# **CHAPTER 1**

# **INTRODUCTION**

## Background of Wind Energy Harvesting

Although for thousand years of utilization of windy energy for basic applications like windmills and water pumps, utilization of wind for energy harvesting is never preferred because of its fluctuating and unknown nature. Like many developments in technology, modern wind energy utilization by means of wind turbines started 40 years ago due to search for alternative energy sources except oil, whose deficiency and high prices were a global crisis issue. Besides, air pollution and other environmental problems made it indispensable to search for clean and renewable energy sources such as wind. To summarize, OPEC crisis in 1970s and environmental problems worked as a catalyst in development progress of wind turbines. At first times of development, all the countries excluding Denmark tried to produce these wind turbines by experiences used in aerospace technology which has very high power ratings of MWs. After the understanding of the fact that produced turbines were bulky and inefficient in terms of reasonable cost of energy and required technology is different than the one used in airplane motors, all governments started to follow Denmark’s path. Denmark started the wind turbine technology by developing small wind turbines first and encouraged the individuals and small companies. These first turbines were operating at fixed speed and their structure was very simple. This concept of Squirrel Cage Induction Generator (SCIG) was called later as “Danish concept” and became a milestone for modern wind turbines. Today, more than 40 per cent of Denmark’s energy supply comes from wind power and the plan is to reach 50 per cent by 2020, as set out in the 2012 Energy Act. Total wind energy capacity in Denmark was 4,890 MW by the end of 2014, 3,620 MW onshore and 1,271 MW offshore [1]. Denmark has some of most important wind energy manufacturers worldwide such as [Vestas](https://www.vestas.com/) and [Bonus Energy A/S-lately was acquired by Siemens](http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/). Nowadays, there are different types of wind turbines exist in the market both in mechanical and electrical aspects. Global trend is going above 5MW of output power and especially generator technologies are under development in order to maximize produced energy [2]–[4].

Global annual and cumulative installed wind capacities between 2001 and 2016 are given in Fig. 1-1 and 1-2, respectively. As it can be seen from graphs, wind energy harvesting has an increasing trend.

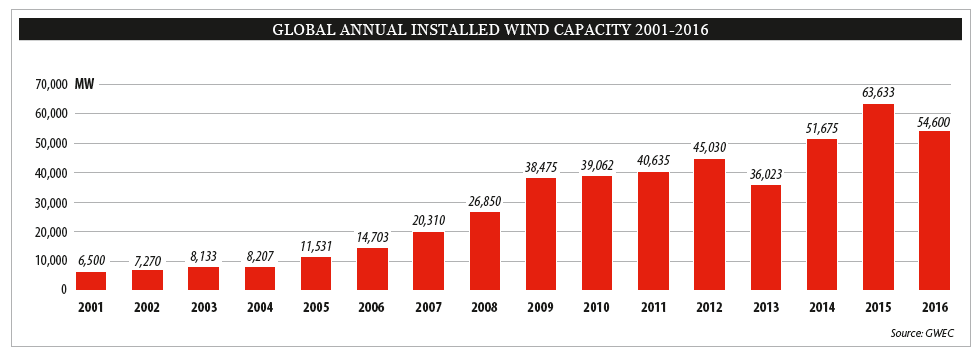


Fig. 1‑1. Global annual installed wind capacity 2001-2016 [5]

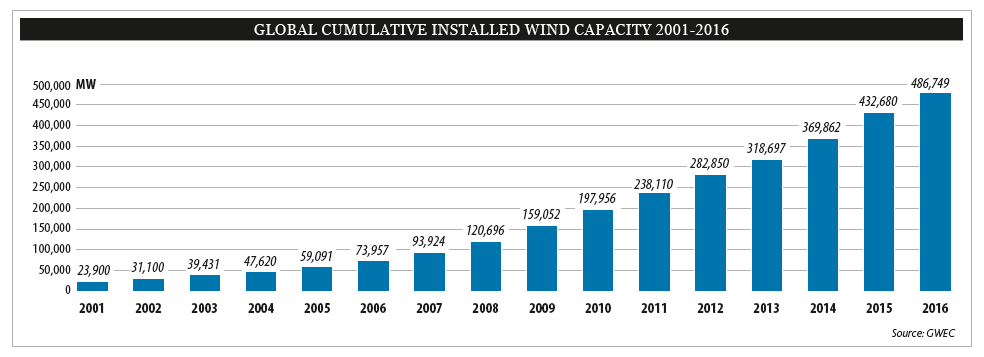


Fig. 1‑2. Global cumulative installed wind capacity 2001-2016 [5]

According to annual market update report of GWEC, it’s expected to reach 791 GW of global cumulative wind energy capacity by 2020, although it’s estimated that annual capacity growth rate will be stabilize around five percent level. Detailed market forecast of GWEC for 2016-2020 is given in Fig. 1-3.

Increase in utilization of wind energy in Turkey is very similar to global trends. Wind power supplied about 6% of Turkey’s electricity consumption in 2015 [6]. Turkey has nearly stable increase rate of installation rate of wind power plants for past 5 years. Fig. 1-4 shows the variation of cumulative installations for wind power plants in Turkey. Fig. 1-5 shows the global statistics of top 10 new installed capacity between January-December 2016. According to TWEA, it’s expected to reach total installed capacity of 10 GW, under the current regulatory framework. Turkey’s wind resources are estimated at more than 48 GW from areas with over 7 m/s wind speed at 50 meters height [6]. According to Renewable Energy Law, newly installed power plants are encouraged financially to come into operation by long-term (10 years) constant feed-in tariffs and additional bonus of up to USD 3.7 cent/kWh for using locally manufactured wind power plant parts [6].

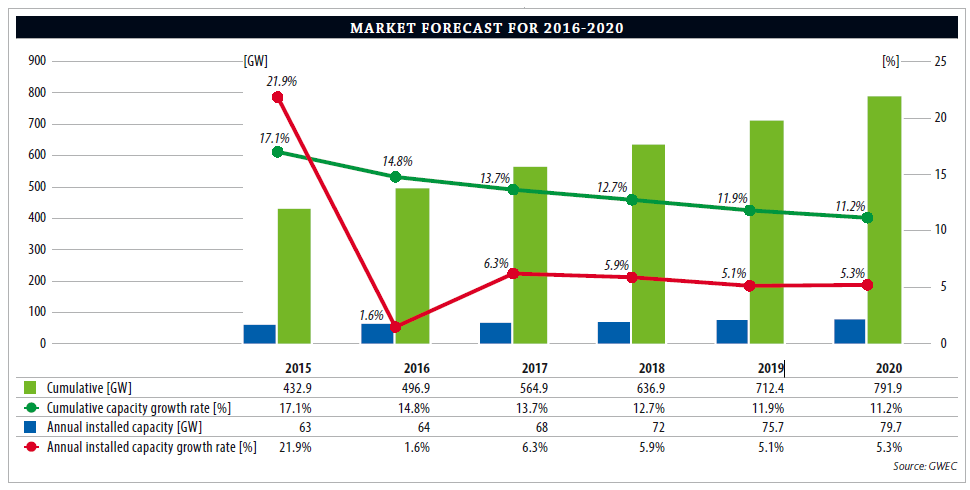


Fig. 1‑3. Global wind energy market forecast [6]

It can be concluded that from wind power capacity installation performance and financial growth support to newly installed wind power plants in the last decade, Turkey shows some promise to become in top 5 countries of wind energy capacity in next years.

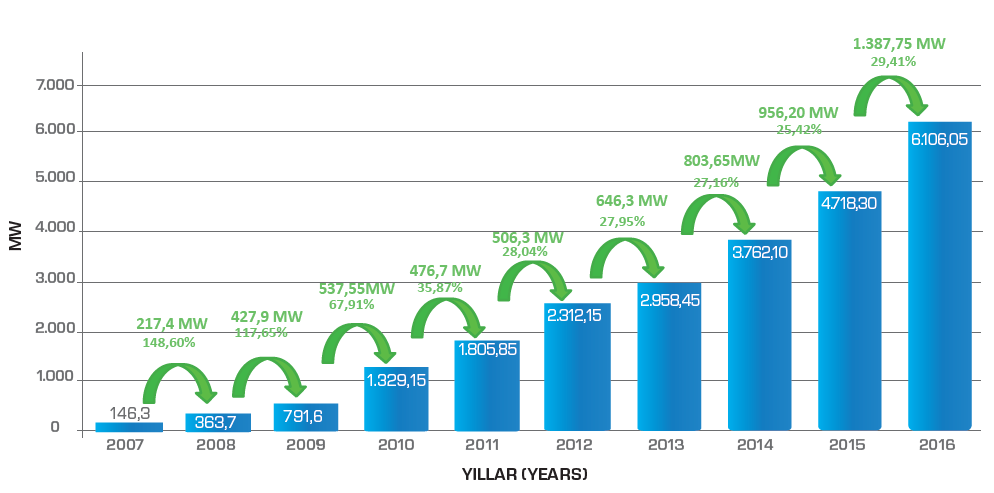


Fig. 1‑4. Cumulative installations for wind power plants in Turkey [7]

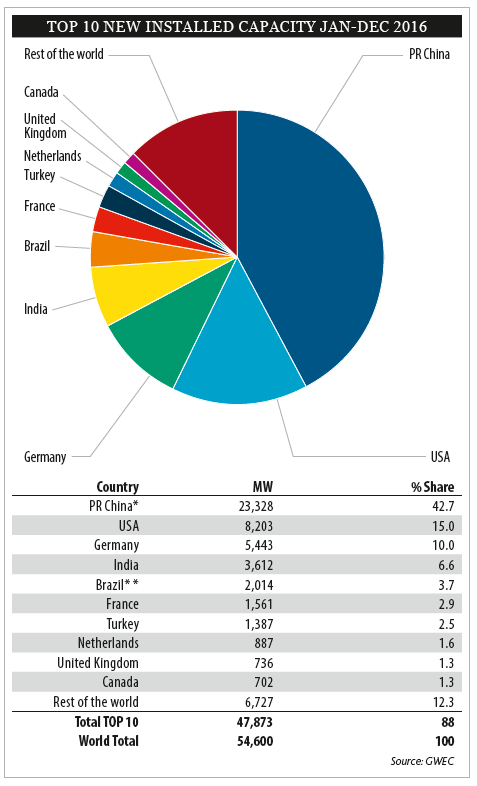


Fig. 1‑5. Top 10 new installed WPP(Wind Power Plant) capacity between January-December 2016 [5]

Wind turbine design is an important issue for renewable energy. Especially for the last decade its technology is substantially matured with variable speed applications. Although there are physical and aerodynamical limitations due to natural causes of wind phenomenon, different arrangements of wind turbine generator systems are invented to maximize the captured energy. By this improved technologies both in power electronics and generators, manufacturing and installation costs are reduced. Therefore, wind energy harvesting concepts started to penetrate the global markets. According to [8] the global installed utility scale wind power was 197 GW at the end of 2010 (an increase of 24.1%) while the global market for small wind turbines (SWTs) grew by only 4%. Evolution of wind turbine size and power electronics can be seen in Fig. 1-6. As the sizes and power levels of wind turbines are increased, importance of efficiency and grid connection subjects also increased. Because wind power plants gradually becomes inevitable parts of electrical grids in most countries and they are expected to conform grid codes and fault ride through capabilities.

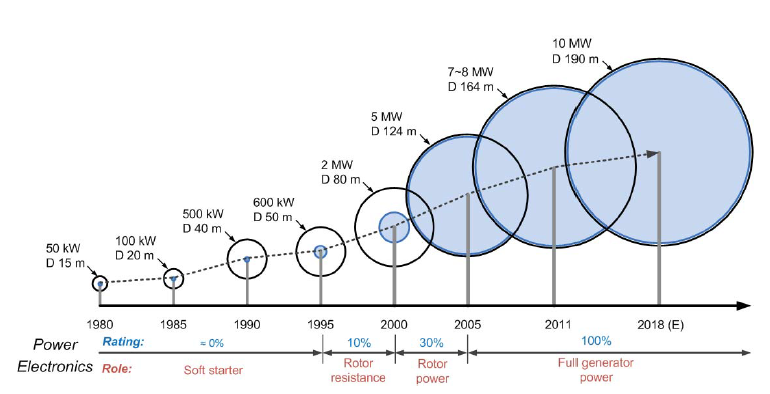


Fig. 1‑6. Evolution of wind turbines [9]

When designing and investing a wind power stations, 3 main properties which are necessary to validate are given as follows:

* Low cost
* Long-lasting
* Low service requirement

These are called L3 conditions [10]. If we go in detail of these conditions from the engineering point of view, lightweight, low cost, low speed, high torque and variable speed operation should be taken into account during the design stage of wind power plant (WPP) [11]. Wind turbine generators dominating the markets nowadays have 300-800 kW power output capacity in average. But the challenges and trends are toward to 1 MW per turbine thanks to promising concepts such as direct-drive [12]. Higher overall efficiency, lower noise, reliability, light weight and reduced maintenance costs are the main advantages of direct drive concept. Direct drive solutions offer simpler and more efficient structures for drivetrain of wind turbines, therefore smaller nacelle can be obtained. Addition to this, using modern rare-earth permanent magnets such as NdFeB, higher energy densities become reachable and more powerful novel generators can be manufactured. One disadvantage of direct drive concept is that they have larger diameters than conventional geared wind turbines in order to provide same output power in low speeds. In this study, direct drive axial flux permanent magnet topology is chosen to design among other topologies. Generators with permanent magnets will be covered more detailed in the next chapter.

Cost per swept area is more valid factor than cost per rated power when evaluating a wind turbine by manufacturers [8]. However, cost per rated power term is used in technical designs and investment planning.

Wind turbines can be categorized in two types according to their rotational axis position:

* Horizontal axis wind turbines (HAWT), example of it is given in Fig. 1-7 (a)
* Vertical axis wind turbines (VAWT) example of it is given in Fig. 1-7 (b)

 **

(b)

(a)

Fig. 1‑7. Wind turbine types according to rotation axis (a) horizontal axis (b) vertical axis

As the name refers, in horizontal axis wind turbines axis of rotation of the shaft is parallel with ground while in vertical axis wind turbines shaft axis is perpendicular to ground. Horizontal axis wind turbines are dominant in market due to its robust structure and high overall efficiency. Vertical axis turbines are generally used in small wind applications in levels of kWs. In vertical axis wind turbines angle of strike of the air is inherently varies with the rotation and it’s hard to capture energy especially under unbalanced wind flow conditions, while pitch and yaw control of the turbine can be successfully implemented in horizontal axis turbines. In general, the efficiency of small wind turbines is low compared with large wind turbines [8]. There are no standards about what wind speed manufacturers should give the output power of their turbine (rated power). Therefore, there are some differences between the manufacturer's plate values and actual measured values.

