine performance is determined by two analyses namely electromagnetic analysis and thermal analysis as shown in Fig. 1.17.

The electromagnetic analysis is concerned with the enhancement of electromotive force (EMF), power density, efficiency, overload capability. The thermal analysis is required for the selection of insulating material, selection of PM and core material and ensuring the proper cooling of the generating system. The main objective of the optimal design is to take all the features into account during the analysis as shown in Fig. 1.18.

To design and analyze a generator, mainly two techniques are reported, analytical and finite element analysis. In FEM, for the calculation of electromagnetic field distribution, the geometry has to be discretized and thus the solution becomes more complex, time-consuming but at the same time, accuracy improves [118]. Analytical models are important tools for design, analysis, and optimization of electrical machines because; these are very quick in computing the electromagnetic field solutions.

In [119], [120] authors have reported an analytical model and computed the performance of PM machines based on subdomain modeling technique but it requires enough information about boundary conditions and mathematical calculations are rigorous. Reluctance network modeling is popular simplified technique owing to its simplicity, fast and accurate prediction of performance for all kind of machines. In this context, the machine is represented by lumped parameter reluctance network and the reluctance of air gap is modeled considering the effective air gap length using the carter coefficient. This accounts for the slotting effect of the machine for the performance evaluation [121]. The leakage flux affects the performance and the analysis is effectively evaluated [122] in terms of flux density distribution.

Today, researchers are working on variable air gap reluctance network which implies reluctance of air gap varies with variation in the position of the rotor which in turn provides an actual variation of the presence of the air gap. This accounts for the actual distribution of flux in the air gap. For computation of interaction between stator teeth and PMs, many techniques have been proposed [123]. Few papers have incorporated the effects of saturation, slotting and armature reaction in the machine reluctance network model for performance evaluation and optimization. In addition, modified RNM is proposed that included variable reluctances to perform dynamic modeling. The RNM is a good compromise between accuracy and computational time of magnetic field calculations [124]–[126].