Another important issue is the speed control of these turbine blades in terms of aerodynamic means. At this point two main control techniques are exist: stall control and pitch control. Generally in stall controlled technique, turbine blades are fixed aerodynamic structures and these turbines need high peak torque to limit turbine speed while in pitch control technique, blade pitch angle can be changed during operation of turbine i.e. angle of attack of air can be adjusted therefore these turbines do not need over torque for limit the speed [13]. In variable speed applications pitch control is a commonly used technique [14].

Main parts of the wind turbine consist of turbine blades and shaft, gearbox and the generator. The main generators used in wind turbines are synchronous and induction generator concepts. In conventional applications, gearbox is connected between turbine shaft and generator and used for increasing the low speed of turbine blades to high speed of generator. In direct drive wind turbines, generator directly connected to main shaft of the turbine and operate at low speeds. Geared and direct drive schematics of wind turbines are shown in Fig. 1-8. Wind turbines can be categorized into three main groups according to generator rotational speed. These are fixed speed, limited variable speed and variable speed [15]. Although first examples of wind turbines were generally fixed speed ones like Danish concept, modern wind turbines nowadays use variable speed concept because of higher power and higher torque advantages. More detailed explanations and schematics about categorizing wind turbines according to their drivetrain, generators and flux orientations will be given in the next chapter.

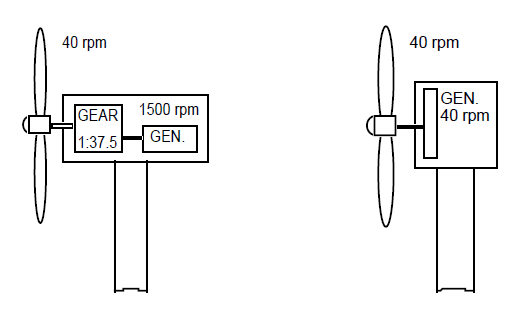


Fig. 1‑8. Conventional geared (left) and direct drive wind turbines [16]

(a)

(b)

## Problem Statement and Research Objective

As the wind energy conversion systems become more capable player of the global energy sector and installed capacities of the WECs increased every year, reliability for these systems becomes more important issue. Especially with the increased power rates of these turbines, size and volumes are also increase and modularity becomes vital.

In this thesis work, a Direct Drive Axial Flux Permanent Magnet wind turbine generator is chosen and designed because of its high torque density and volume advantage. Designed and proposed generator has output power of 5 MW. Gearless drive train is chosen especially for increase overall efficiency and reduce maintenance costs. Proposed generator also has a modular structure, thus reliability and high efficiency is desired even in a fault-state. Parameters of the designed machine will be chosen according to genetic algorithm optimization and FEA validation. Also in this study, proposed generator system is compared with its MW level counterparts. Table 1-1 shows the recent MW level wind turbine models with respect to their brand, model, origin, generator type and output power [17]–[26]. Based on these table values, it can be said that trend is going to 10 MW per turbine in a few years. When increasing importance of “reliability”, “modularity” and “fault-tolerance” taken into account, it is expected that the proposed generator system and its comparison with existed commercial counterparts will contribute significantly in the MW level wind energy harvesting technologies.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Brand | Model | Origin | Turbine Power(MW) | Type |
| Sinovel | SL5000/128 | China | 5 | DFIG |
| Sinovel | SL5000/155 | China | 6 | DFIG |
| Vestas | V105/V112/V117/V126/V136 | Denmark | 3.45 | PMSG |
| MHI-Vestas | V164-8.0 MW | Denmark | 8 | PMSG |
| GE Wind | 3.8-130 | US | 3.8 | DFIG |
| GE Wind | 3.6-137 | US | 3.6 | DFIG |
| GE Wind | GE 4.0 | US | 4 | DD PMSG |
| Nordex | N131/3600 | Germany | 3.6 | DFIG |
| Nordex | N117/3600 | Germany | 3.6 | DFIG |
| Siemens Wind | SWT-3.6-130 | Germany | 3.6 | DD PMSG |
| Siemens Wind | SWT-8.8-154 | Germany | 8 | DD PMSG |
| Enercon | E-126 EP4 | Germany | 4.2 | DD EESG |
| Enercon | E-126 | Germany | 7.58 | DD EESG |
| Gamesa | G128/G132 | Spain | 5 | 2G PMSG |

Table 1‑1. Recent MW level wind turbine generators worldwide [17]–[26]

In this table, it’s intended to pick the comparison candidates according to their output power, which is around 5MW and beyond. Similar investigation was made for Turkish wind energy market focused on turbine manufacturers and TWEA data. According to recent TWEA (TUREB) Statistics, graph of operational wind power plants with their turbine manufacturers in Turkey is given in Fig. 1-9.

Output power classification of wind turbines under operation in Turkey is given in Table 1-2. As it can be seen from table, general wind energy profile of Turkey is mostly based on mid-MW levels of 1-2 MWs per turbine. Therefore it can be said that 5 MW output power per wind turbine is a new concept maybe not for global market but for Turkey.

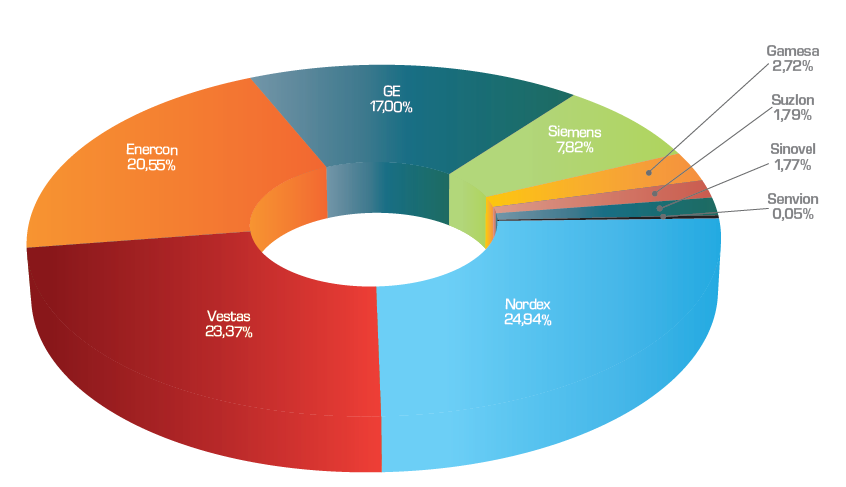


Fig. 1‑9. Operational wind power plants with their turbine manufacturers in Turkey [7]

|  |  |  |
| --- | --- | --- |
| **Output Power<2 MW** | **2MW< Output Power <3 MW** | **3MW< Output Power <4MW** |
| Enercon E-70 | SUZLON S95 | GE 3.2-103 |
| Enercon E-40 | SUZLON S88 | SIEMENS SWT-3.2-108 |
| Enercon E-48 | NORDEX N117 | SIEMENS SWT-3.2-113 |
| Enercon E-44 | NORDEX N90 | VESTAS V112-3.3 |
| Enercon E-82 (2 MW) | NORDEX N100 | VESTAS V126-3.3 |
| Enercon E-53 | SIEMENS SWT-2.3-101 | SENVION 3.4M104 |
| VESTAS V100-2.0 | SIEMENS SWT-2.3-108 |  |
| VESTAS V44-600 | GE 2.75-103 |  |
| VESTAS V90-2.0 | GE 2.85-103 |  |
| VESTAS V90-1.8 | GE 2.5-100 |  |
| VESTAS V52-850 | GE 2.75-100 |  |
| VESTAS V110-2.0 | Enercon E-92 |  |
| VESTAS V80-2.0 | Enercon E-82 E2 |  |
| GE 1.7-100 | Enercon E-82 (3 MW) |  |
| GE 1.6-100 | ALSTOM ECO110 |  |
| GE 1.5se | GAMESA G114 |  |
| GE 1.7-103 | VESTAS V90-3.0 |  |
| GAMESA G90 | VESTAS V112 3.0 |  |
| GAMESA G97 |  |  |
| SINOVEL SL1500/90 |  |  |
| SINOVEL SL1500/82 |  |  |

Table 1‑2. Utilized MW level wind turbine distribution in Turkey according to output power

Total installed capacity share of these wind turbine manufacturers in Turkey is given in Fig. 1-10 below. Comparison of proposed generator with existed MW level wind turbines and related benchmarking will be explained in the conclusion chapter.

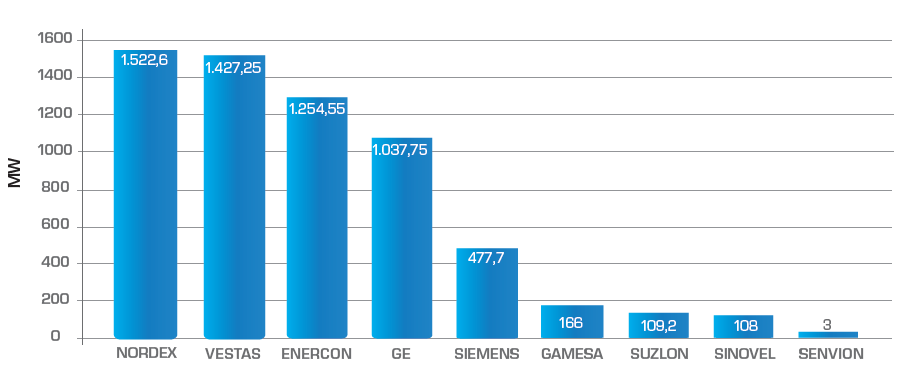


Fig. 1‑10. Total installed capacity share of wind turbine manufacturers in Turkish wind energy market [7]



## Thesis Outline

In Chapter-2, general overview of wind energy conversion systems and challenges in this area will be summarized. For this purpose, generator systems used in wind energy conversion systems will be classified according to electrical and mechanical aspects. Importance of modularity will be described. Finally, chosen direct drive AFPM generator system will be explained and advantages and disadvantages of it will be evaluated.

In Chapter-3, detailed analytical design equations of the proposed AFPM generator will be described and related drawings will be given. Following in this chapter, FEA results and analytical calculation results for the sample 50 kW AFPM generator will be compared and results will be discussed in order to check the accuracy of the analytical design methodology proposed in this thesis.

In Chapter-4, optimization process will be introduced and optimized parameters of the proposed AFPM generator will be presented. First, evolutionary algorithm and nature of the genetic algorithm will be described. Then all details of the optimization procedure followed in this thesis will be described. Finally, optimized design parameters and analytically calculated performance values of the proposed 5MW 12 rpm generator will be presented. Discussion of the mass and cost components of the proposed design will be given at the end of this chapter.

In Chapter-5, finite element analysis of the proposed design is reviewed and results of this analysis will be compared with analytically calculated design parameters in order to verify the proposed AFPM design. Finally, comparison of the proposed generator with similar MW-level wind turbine generators on the market will be presented in terms of different aspects.

In Chapter-6, conclusions and future work about this thesis study will be discussed.

# **CHAPTER 2**

# **REVIEW OF WIND ENERGY CONVERSION (WEC) SYSTEMS**

In previous chapter, background of wind energy conversion systems is introduced and related wind energy statistics are summarized and tabulated. In this chapter, detailed survey of wind energy fundamentals and general overview of wind energy conversion systems will be summarized. To accomplish this, this chapter is divided into five main parts. In the first part, wind power equations and key parameters will be discussed. This data especially used in wind turbine investment calculations and wind potential estimation techniques. Then challenges in wind energy conversion systems will be introduced and common problems will be addressed. In the next part, existing wind turbine technologies will be classified and evaluated according to their mechanical and electrical aspects. Then three main flux orientations in PM based systems will be shown and explained. Finally, the importance of modularity in wind energy conversion systems and the advantages and disadvantages of axial flux PM machines will be evaluated. Also in the last part, reasons for choosing direct drive axial flux permanent magnet generator concept will be explained.

## Power Equations and Parameters

The available shaft power (output power) *P* from a horizontal axis wind turbine can be expressed as a function of the wind speed as follows:

(2-1)

where , is the mass density of air , is the power coefficient which is a function of the tip speed ratio *λ* and the pitch angle *β*, is radius of the turbine blade and  is the wind velocity. Power coefficient, sometimes called performance coefficient, can be defined as the ratio between the captured wind power and the available input power of the wind. Therefore, it tells us how efficient the turbine is. Generally imperfections in blade manufacture reduces the actual energy yield of the turbine less than the useable energy. Theoretically, maximum 59% (approximately 16/27) of energy carried by the wind can be extracted by an ideal wind turbine. This result is concluded by German physicist Albert Betz in 1919. This limitation is valid for both vertical and horizontal axis wind turbines. Maximum value of performance coefficient (*Cp*) is limited by Betz criterion. Since physical limitations exist in nature such as friction and other mechanical losses, maximum value of the performance coefficient *Cp* is always lower than theoretical maximum of Betz constant.

In [27] power coefficient is defined as a nonlinear function of TSR (λ) and pitch angle (β)  as follows,

(2-2)

where,

(2-3)

These coefficients shown above depend on the turbine physical characteristics. Investigation of these values is out of scope of this thesis. Tip speed ratio (TSR) is defined as a ratio of linear tip speed of turbine blade to speed of the wind as shown in (4). This ratio is very useful when designing a wind turbine. Optimal TSR is desired to obtain maximum power from wind as much as possible.

(2-4)

where,  *v* is the wind speed, *wm*  is the rotational rotor speed and *R* is the rotor radius. TSR is a kind of measurement of how fast turbine blades rotate. Until a proper limit, higher rotational speeds leads to higher output power levels. Therefore, high TSR is aimed when designing a wind turbine. Although TSR calculations will not be actively utilized in this thesis work, this topic is very important because of the sizing issues. If turbine blades rotate too slow then incoming air to the turbine is not used efficiently as natural result of Betz limit. If turbine blades rotates too fast, blades act as a solid wall to the turbine and then efficiency decreases again. As mentioned earlier in previous chapter, variable speed horizontal axis wind turbines use pitch control actively in order not to encounter high torque transients by controlling the angle of attack of air to the blades especially in harsh wind conditions. Besides, high TSR has several other disadvantages. Edges of the blades, which rotate at very high speeds, are subject to faster erosion due to environmental factors such as sand or dust particles [28]. Also high rotational speed of blades result in audible noise and vibration. To avoid bad consequences (low efficiency, physical breakdown) of turbulence issue, choosing optimal TSR is really important. Each wind turbine has unique value of TSR regardless of the generator topology used in manufacture [29]. Approximate optimal TSR for a conventional three blade wind turbine system is given as 5~6 in [30].

Minimum wind speed that is needed to start to rotate the blades is cut-in wind speed, while the cut-out speed is the maximum speed of wind that turbine is allowed to continue operation. Intermittent nature of the wind determines the production variation of the WECs. There are some approaches for estimate the wind profile at given place. Weibull distribution is used to represent the wind speed distribution and it gives an indication of what percentage of time a certain wind speed occurs in a given site. This indication is required because of the probabilistic nature of wind. Weibull distribution and Rayleigh distributions are used to estimate and analyze the wind speed distribution. IEC 61400 standard, which is specialized for design requirements of wind turbine, mentions Rayleigh and Weibull distributions as the most common distributions for wind profile [31]. Weibull () and Rayleigh () cumulative probability functions are given in (5) and (6), respectively.

 (2-5)

 (2-6)

where *v, vm, c* and *k* are wind speed , mean wind speed, scale parameter and shape parameters. Rayleigh distribution is special case of Weibull distribution when shape parameter equals to 2 and mean wind speed value is required. In [32], authors calculate the wind speed probability density values of the Bozcaada region of Turkey from both time series measured data and distributions of Weibull and Rayleigh. This distribution can be seen in Fig. 2-1.

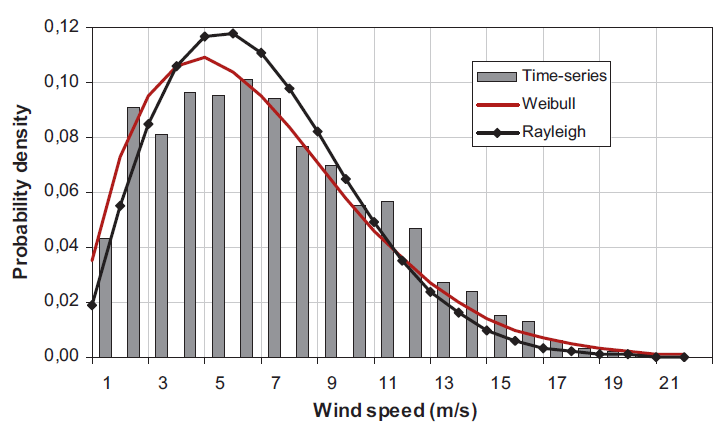


Fig. 2-1. Wind speed probability density functions for Bozcaada region [32]

## Challenges in WEC Systems

Main focus and effort during the design and implementation of wind turbines is to obtain more efficient and cost effective solutions hence to reduce the cost of energy, which can be considered as a key issue. Therefore, every detail about machine design, grid connection and other technical trend parameters have to fulfill this economical objective.

As the power scales of wind turbine increases, penetration of these energy sources into electrical grid becomes inevitable. Demand side management techniques and different storage technologies such as flywheels and batteries are developed for grid connection and disturbance support such as short term fluctuations. This integration dictates wind turbines to conform the grid codes in which quality and requirements of power plants described in terms of frequency and voltage support. Therefore, modern wind turbines with high power capacities have to keep connected and support grid in terms of voltage regulation and reactive power during the disturbances. This ability is also called low voltage ride through (LVRT) capability.

Another important challenge about wind turbines is the ease of maintenance. Reliability is related to failure rates of different parts of a wind turbine. Thus performance of every component of wind turbine determines the reliability of the wind turbine. Especially, for offshore wind turbines where access for repair and maintenance is difficult, improving reliability becomes an important key parameter during the design [33]. For example, mechanical parts which have high withstand ability for humidity is preferable for offshore wind turbines. Failure rates and corresponding downtimes for different parts of generator are obtained in [33]and given in Fig. 2-2. According to this statistics based on collected data it can be concluded that main failures and longest downtimes result from gearboxes and electrical systems.

As a rule of thumb in generator design it is important to avoid gearbox because of its mechanical parts and need for periodic maintenance and lubrication. Increased maintenance periods are big advantage for wind turbines whose locations are hard to reach such as offshore wind turbines [34]. Drivetrain of a VSCF (variable speed constant frequency) turbine generally consists of blades, low and high speed shafts, gear-box and generator. Turbine shaft can be referred as low speed shaft while generator shaft is referred as high speed shaft. Gearbox in a wind turbine system is responsible of transmission of aerodynamic power from turbine to the generator shaft. In geared type of generator, turbine blades with hub structure connected to shaft of the generator via a gear-box, which increases the rotational speed of the low-speed shaft. Gearbox allows generator to operate at high speeds, therefore smaller diameters can be used with same amount of torque needs. Gear ratio is a measure of relationship between output and input speeds of dynamic system. Drawings of nacelles of two commercial wind turbines which are geared and gearless are given in Fig. 2-3 and Fig. 2-4 respectively.

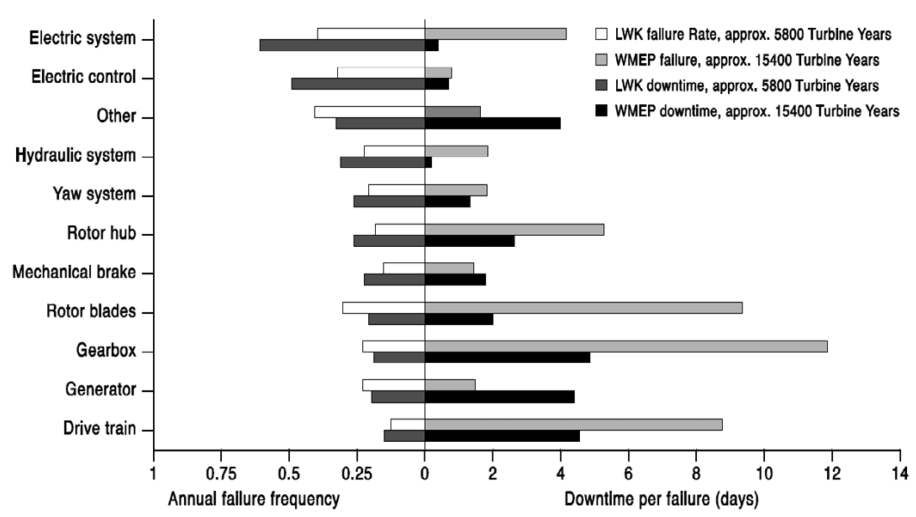


Fig. 2-2. Failure frequency and downtime for different part of wind turbine [33]

Gearbox system is the main source of mechanical faults and losses in wind turbine systems. Also, it’s necessary to make periodic lubrication and maintenance for gearbox components in order to avoid an unexpected failure. Environmental drawback of the gearbox is audible noise created by mechanical parts [15]. Because of these reasons, manufacturers and designers start to develop gearless drive systems for wind turbines from early 1990s. However, geared systems still offer cheaper solutions than large diameter direct drive systems [35].

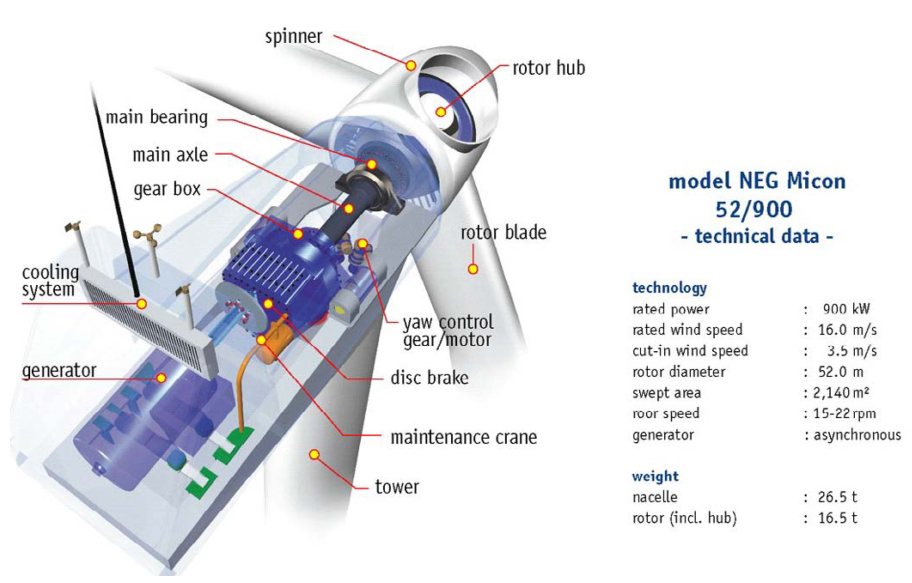


Fig. 2-3. NEG Micon wind turbine with gearbox [33]

As the name refers, in direct drive generators gearbox and all bearing structures are eliminated. Therefore, turbine blades and generator are connected on the same shaft rotating at low speed. With this eliminated gearbox and other mechanical structures, direct drive systems offer lower maintenance cost, increased efficiency and reliability. The main purposes of the direct-drive concept for wind turbines are;

* to increase the efficiency thus energy yield
* to reduce the gearbox failures
* to reduce the maintenance cost

In electrical generator design, one of the main criterion is torque. Due to tip speed limitation and natural result of gearless topology, direct drive wind turbine generators operate at low speed. Relationship between power and torque according formula which defines the output power of generator:

(2-7)

where, *P* is the output power, *T* is the torque and *wm* is the mechanical speed of the shaft. Torque must be increase inverse proportional to decrease of angular speed in direct drive generators in order to produce same amount of power as in the geared drive case. In some designs ratio of axial length to air gap diameter, *k* is optimized [36]. According to [37], electromagnetic torque of an axial flux permanent magnet machine is proportional to outer diameter as shown in (8).

(2-8)

To do that when scaling up the turbine sizes, amount of material should be increased in order to maintain the air-gap against magnetic attraction forces between stator and rotor parts. This means direct drive machines are heavier and larger in diameter rather than other types of machines in order to produce the same amount of power. More material also means extra cost, which is a disadvantage for this type of generators. Torque per volume and torque per mass parameters are important during the design of the generator systems. EESG and PMSG are two main direct drive solutions exist in the market. One of the commercial direct drive EESG of Enercon is shown on Fig. 2-4. Radial flux orientation is mostly preferred among direct drive generators [34]. However RFPM can be disadvantage when allocated space for generator is limited for specific applications such as nacelle or electric vehicle wheel motor. Transverse flux PM generators can produce higher torques with lower copper losses. However complicated construction is an important penalty for transverse flux option, especially when maintenance problems are taken into account. Direct drive axial flux type permanent magnet machines are advantageous in torque to volume ratio among other machine topologies while torque per mass values are not much attractive. Torque per volume advantage is due to shorter axial length and compact structure rather than radial flux counterpart. Torque per mass disadvantage is related to large diameter which is a penalty of this type of generators. Because of reasons aforementioned above, trend is going through the high torque direct drive generators as it eliminates gearbox losses and minimizes maintenance and repair cost hence increases the overall efficiency and reliability of the system.

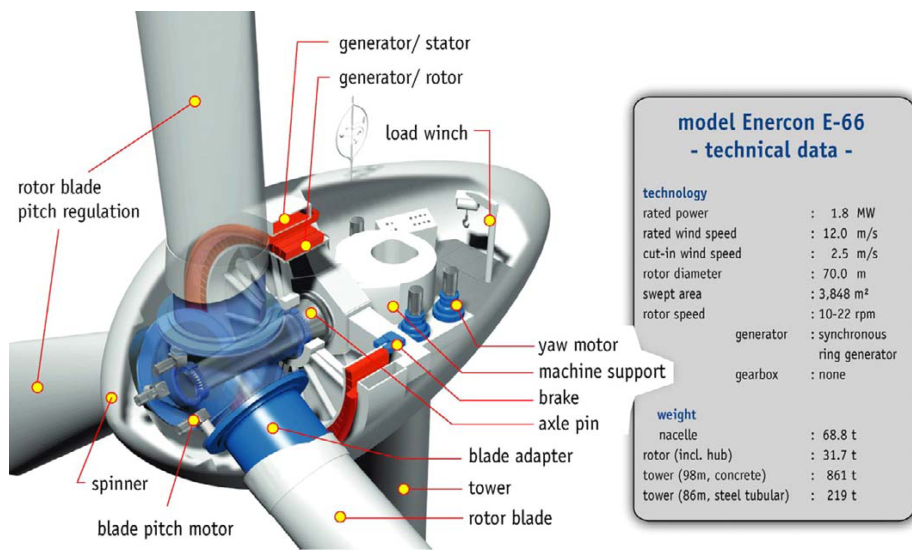


Fig. 2-4. Enercon E-66 wind turbine without gearbox [33]

Modularity on the other hand, is related to availability of maximum portion of mechanical or electrical structure of generator during the failure periods. With the rapidly increased power levels of 5 MW and above for per turbine, nowadays trend is going through the modular multi-level power electronic converters and modular machine structures for large wind turbine generators [2]–[4]. Mechanical modularity can be considered as operating parallel machines instead of one bulky generator. Contrary to conventional generators, modular generators have the ability of continue to operate with its healthy modules under fault conditions of defective modules. Therefore, reliability and overall efficiency is increased. Challenges for increasing efficiency of wind turbines from the control point of view can be considered as fault monitoring and diagnostic, forecasting error and predictive controls [10].



## Current Wind Turbine Generator Technologies

In this section, generators are categorized according to their mechanical and electrical properties. In mechanical categorization, drivetrain approach is considered ie. whether drivetrain includes gearbox or not. In electrical categorization, most used generator types in WECs namely induction and synchronous generators are considered in terms of wind turbine point of view. Thus, main approach in this part when describing their properties is based on whether they are induction or synchronous generators. Wind turbines are mainly categorized in the literature according to their rotational speeds. These speed categories are fixed speed, limited variable speed or variable speed. Variable speed configuration is the most used one among other speed options because it’s more grid-supportive by means of power electronic converter it provides [14]. These type of turbines are capable of operating at different wind speeds and more flexible in terms of torque and reactive power control [15].

## Induction Generators

## Squirrel Cage Induction Generators (SCIG)

This type of generator can be used with both fixed (also known as Danish Concept) and variable speed. However, SCIGs are commonly used for constant speed operation. The most common configuration of this generator consists of three stage gearbox connected to SCIG and compensating capacitors [33]. Generator speed is determined according to grid electrical frequency. Sometimes soft-starter can be used after the generator for smoother grid connection [38]. This type of SCIG is given in Fig. 2-5.