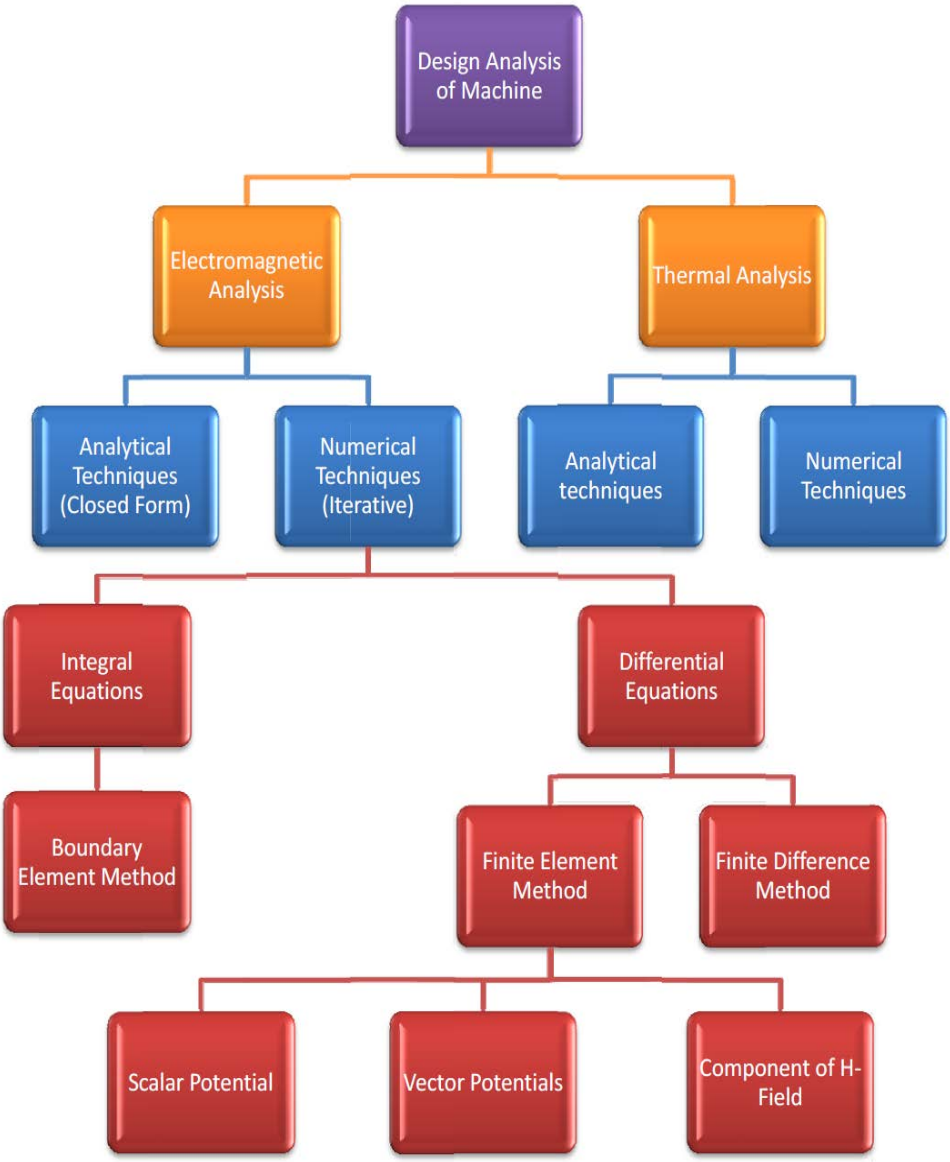


Fig. 1.17 Design Analysis of a machine

1.7 Thermal Modeling

The optimal sizing of electrical machine is done by carrying out thermal analysis in Conjunction with the conventional electromagnetic analysis. The rating and life span of an electrical machine is primarily decided by the temperature rise in a specified frame size. Excessive temperature rise create adverse effects on the insulating materials such as deterioration of insulating material, mechanical deformation and fatigue. The main cause of insulation deterioration is increased oxidation process resulting in a complete loss of dielectric property [127].