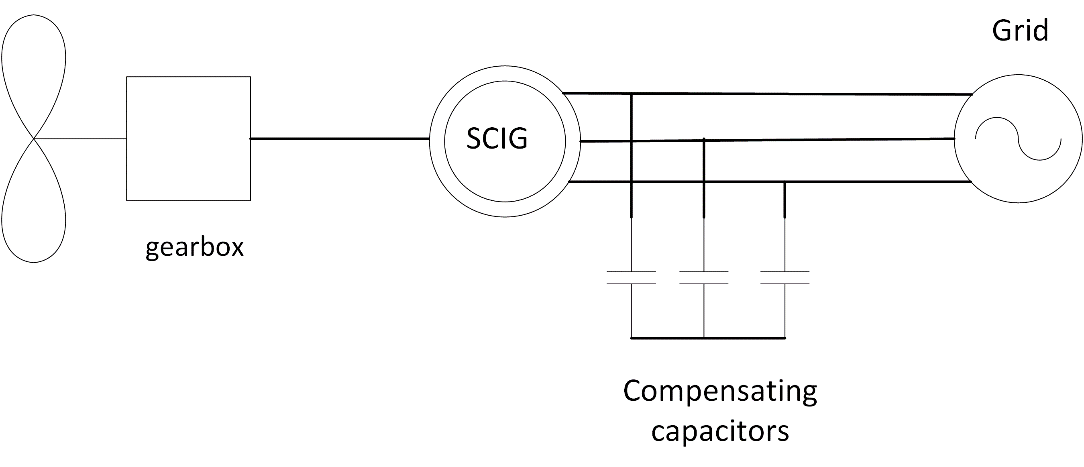


Fig. 2-5. SCIG Danish concept wind turbine schematic

Robustness, off-the-shelf parts, lower investment costs, stable operation and lower maintenance makes SCIG preferable in WECs. But in order to get more efficient operation SCIG should be constructed with low number of poles because high number of poles construction becomes a mechanical drawback for SCIG. Besides, high number of poles leads to higher leakage flux losses in practical. Therefore gear-boxes are generally used with SCIGs. Due to fixed speed operation above rated wind speeds, limited output power is another drawback of this system. Lack of power electronic unit results in poor capability of reactive power control and voltage level problems. Need for magnetizing current in order to create magnetic field for stator, makes induction generator reactive power-dependent. Capacitor banks or Static Synchronous Compensators (STATCOM) are commonly used for reactive power compensation with SCIGs. Wind speed fluctuations and tower-shadow effect directly converted in torque dips and fatigue loads on turbine sub-mechanical systems [14], [39].

In variable speed applications of SCIG back-to-back voltage source converters (VSCs) are employed in order to meet the grid codes [40]. Schematic diagram of this type WEC is given in Fig. 2-6. Generator given in Fig. 2-3 was also a constant speed SCIG namely, Danish Concept.

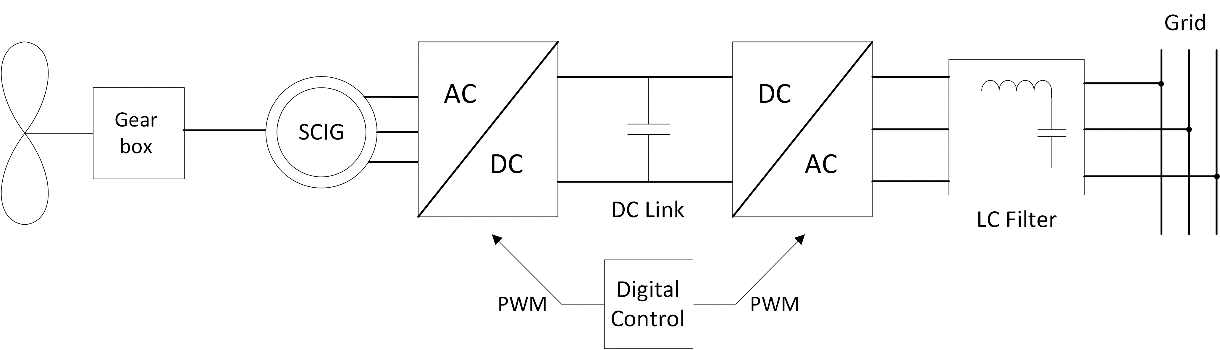


Fig. 2-6. SCIG with back-to-back VSC converter

## Wound Rotor Induction Generators (WRIG)

Wound rotor induction generators are also known as the Optislip concept and have been applied by Vestas since 1990s [38]. These type of generators are used for limited variable speed applications, thus there will be dynamic slip control [40]. This control is applied by connecting electronically controlled resistor blocks to rotor of the generator. Mechanical loads are reduced in this type of configuration because of controllable speed. Slip denotes the relation between the rotor speed and synchronous speed. It is given by the formula as follows,

(2-9)

where, *s* is the slip, *Ns* is synchronous speed, *Nr* is rotor speed. Higher slip magnitudes indicate higher power losses on rotor connected resistors hence lower efficiency. Gearboxes in this system can have multiple stages just as the SCIG case. Also there exist shunt capacitors connected to line for compensation purposes.

Typical WRIG schematic diagram with these capacitors is shown in Fig. 2-7. It can be concluded that main advantage of this concept is limited variable speed operation ability due to resistors connected series with power electronic converter. The main disadvantage of WRIG is lower efficiency due to heat losses on resistors while increasing variable speed range. Vestas V80 wind turbine has the output power of 2 MW and utilizes WRIG technology. An image of this wind turbine is given in Fig. 2-8.

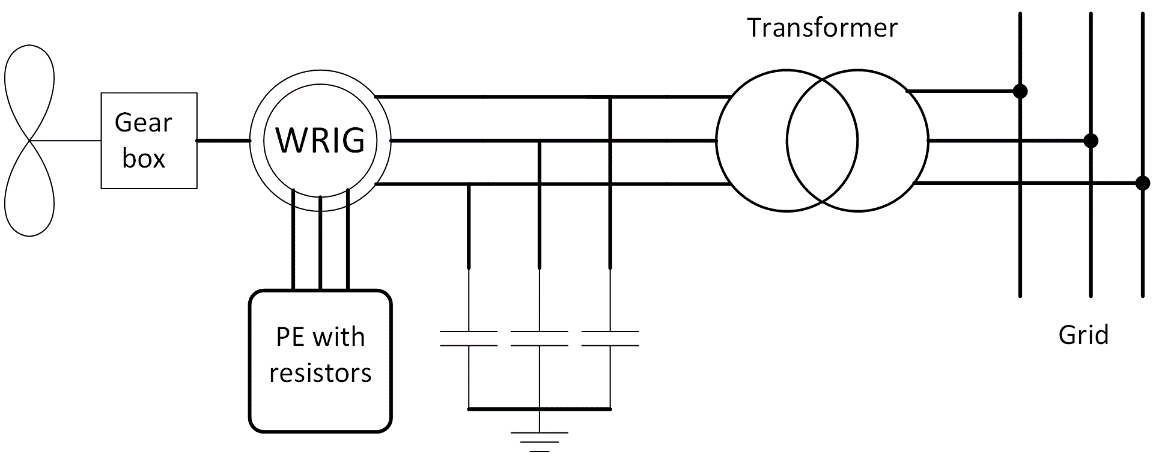


Fig. 2-7. WRIG schematic diagram



Fig. 2-8. Vestas V80 wound rotor induction generator (Courtesy of Vestas) [41]

## Doubly-fed Induction Generator (DFIG)

Among wind turbine generator types, doubly-fed induction generator system with 3 stage gearbox (DFIG-3G) is the most common configuration at present [42]. Although it consists more complicated power electronic control, it can control active and reactive power flow within supply side or rotor side. Stator is connected to grid via transformer while rotor is connected to grid via power electronic converter blocks. This power electronic converter is rated at fraction (usually between 20-30%) of generator power [43], therefore these converters are called as partial scale converter. The main objective of this power electronic block is to adjust speed range and grid reactive power support. Sometimes second PGSC (parallel grid side converter) is used parallel with dc-link in order to control unbalanced conditions better. Configuration of DFIG is shown in Fig. 2-9. Multistage or single stage gearbox can be used with DFIGs.

****

Fig. 2-9. Conventional grid connected DFIG, RSC: Rotor side converter, GSC: Grid side converter

Slip rings and gearbox are the main disadvantages of this generator. DFIGs are not suitable for direct drive because of efficiency problems. As mentioned before, as machine rotational speed decreases, torque must be increase in order to produce same amount of power. Therefore generator size should be increased. However, as the diameter of DFIG increases airgap also increase and magnetizing current increases. Higher magnetizing current means lower efficiency. Besides, generators with larger diameters have large number of poles hence leakage flux problems can occur just as in the SCIG case. Stator of the DFIG is directly connected to the grid, thus possible active and reactive power support can be realized via partial scale converter of rotor. Back-to-back converter seen in Fig. 2-9 can be used with crowbar in order limit the current and provide fault handling capacity [43] . A commercial DFIG wind turbine Nordex N131/3600 is given Fig. 2-10. It’s rated at 3.6 MW and has 3 stage gear-box.



Fig. 2-10. NORDEX N131 (courtesy of NORDEX) [44]

Variable speed operation and efficient converter with active/reactive power control rather than WRIG, low price, easy off-the-shelf availability are main advantages of DFIG. Dependency on gearbox, complex power electronic and fractional scale adjustable reactive power control, slip rings, high stator peak torques during fault conditions, weak LVRT capability than synchronous generators with full-scale converters are the main disadvantages of this type of wind turbine generators. Especially with the increasing importance of grid integration, it’s expected that DFIGs will become less preferable [33], [45]. In Fig. 2-11, market share of different wind turbine generator technologies for Europe can be seen. As it can be seen on figure, market share of DFIG has a decreasing trend due to the aforementioned disadvantages above.

Fig. 2-11. Market share of different wind turbine generators for Europe between 2006 and 2015 [46]

## Synchronous Generators

## Electrically Excited Synchronous Generators (EESG)

Synchronous generators for wind turbines connected to grid via full scale back-to-back power electronic converters. In wound rotor synchronous generators (WRSG), additional partial scale converter is used for rotor DC excitation for required field [43]. Therefore WRSGs are also called as electrically excited synchronous generators (EESG). Rotor of synchronous generator can be excited permanent magnets (PM) also, but this type of generator will be described in the next subsection. One of the most prominent manufacturer of EESG is Enercon. In Fig. 2-12, one of the gearless Enercon wind turbine can be seen. EESG of this commercial wind turbine has 4.2 MW of output power and rotor diameter of 127 meters. One of the main advantages of this concept is that EESG can be operated with variable speed applications with suitable grid connected power electronic blocks. Additionally, this machine type has cost advantage compared to the direct-drive PM machine due to eliminated PM cost. Power converter losses and high cost of the full scale converter are the main disadvantages of this power take off system. But, it can provide wide control ability of wind turbine generator [38]. It can be either geared or direct-driven. However, direct-driven concept is more popular due to elimination of gearbox losses and increased efficiency. It is manufactured in large size and number of poles, therefore EESG can be heavy and expensive solution. Schematic diagram of EESG is given in Fig. 2-13 with gearbox depicted with dashed lines in order to show it’s optional for EESG.



Fig. 2-12. Enercon E-126 EP4, 4.2 MW wind turbine during the installation [47]

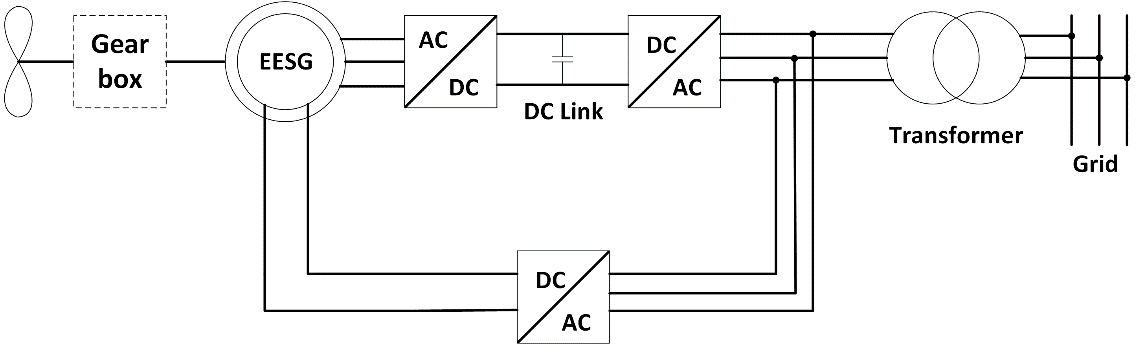


Fig. 2-13. EESG-Electrically Excited Synchronous Generator grid connection

## Permanent Magnet Synchronous Generators (PMSG)

In this generator type field excitation is provided by permanent magnets instead of the DC excited field winding. Permanent magnet synchronous generators are available in both direct-driven and multi-stage geared versions. In geared version, gearbox compensate the space and volume disadvantage caused by direct drive concept. Direct drive PMSGs are preferred because of their higher energy yield and higher power-to-weight ratios than electrically excited generators. Therefore, overall efficiency is increased in direct drive PMSGs due to its robust structure [48]. Due its full scale converter, fault-ride-through capabilities and reactive power support ability are important advantages of PMSG. Full-scale converter also allows generator to operate at different frequencies [33]. However, high prices of permanent magnets and fluctuations in these prices, as occurred in 2010 due to China’s precautive actions [33], can be considered as a disadvantage of this concept. Demagnetization risk of PMs is another disadvantage of PMSG. As a good alternative for PM excited synchronous generator, popularity of EESG depends on the PM prices. It can be said that reduction in magnet prices and disadvantages discussed in EESG section cause EESG less preferable against permanent magnet synchronous generators.

Recently, capacity of PMSG wind turbines has increased up to nearly 10 MW [9], [49]. Schematic of PMSG with multiple stage gearbox is given in Fig. 2-14 below. Vestas offshore wind turbine V164 whose output rated power is 8MW, given in Fig. 2-15.

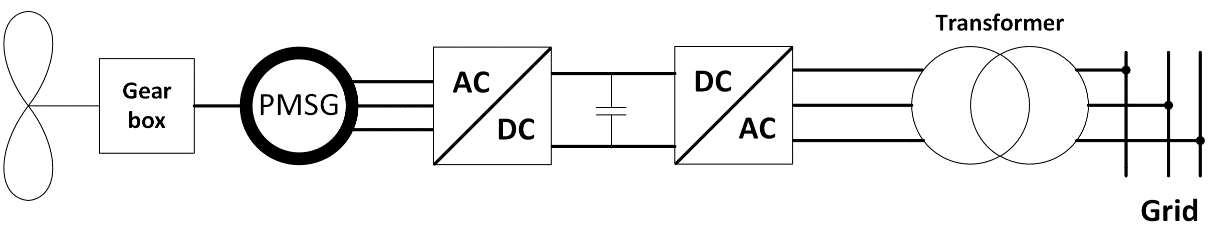


Fig. 2-14. Permanent magnet synchronous generator with gear-box and full scale power electronic converter



Fig. 2-15. Vestas V164 8MW Offshore wind turbine [49]

As mentioned before in direct drive section, gear box structure causes mechanical loss and requires periodical maintenance. Once gearbox fails, wind turbine can’t able to produce energy. Hence this results in downtime losses. Maintenance and repair losses makes wind turbine inefficient and expensive investment. Therefore, the trend is using direct-driven or single stage gearbox with PMSGs [35], [48]. Single stage gearbox still have mechanical losses rather than gearless system. However, it reduces the rotor diameter and total mass of the direct-driven version.