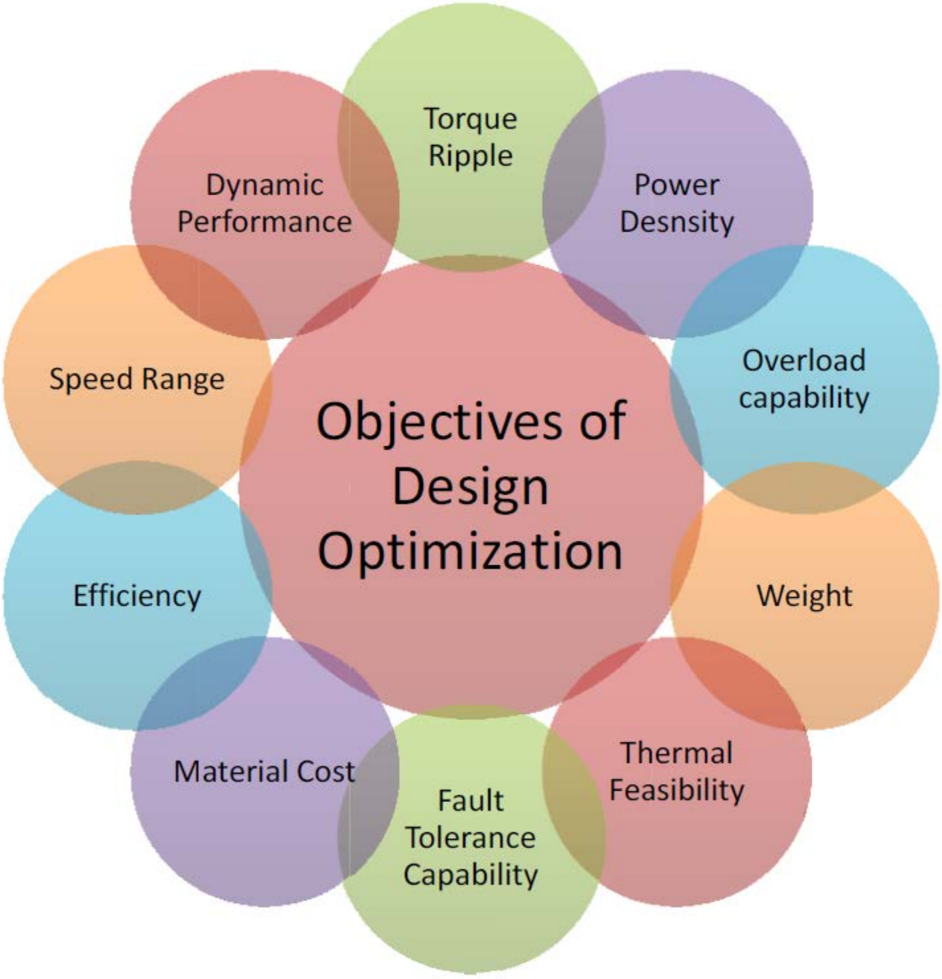


Fig. 1.18 Objective of design Analysis

It also causes demagnetization of PM when local temperature exceeds beyond Curie temperature. Permanent magnet and insulation of PMSM are two important components sensitive to temperature. As the temperature rises operating region of magnet keep on reducing. Eventually beyond a certain temperature permanent magnets do not have any operating region and is totally demagnetised, causing complete failure of permanent magnet machine [128]–[131]. Similarly insulation of winding has temperature limitation. Currently magnets with operating temperature of 180^{O} C or more are available [132], but still dependence of their operating region on temperature. It is essential to monitor the rise in temperature for design and practical application of motor. The problems of demagnetisation of magnet, deterioration of winding insulation etc. are already discussed in [133-135]. Though in present scenario great advancements in material properties of magnets has been achieved, considering the above mentioned problems thermal modelling becomes very important.

Broadly, thermal analysis can be performed using two methods. The first method is the finite element numerical technique, that provide accurate results for the conduction mode but the convection mode and the radiation mode are hard to model. Moreover, this approach has a limitation to include variation in the machine design parameters. The other method is based on lumped parameters, where the machine components are divided into numerous elements, each of them represents a node with a thermal capacitance and a heat source. These are interconnected with the thermal resistance to create an equivalent thermal network.

1.8 Objective of the Thesis

This thesis is focused on the design optimization, electromagnetic performance aspects and thermal model of PMSG for wind power application. For this, it requires an analytical method for theoretical design and their optimization with respect to dimensional parameters and material properties. The Improved Magnetic Circuit (IMC) is taken for this purpose for design. It is a fast and accurate method and predicts the electromagnetic performance by the help of magnetomotive force (MMF) sources and the reluctance of the network. This machine can further go for their thermal modeling for their temperature distribution inside the model because this model has a permanent magnet which is highly temperature sensitive. For the thermal modeling, the lumped parameter is most suited for it. For the further validation of the model finite element method is adopted for it.

To validate the developed model experimentally, two radial flux PMSG is designed, fabricated and tested.

The prominent contributions of the thesis are:

i. To find a suitable novel permanent magnet synchronous generator for wind power application.
ii. To design and performance analysis of the generator using improved reluctance network model and finite element model (FEM) analysis.
iii. To fabricate the two PMSGs for the validating the electromagnetic performance of the predicted result using the analytical method and FEM simulated results.
iv. To study the influence of design parameter on the electromagnetic performances of the permanent magnet generator.
v. To develop a simple lumped parameter thermal model for the proposed generator and validated with 2-D FEM analysis.

1.9 Thesis Layout

To achieve the above-mentioned objectives in section 1.8, this thesis is divided into six chapters as shown in the flow chart in Figure 1.10.

A brief description of them is given below:

Chapter 1. Describes the introduction and literature survey on the scope of wind power, different topology of permanent magnet synchronous generator, different analytical modeling and thermal modeling for PMSG.

Chapter 2. Describes the various analytical model for electromagnetic performances of single stator single rotor five phase PMSG (SSFP-PMSG) and Novel magnetically coupled Dual stator single rotor five phase PMSG (NMCDSFP-PMSG) and effect with dimensional parameters.

Chapter 3. Describes the fabrication and preliminary performance of both the PMSG.

Chapter 4. Describes the validation of the electromagnetic performance of both the PMSGs.

Chapter 5. Describes the thermal modeling of both the PMSGs.