In direct-drive generators, since the rotational speed is very low, diameters are increased in order to obtain higher torque values, hence power levels stay same or goes up. However, increase in diameter and total generator volumes are not feasible for reliability, modularity and transportation. A Germany originated company named Multibrid, designed and commissioned a PMSG with one stage gearbox, Multibrid M5000. Main focus is to reduce the large size of multi MW large direct drive PMSGs. However, this design has the disadvantage of gearbox but cheaper than direct-drive generator. In Fig. 2-16, a picture of 5 MW Multibrid M5000 wind turbine is given.



Fig. 2-16. Multibrid M5000 5MW wind turbine generator(Courtesy of Multibrid and Areva) [50]

It’s can be concluded that direct-drive technology among PMSG are gaining attention in last decade due to increased efficiency and reliability issues especially for offshore wind turbines [51]–[53]. In Fig. 2-17, schematic of direct drive PMSG is given.

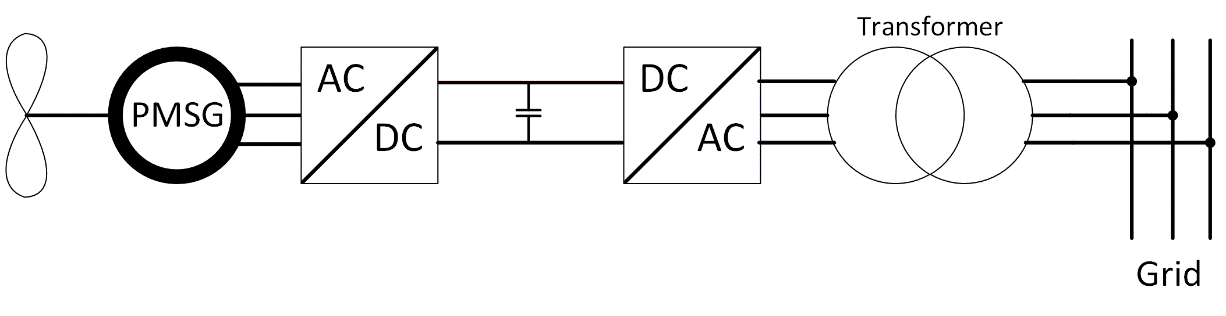


Fig. 2-17. Schematic of direct-driven PMSG

Permanent magnets in PMSGs are arranged in different configuration related to their flux path. These are called as radial flux, axial flux and transverse flux. In radial flux concept, path of the magnetic flux is perpendicular to the direction of the rotor shaft. In axial flux concept, path of the magnetic flux is parallel to the direction of the rotor shaft. Finally in transverse flux concept, path of the magnetic flux is perpendicular to the direction of the rotor rotation. Additionally, PM machines can be classified according to their mechanical structures such as slot type and stator/rotor position [34].The sections of a PMSG parts can be classified as active and inactive parts. Active part consists of electromagnetic elements in machine such as PMs, iron core and copper. Inactive part consists of mechanical parts such as steel, shaft and other mechanical frame structures.

In this thesis work, direct drive PMSG is chosen for the design because of its higher energy yield, improved reliability, higher overall efficiency, relatively long maintenance periods and better fault ride-through capability rather than the other electrically excited and multistage geared generator counterparts. Reliability and availability can be increased by developing modular and fault tolerant PMSG. Modularity will be discussed and explained in next subsections.

## Flux Orientations in PMSG based Systems

As mentioned before, in PMSG based systems the main electromagnetic flux on rotor side is provided by rare-earth permanent magnets. Therefore, the flux paths for these permanent magnets and active parts of the generator is important in terms of evaluating magnetic equivalent circuit of system. In this subsection, different flux orientations and considerations of PM based synchronous generators will be given. To do this, subsection is divided into three parts, namely radial flux, axial flux and transverse flux sections.

## Radial Flux (RFPM)

In the radial flux configuration, permanent magnets are arranged so that magnetic flux passes the airgap in radial direction. Radial flux configuration is the most common concept in permanent magnets based large direct drive synchronous generators, due to their high torque density and simple structure [15]. If PMs are mounted on the rotor surface this type is called as surface mounted permanent magnet machine. Otherwise PMs are placed in slots (buried) of rotor part, aiming to concentrate the flux especially when low remanent flux density magnets are used and still high airgap flux density is needed. RFPM generators can be sometimes constructed with outer rotor inner stator configuration in order to utilize high number of poles with increased cooling capability of outer rotor surface [38]. Iron cored and air-cored are two core types used with inner rotor and outer rotor configuration, respectively. Diameter of RFPM can be adjusted with longer axial length. A typical radial flux surface mounted PM generator arrangement is given in Fig. 2-18. Buried PM version of RFPM is given in Fig. 2-19. As seen on figures, flux crosses the airgap in radial path in both configuration.

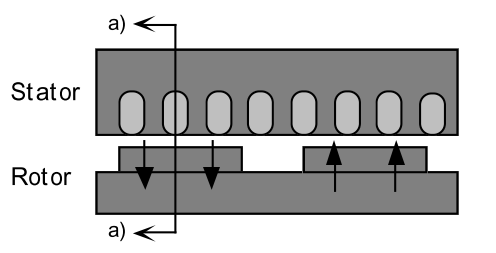


Fig. 2-18. RFPM with surface mounted permanent magnets [13]

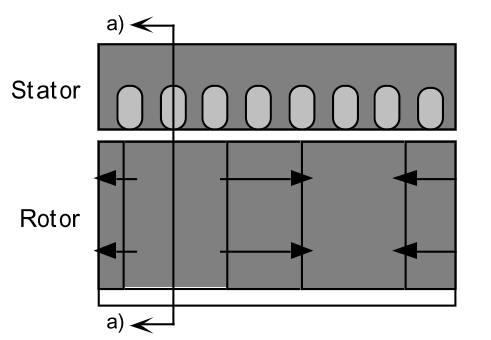


Fig. 2-19. RFPM with buried permanent magnets for flux concentration [13]

RFPM generator can be manufactured in small diameters due to adjustable axial length as aforementioned above. However, long axial length is disadvantage for nacelle and space of wind turbine generator. Additionally, thermal expansion of rotor and stator parts may be problematic in determining air gap clearance [13]. Internal rotor type is the most used RFPM in industry applications. Complete view of conventional inner rotor surface mounted PM type radial flux machine is given in Fig. 2-20.

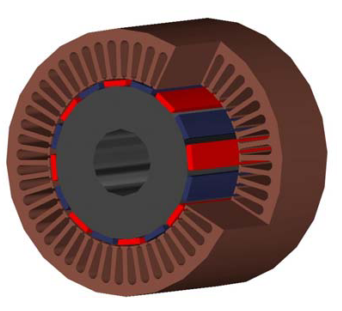


Fig. 2-20. Conventional internal rotor RFPM complete view [54]

## Axial Flux (AFPM)

Starting from early 90s, AFPM has been extensively used as an alternative for radial flux counterpart [55]–[58]. In axial flux permanent magnet generators (AFPM) magnetic flux crosses the air gap in the axial direction. The main advantage of AFPM is that it has relatively shorter axial length, therefore higher torque per volume ratios are achieved [15]. In multistage variations of this machine, outer diameter can be limited without decreasing the torque density significantly. Ratio of inner diameter to outer diameter should be chosen carefully in order to achieve higher output power [59]. This property is preferred when working with limited nacelle space. Adjustable planar air gap is another advantage over the radial flux machines [60]. There are different types of stator/rotor configurations of AFPMs. AFPMs can be classified as slotted and slotless machines, considering the stator winding position. A table showing the various types of AFPM generators according to different criterions is given in Fig. 2-21.

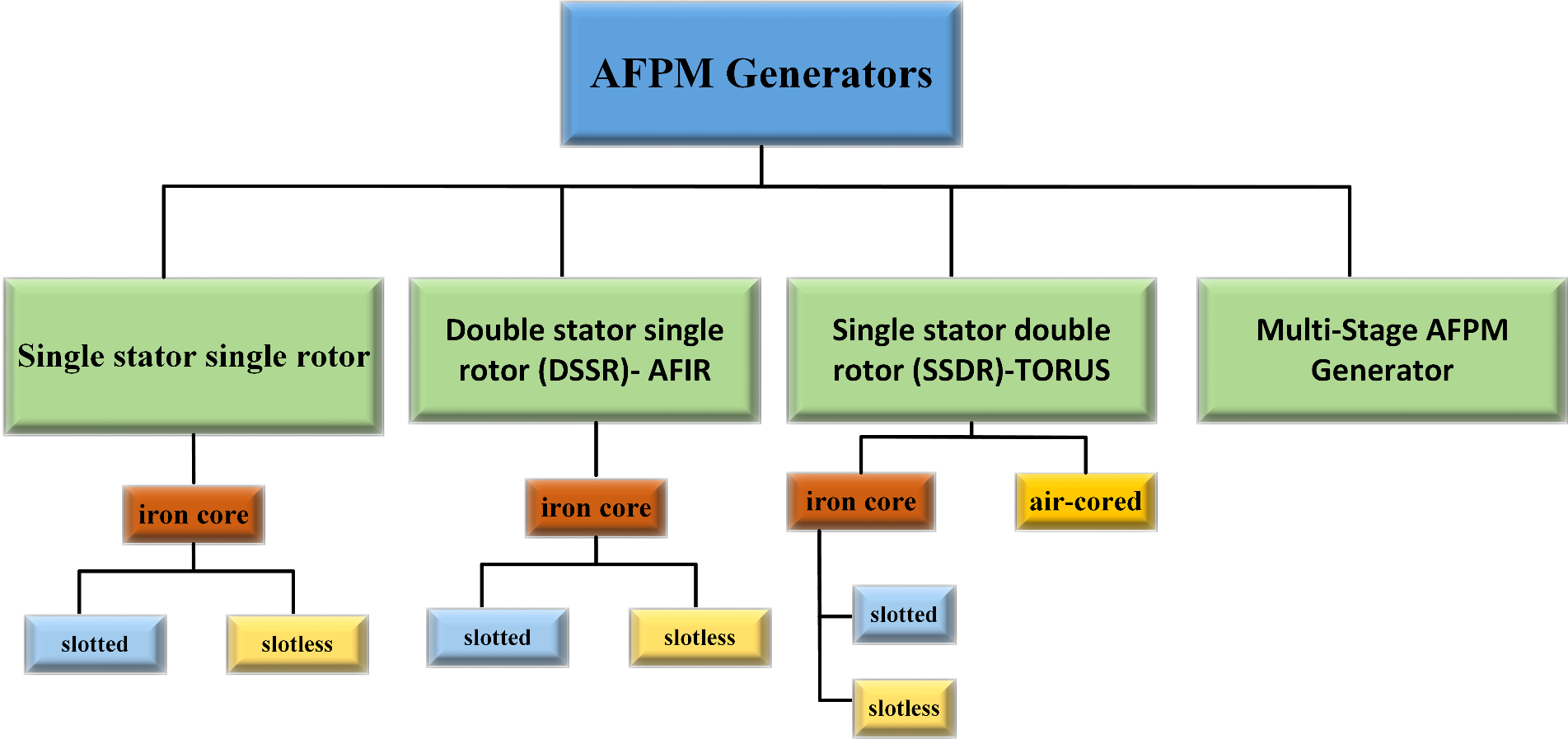


Fig. 2-21. Classification of AFPM generator

Most basic structure of AFPM is the single stator single rotor structure as given in Fig. 2-22. However, strong magnetic attraction force between stator and rotor compelled designers to design the axial structure of the generator with multiple stators/rotors and slotless variations in order to balance the magnetic attraction forces mentioned above [59]. However, attraction and thrust forces are equalized thanks to balanced rotor discs and non-slotted stator. Non-slotted special type AFPM generator, which is called TORUS is given in Fig. 2-23. Rotor of this type of generator consist of two discs with PMs mounted on them and stator consisted of iron core and wound coils. In some of the literature, this type of machine is referred as single stator double rotor (SSDR) [58], [59]. Disadvantage of that version is stator iron core losses.

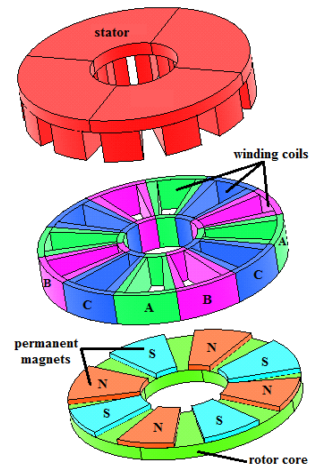


Fig. 2-22. Single sided configuration of AFPM (single stator and single rotor) [58]

Due to its short axial length, AFPMs can be organized with multiple generators on the same shaft axis in order to improve fault tolerance and reliability. AFPMs are relatively advantageous rather than RFPM when aspect ratio of machine (diameter/length) is high, ie. large diameter of disc-shaped generators are used [60].

Cogging torque is eliminated due to slotless structure of AFPM generator. In our study slotless air-cored stator is used with axial flux permanent magnet arrangement. Also in the proposed generator modular design is used. Therefore, parallel generators can be added axially.

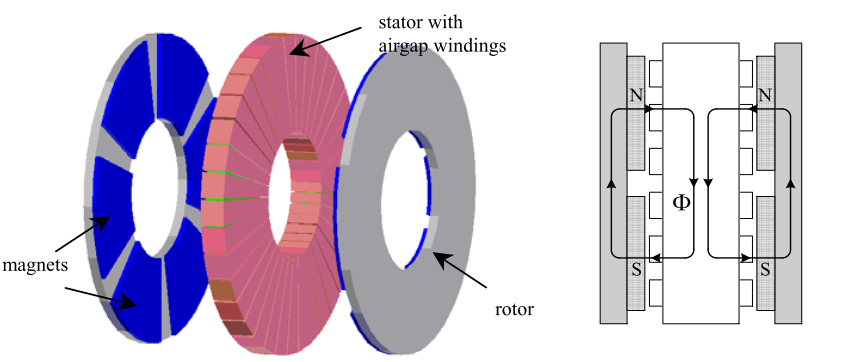


Fig. 2-23. Non slotted TORUS axial flux permanent magnet overview (left) and path of generated flux by permanent magnets (right) [60]

There are two types of slotted TORUS concept: TORUS-NN and TORUS-NS. NN and NS letters used for define magnet placements on rotor discs. Machine overviews and flux paths of both concepts are given in Fig. 2-24 and Fig. 2-25. Main differences between them are flux paths and stator core axial thickness. In our study main aim is to eliminate iron core because of its core losses and weight. In coreless AFPMs iron losses and torque pulsations are less than other types of AFPMs. General view of coreless TORUS type AFPM generator is given in Fig. 2-26. Detailed schematics of proposed coreless, outer rotor AFPM and related flux organizations will be given in Chapter 3.

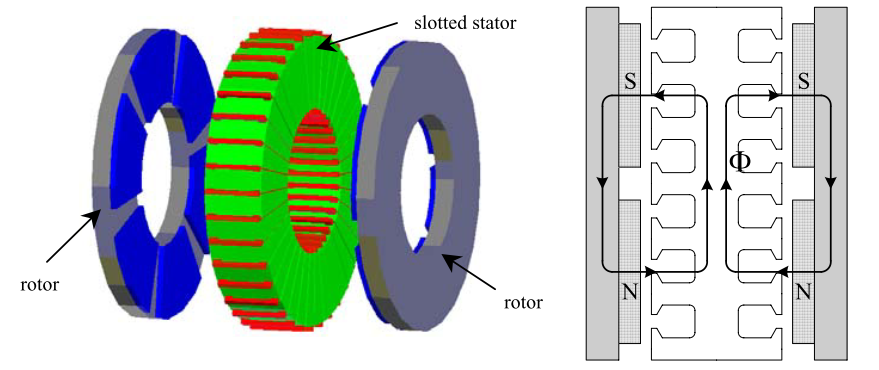


Fig. 2-24. NN-type slotted TORUS axial flux permanent magnet overview (left) and path of generated flux by permanent magnets (right) [60]

As mentioned before in RFPM part, AFPM generator can also have different stator and rotor configurations. In TORUS configuration, we mentioned about two rotor discs which are positioned at the outer region of generator. However, axial flux inner rotor (AFIR) type axial flux generators have two stator blocks at the outer region and one rotor block at the inner region. In some of the literature, this type of machine is referred as double stator single rotor (DSSR) [58], [59].AFIRs can have slotless and slotted versions, just as in the TORUS configurations.

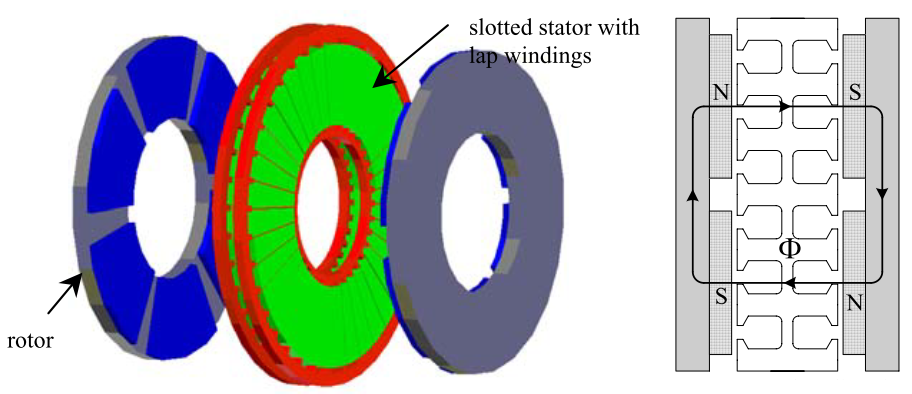


Fig. 2-25. NS-type slotted TORUS axial flux permanent magnet overview (left) and path of generated flux by permanent magnets (right) [60]

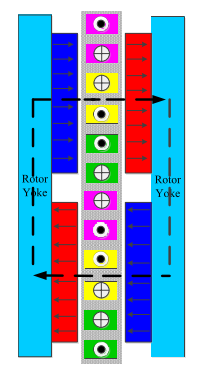


Fig. 2-26. NS-type coreless TORUS axial flux permanent magnet overview [59]

Stator configuration is similar to as it was in TORUS concept. But, in rotor part magnets are not mounted on rotor disc. Instead, permanent magnet formed an interior type structure. Overview and flux paths of slotless AFIR and slotted AFIR are given in Fig.2-27 and Fig. 2-28, respectively.

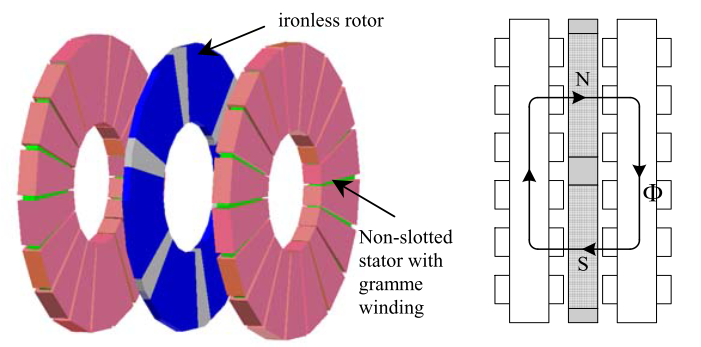


Fig. 2-27. Slotless AFIR overview (left) and path of generated flux by permanent magnets (right) [60]

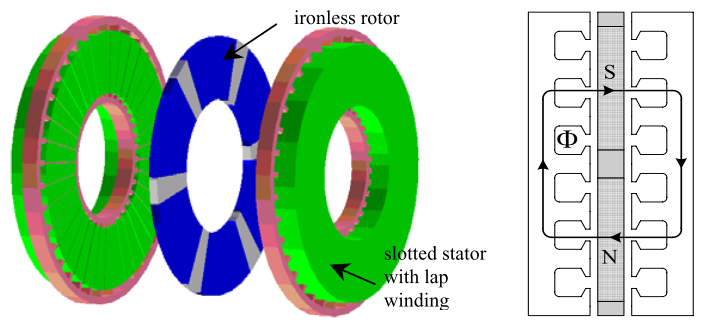


Fig. 2-28. Slotted AFIR overview (left) and path of generated flux by permanent magnets (right) [60]

AFPMs generally used with multi-stage configurations in order to increase torque and output power. In this configuration stages of generators stacked axially on the same shaft with (n) stator discs and (n+1) rotor discs, where “n” represents the number of stages. Multi-stage configurations of AFPMs are can again be classified as slotless and slotted structures. Properties of these structures are same as that of single stage TORUS and single stage AFIR type slotless and slotted configurations. An example of 2-stage AFPM generator with slotted stator configuration is given in Fig. 2-29. Multi-stage AFPM configurations can be used in ship propulsion and high speed generators. Similar to TORUS, multistage AFPM can be also constructed in ironless fashion. Flux path of the coreless multistage AFPM generator is given in Fig. 2-30. Detailed information about multistage slotted and slotless configurations of multistage AFPMs can be found in literature [13], [34], [54], [59], [60].

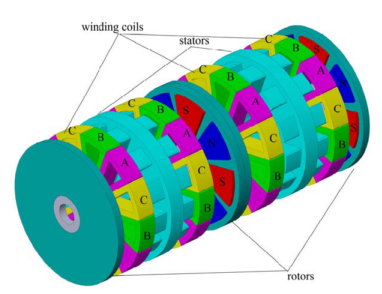


Fig. 2-29. Multistage AFPM generator [59]

Apart from the AFPM topologies discussed above, there are some other novel topologies which uses field control techniques. Another novel topology is double sided hybrid AFPM generators. These variations are not in the scope of this study but they can be found in literature [58], [60]–[63].

To summarize, the advantages of AFPM are: shorter axial length, reduction in cogging torque and torque quality problems, high torque per volume ratio, simplicity in adjusting airgap due to axially stacked stage/stages. Besides, lower torque per weight, large outer diameter as mentioned above, problematic core manufacturing process and higher cost than conventional RFPM are the main disadvantages of AFPM for suitable wind turbine generator [34].

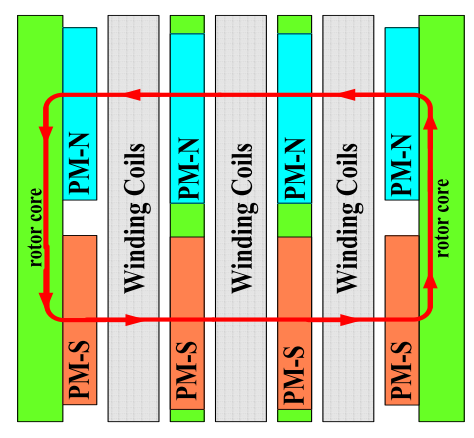


Fig. 2-30. Coreless multistage AFPM generator flux path [58]

In this thesis, coreless version of axial flux permanent magnet machine is studied due to its advantages of axial length and high torque per volume. In this type of machine, generator blocks are added axially to form the whole system. Magnets are placed on the surfaces of C-shaped rotor cores, facing the air-gap stator windings. Stator part consist of air cored concentrated windings. Detailed information about proposed generator and flux patterns will be given in following chapters.

## Transverse Flux (TFPM)

In transverse flux machines, the main path of magnetic flux is perpendicular to the rotation of the rotor part. It’s suitable for direct drive wind turbine application, considering its high torque density. Although high torque density provides efficient utilization of active materials in TFPM, when airgap is increases cost advantage of this concept decreases due to reduced force density. Sample view of TFPM is given in Fig. 2-31. Three dimensional flux path in this type of machine is given in Fig. 2-32. This kind of flux path becomes problematic during analysis and construction.

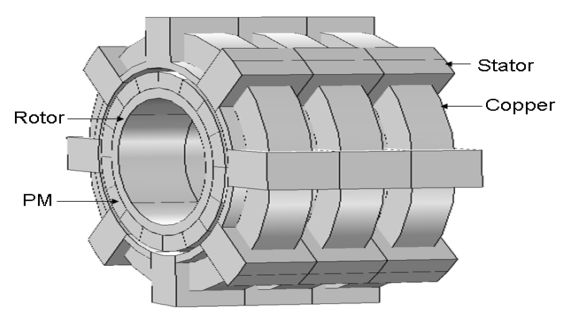


Fig. 2-31. Transverse flux machine view [64]

The main advantages of this concept are higher torque per mass ratio, simple winding construction among other PMSGs and available space for more windings than RFPM and AFPM. However, manufacturing issues due to the complex structure and low power factor eliminates TFPMs from the wind turbine generator configurations [15], [59]. Design improvements must be done in order to use TFPMs in wind turbine generators efficiently.

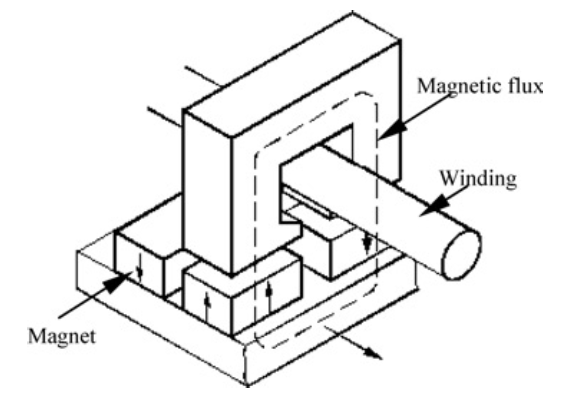


Fig. 2-32. Transverse flux machine three dimensional flux path [38]

## Importance of Modularity in WEC Systems and AFPM

Modular construction of electrical machines aims to get easier assemble and disassemble operations during maintenance and repair conditions. This concept also allows each module to work individually thus better fault-tolerance. In our study, modularity term has two meanings: axially stacked generators and C-shaped modular cores. First one is related to length advantage of selected generator type. By this modular structure technique, identical machines can be stacked in order to increase torque and power output under limited outer diameter conditions. These stacked generator sets can be grouped in parallel fashion, thus overall reliability of the system increases. Additionally, these axially stacked generators gives fault-tolerance to whole system. For instance, if one or more generators become defective during operation, not all but healthy stacks will continue to operate until the fault is cleared. Therefore, frequency of downtimes will reduce and efficiency of the wind turbine will increase. The latter is related to modular structure of the machine. For example, under fault conditions, defective cores can be changed and/or maintained easily. As mentioned in earlier parts, modularity is related to reliability. In other words, wind turbine generator system which constructed in modular fashion, provides better efficiency. Reliability is related not only with modularity of machine but properties of sub-module parts such as thermal issues about power electronics. Nowadays with the increased importance of grid connection safety and stability, efficiency and reliability become a critical properties of wind turbines. For instance, in offshore wind turbines it’s very important to operate the system continuously and to utilize the sub-module parts efficiently. Because, maintenance difficulty related to location is a big disadvantage for offshore wind turbines.

Modularity is not only related to technical problems but also related to economic issues. When large diameters and single bulky structure is considered, modular solutions for permanent magnet direct drive generator topologies become preferable. For example, using multistage generators at relatively low output power ratings is a better solution than using a single huge generator in terms of production, transportation and installation costs. Additionally, crane costs for installation and maintenance will reduce due to low mass of single stack of generator. Another important advantage of modularity is that downtime costs, which is the cost of missing electricity generation income during the downtime of the turbine due to an unexpected failure, can be reduced. As aforementioned in previous parts, a modular axial flux permanent magnet generator is proposed for wind turbine generator systems. Modularity and reliability are the key parameters for our proposed generator.

## Conclusion

In this chapter, fundamental equations and issues of wind energy harvesting technology are summarized. After this introduction part, the main challenges and critical issues of wind turbine systems are given. According to literature [2]–[4], generator technology gaining more attention than its past by reaching megawatts of power capability per turbine. Therefore its design is the main focus point of both this study and current research activities on this area. In the following sections, general overview of the most common wind turbine generator systems are given in detail in order to find suitable generator for MW-level wind turbines. Gearboxes are the main source of losses and faults in wind turbines. Induction generators and especially the DFIG with gearbox is the most common generator type because of its price and experience in both field and production. However, direct drive permanent magnet synchronous generators (PMSG-DD) are found more reliable and feasible solution in terms of efficiency, reliability and fault-ride-through capability. Thus, direct drive PMSG is chosen for the proposed design in this study. Then, flux orientations in PMSGs are discussed in this chapter and axial flux version is preferred among other types of PMSG because of its higher torque over volume ratio and axial length advantages. In this study, axially stacked modular generator with direct drive concept is preferred because of this reliability view. Additionally, using axially stacked generators in AFPM generator configuration can increase the total output power and torque under limited outer diameter conditions. Advantages and disadvantages of every concept and generator types are given in related sub-sections.

After detailed review of generator types and flux orientations in PMSGs, modularity concept is discussed. It’s been concluded that utilizing the generator in modular fashion will increase the efficiency and reliability. There are also economic aspects of using modular technologies in wind turbine design. Installation costs, crane costs for maintenance and installation, transportation costs and downtime costs can be reduced with modular design concept. Detailed design calculations of proposed direct-drive modular axial flux permanent magnet synchronous generator will be given in the next chapter.