Chapter 6. Describes the conclusion and Future work.

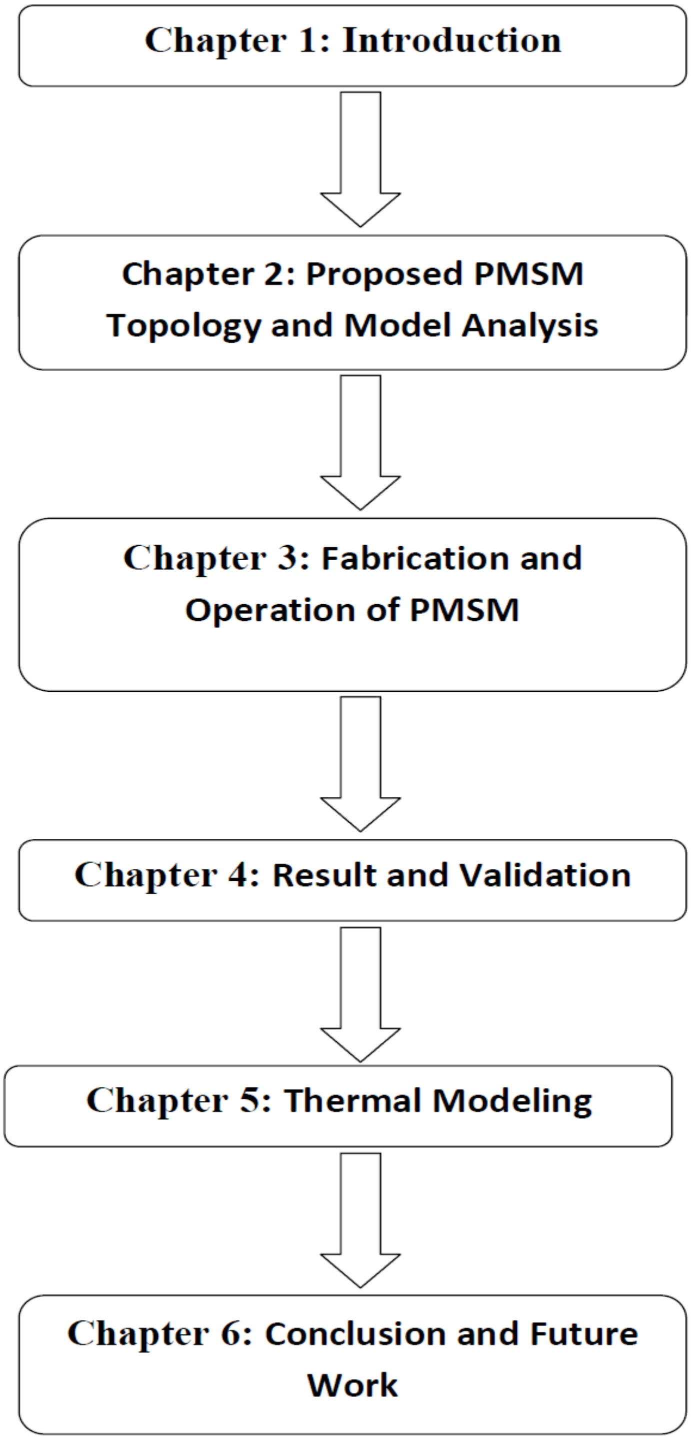


Fig. 1.19 Thesis layout

1.10 Concluding Remarks

The chapter has discussed the necessity and advantage of wind power generation. It is also discussed about the present and future trends of wind power generation capacity in the Worldwide, Asia and India. PMSG based wind-energy-conversion systems are more popular due to their distinct advantageous features. Dual rotor or stator topologies are adopted for their inherent properties like high power density as well as the more efficient than single stator single rotor PMSG for direct drive application. Multi-phase PMSG could be used because it will increase the generator reliability and fault-tolerant capability. The electromagnetic and thermal analyses are the two main components to enhance the performance of the system. The analysis is a concern to get the optimal design. This chapter reveals that dual stator PMSG is having better performance than single stator so novel dual stator topologies along with conventional single stator PMSG with their electromagnetic performance analysis are proposed in the next Chapter.