# **CHAPTER 3**

# **DESIGN OF THE PROPOSED GENERATOR**

In the previous chapters, background information about wind energy conversion systems and detailed overview of the most used generator types are presented. Then, challenges of modern wind turbine systems and fundamental equations are discussed. Direct drive axial flux permanent magnet generator is chosen for the design in this thesis study because of its lower mechanical losses due to eliminated gearbox, high torque per volume and axial length advantages [15], [48]. In this chapter, electrical and mechanical design parameters of axial flux permanent magnet generators will be described. In order to do this, analytical design equations of proposed generator are presented in the following subsections. Finally, a result comparison of electromagnetic FEA and analytical calculation for a sample 50 kW generator will be presented to ensure the accuracy of the finite element analysis simulations. Analytic design equations described in this chapter are coded in MATLAB and then used in genetic algorithm optimization, which will be discussed in the next chapter.

## 3.1. Mechanical and Electrical Parameters

In this section, main electrical and mechanical parameter calculations of the proposed AFPM generator will be presented. In order to achieve an integrated understanding, dimensions and related drawings of the generator will be shown first. Then, magnetic circuit parameters including the airgap flux density and induced emf of the design will be described. Finally, structural and thermal design notes will be presented. In addition, calculation of the losses will be expressed at the end of this section.

## Dimensions of the Proposed AFPM Generator

In axial flux permanent magnet synchronous generator, inner air-cored stator and outer rotor surface mounted permanent magnets will be used. General overview of the proposed generator is given in Fig. 3-1. In this figure, three axially stacked generator blocks are presented. However, this figure includes only 4 poles section of the proposed system, for the sake of simplicity.

There is a (4/3) ratio between coil pitch and pole pitch in order to achieve maximum flux linkage. Since flux linked by the coil is related to induced voltage [34], [65], choosing optimum value of the pitch ratio has a high importance in electrical machine design. Induced voltage variation of a coil according to different coil pitch/pole pitch ratios, is shown in Fig.3-2. As it can be seen from this figure, 4/3 ratio has the highest induced voltage rating. This type of configuration is also used for modularity in our design.

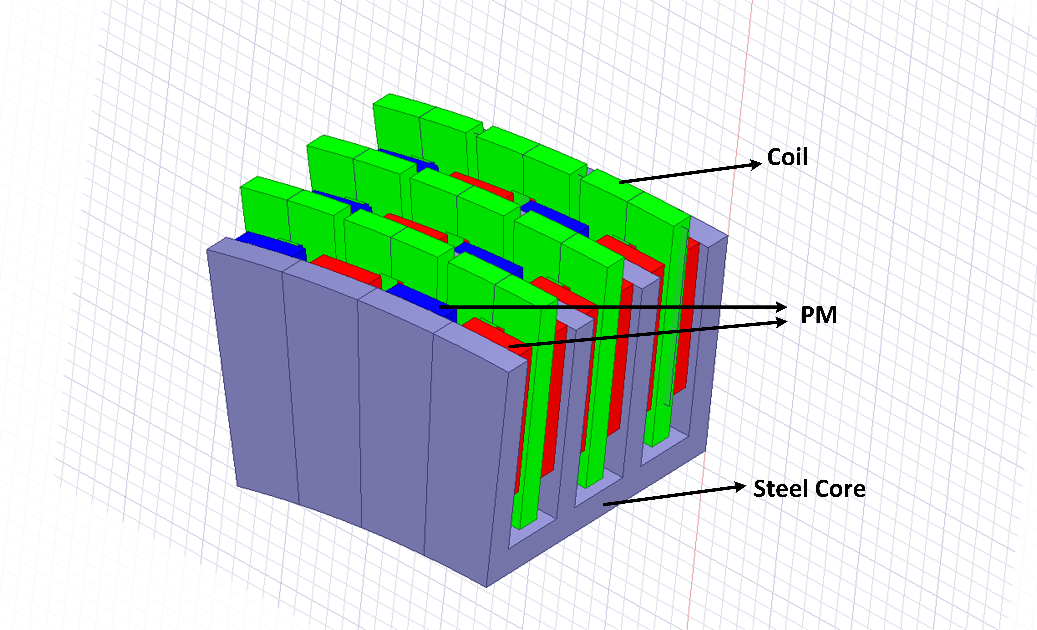


Fig. 3-1. 4-pole section of the proposed axial flux PM generator.

Main dimensions of the proposed AFPM generator are presented with their descriptions in Table 3-1, Table 3-2 and Table 3-3. These dimensions are shown on the machine drawing from different view angles in Fig.3-3, Fig.3-4 and Fig.3-5, respectively.

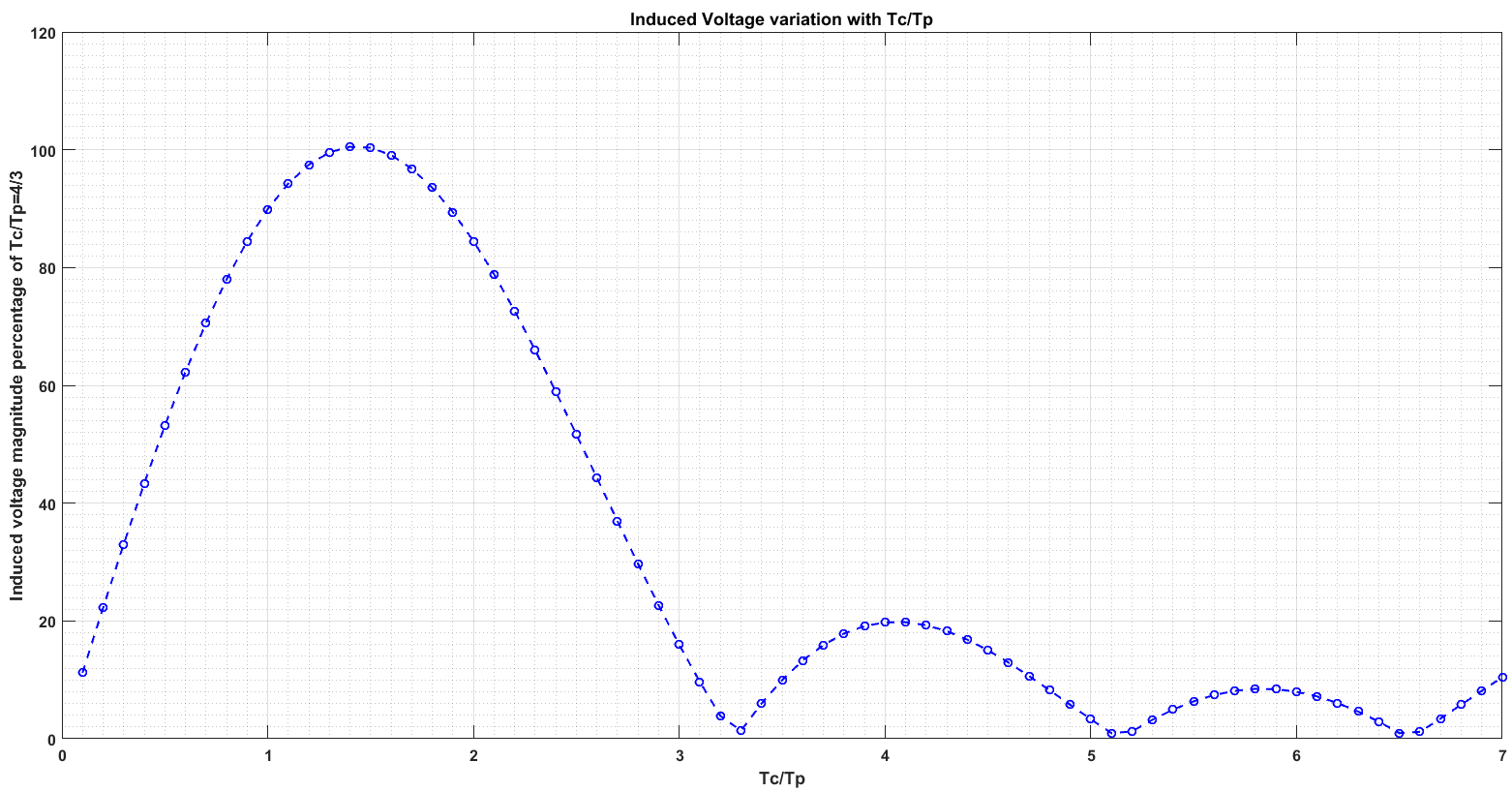


Fig. 3-2. Induced voltage variation with respect to different / ratios.

In Fig.3-3, dimensions for the side view of the proposed AFPM are shown. These parameter definitions are presented in Table 3-1.

Table 3-1. Dimensions of the proposed AFPM generator at side view.

|  |  |
| --- | --- |
| **Dimension** | **Description** |
|  | Airgap clearance |
|  | Coil to steel-web clearance |
|  | Magnet to steel-web clearance |
|  | Height of the winding |
|  | Height of the magnet |
|  | Magnet-to-magnet distance |
|  | Steel-to-steel distance |
|  | Steel web thickness |
|  | Length of the magnet |
|  | Thickness of winding |
|  | Coil pitch |
|  | Coil thickness/coil pitch ratio |

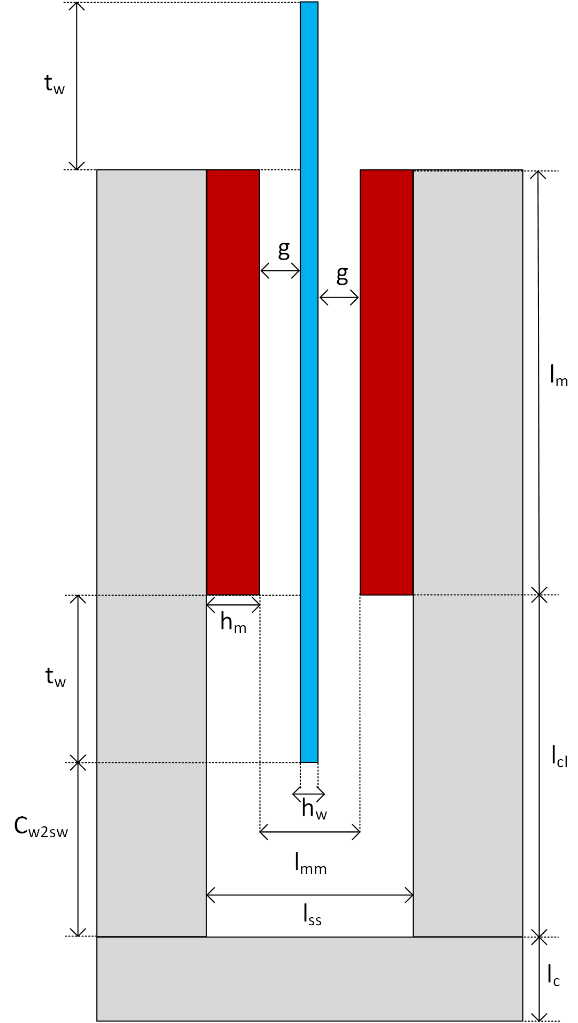


Fig 3-3. C-shaped core from side view with defined dimensions in Table 3-1.

Width(thickness) of the winding value *tw* is calculated by the help of the coil pitch ratio  as follows,

 (3-1)

 is the distance between coil and steel web. This value is used in the optimization algorithm as a constant. However, selection of proper distance is important for design considerations. Value of the coil thickness/pitch ratio  is determined by using optimization. In Fig.3-4, dimensions for the counter view of the one pole of the proposed generator are shown. These parameter definitions are presented in Table 3-2.

Table 3-2. Dimensions of the proposed AFPM generator pole at counter view.

|  |  |
| --- | --- |
| **Dimension** | **Description** |
|  | Pole pitch |
|  | Outer radius |
|  | Inner radius |
|  | Mean radius |
|  | Web radius |
|  | Width of the magnet |
|  | Number of poles |
|  | Web pole pitch |

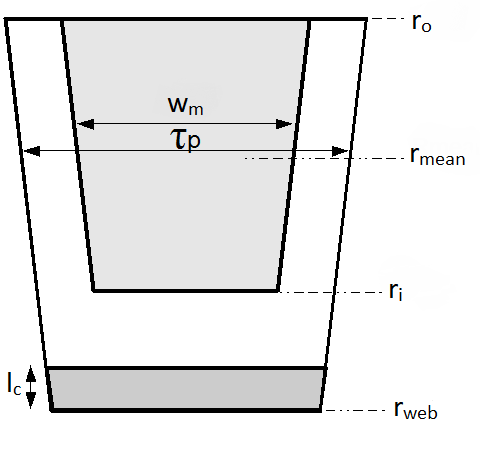


Fig. 3-4. Counter view of one pole of the generator core limb [66].

Pole pitch  distance can be calculated as follows [67],

 (3-2)

Mean radius  and magnet length  are determined by the optimization in our study. Outer radius *ro* and inner radius *r*i lengths are calculated by using magnet length and generator mean radius values as follows,

 (3-3)

 (3-4)

In this study, groove distance is taken as zero and it is assumed that magnets are smoothly surface mounted on the C-cores without any gap. Circumferential distance between the two successive C-cores, namely spacer gap is also assumed as zero. Web pole pitch  is calculated as follows,

 (3-5)

Magnet width distance (magnet pitch) *wm* can be calculated by using magnet pitch-to-pole pitch ratio  as follows,

 (3-6)

Magnet pitch-to-pole pitch ratio  is also referred as pole shoe arc-to-pole pitch ratio in [68] and can be described for our design as follows,

 (3-7)

Lower values of this variable leads to lower utilization of permanent magnets, hence higher values are preferred. However, much higher values of  results in increased leakage flux between permanent magnets thus decreasing the airgap flux density and machine electromagnetic performance [67], [69]. Therefore, value of this ratio is determined by using optimization. Leakage flux phenomenon is depicted in Fig. 3-5 in order to show the effect of higher. Stator outer diameter is important during the design because it should be limited for specific application and determines the main properties of a generator together with the parameter of axial length. Stator outer diameter is calculated as follows,

 (3-8)

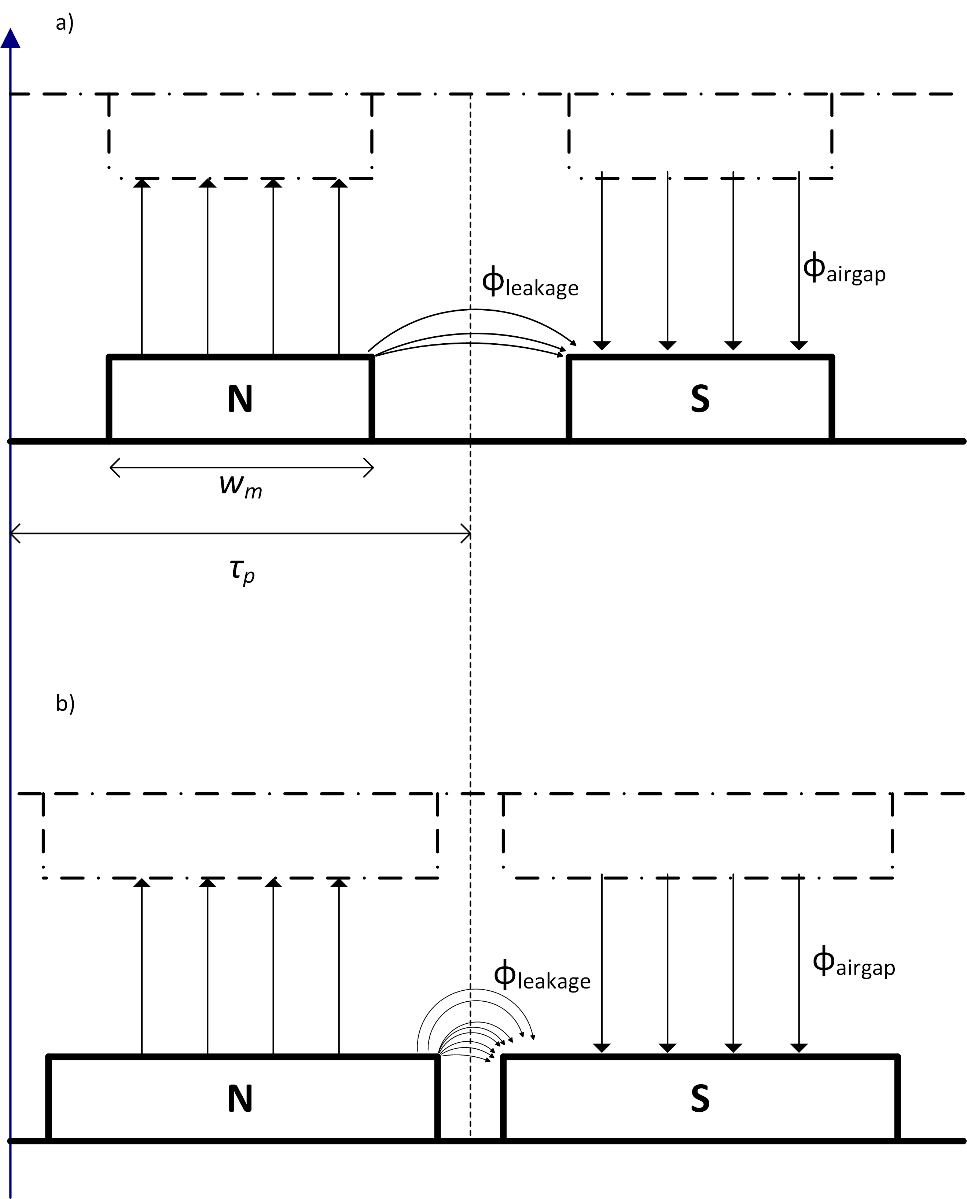


Fig. 3-5. Effect of higher  in terms of leakage flux from the top view of the generator. a) shows lower ratios of  with lower leakage flux. b) Ratio of  is increased thus leakage flux increases and lowering the effective airgap flux density.

In Fig.3-6, dimensions for the C-core coil of the proposed generator are shown at counter view. These parameter definitions are presented in Table 3-3.

Table 3-3. Dimension of the proposed AFPM generator pole at counter view.

|  |  |
| --- | --- |
| **Dimension** | **Description** |
|  | Inner length ratio |
|  | Outer length ratio |
|  | Length ratio difference which corresponds to thickness of the winding |

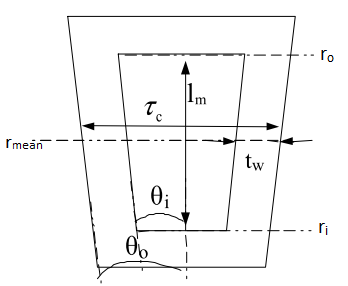


Fig. 3-6. C-core coil with inner and outer length ratios at counter view [66].

Length ratios  and  showed in figure above, are calculated as follows,

 (3-9)

 (3-10)

 (3-11)

where is the difference between two ratios. These length ratios are utilized to define the coil segments in radian and used in the flux linkage calculation. These calculations will be presented in the following subsections.

## Electromagnetic Design

In this section, electromagnetic design stages of the proposed AFPM generator will be described. In order to do this, first magnetic reluctance network of the machine will be presented. Then induced emf and related flux density calculations will be summarized.

* **Magnetic Circuit**

In order to find essential fluxes and flux densities of the proposed generator, flux paths and reluctance network should be defined first [70]. It’s assumed that leakage flux exists in the generator in order to calculate the parameters and analyze the generator more accurately. Therefore, flux paths and equations will be defined accordingly. Reluctances and flux paths are shown in side and top view of the c-cores in Fig. 3-7 and Fig. 3-9, respectively.

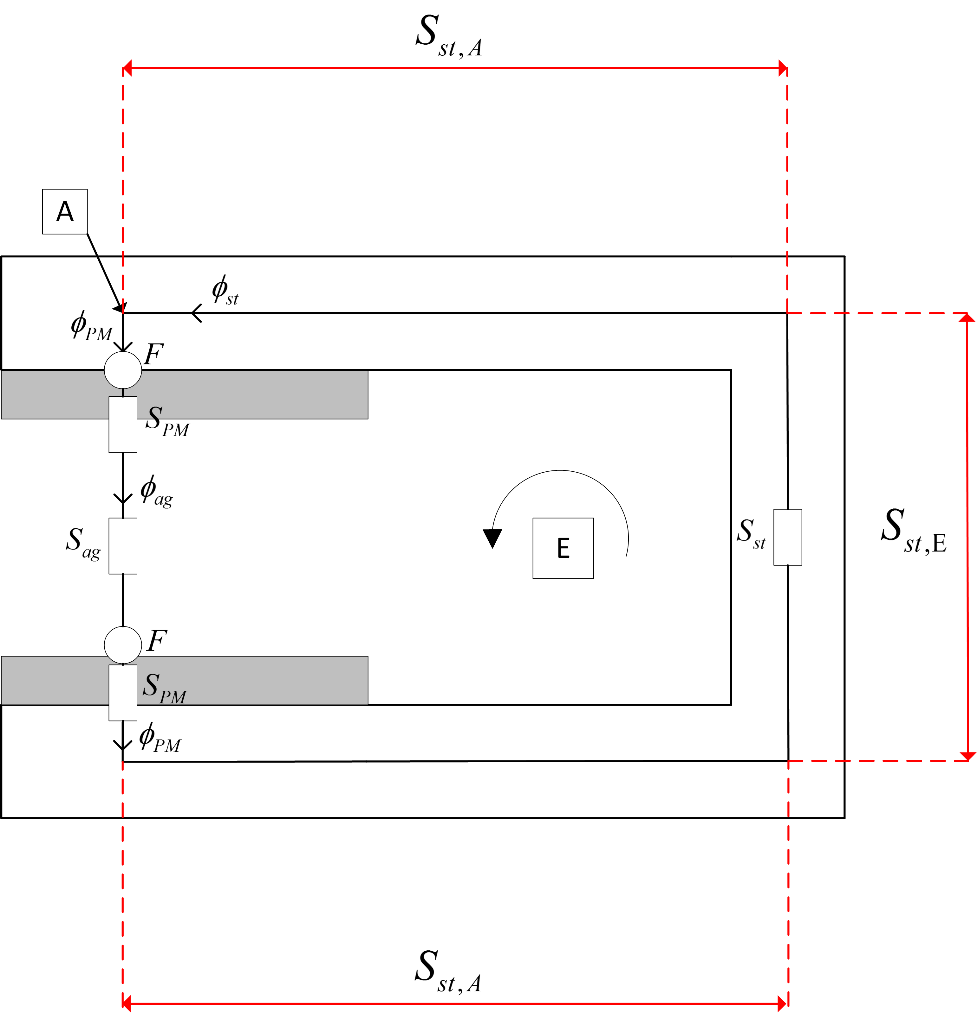


Fig. 3-7. Side view of the C-core for reluctances and flux paths [71].

Airgap reluctance  of the machine is calculated as follows[70],

 (3-12)

where  is the permeability of air. Steel reluctance  can be evaluated as two parts, namely Part A and Part E, depicted in Fig. 3-7. These specific reluctances and resulting total steel reluctance are calculated as follows [70],

 (3-13)

 (3-14)

 (3-15)

where  and  are thickness of outer limb and relative permeability of steel, respectively. Outer () and inner () limb thickness values are determined according to optimization process, which will be described in the next chapter. Reluctance of spacer is calculated as follows,

 (3-16)

Defined spacer reluctance above corresponds to inter-module steel part of core [70]. Reluctance value of the inter-module gap is omitted because gap distance is assumed as zero, as mentioned before. PM reluctance consists of two parts: magnet’s self reluctance and reluctance of the steel region. These two parts are shown in Fig. 3-8.

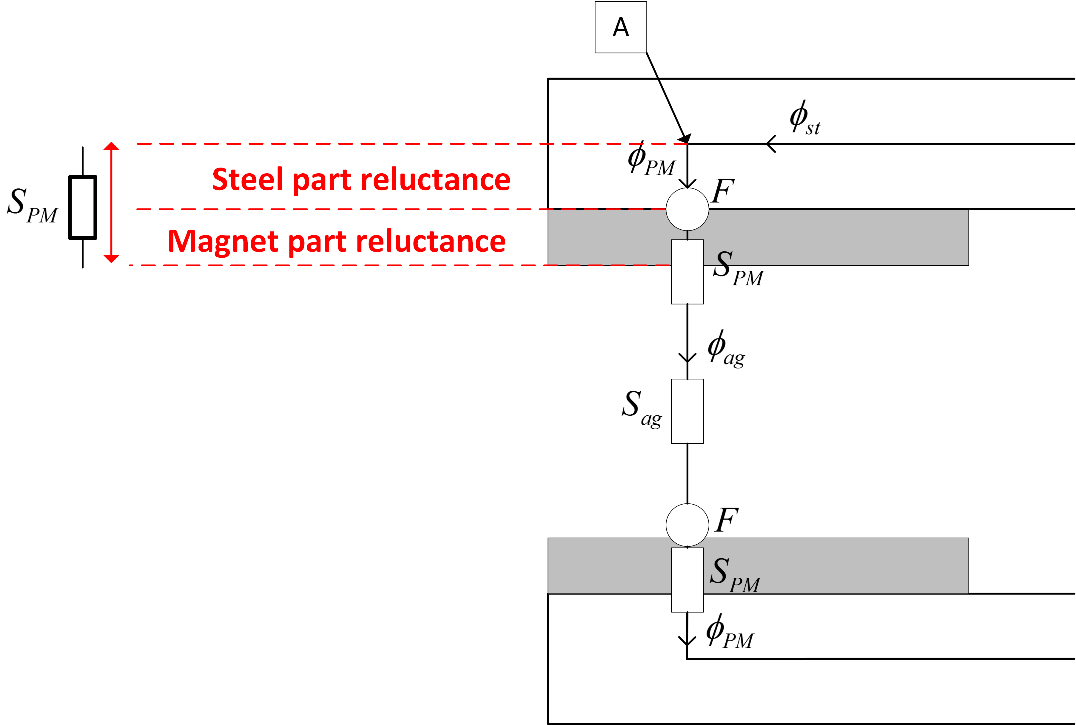


Fig. 3-8. Permanent magnet reluctance components.

PM reluctance *SPM* is calculated as follows [70],

 (3-17)

where  is the permeability of the permanent magnet material. Leakage fluxes in this study are assumed for magnet-magnet leakage direction. Top view of the C-cores showing the fluxes and flux paths including the mentioned leakage reluctances, is given in Fig. 3-9.

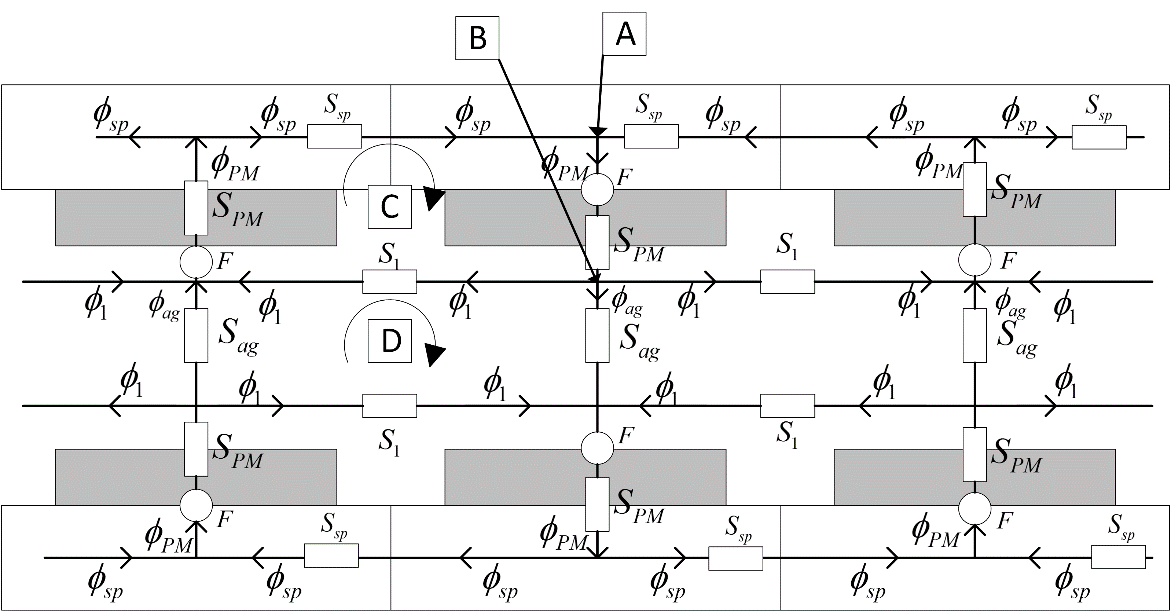


Fig. 3-9. Top view of the C-cores for reluctances and flux paths included leakage effect [70].

As can be seen on Fig. 3-8 and Fig. 3-9, permanent magnets are the main MMF source for the magnetic equivalent circuit. This MMF value provided by the permanent magnets, can be calculated as follows [70],

 (3-18)

where  is the remanent flux density of the permanent magnet. Remanent flux density value is taken as 1.4 T for the selected grade N50 rare-earth magnet [72]. Leakage path reluctance *S1* has two components. These components are shown in Fig. 3-10. According to this figure, leakage reluctance component  corresponds to gap regions facing the magnets in axial direction while reluctance component  corresponds to gap region between magnets in circumferential direction. It is assumed that flux generated by the magnets entering and leaving the magnets in axial direction. Therefore, leakage flux calculations on the side faces of magnets are unnecessary.

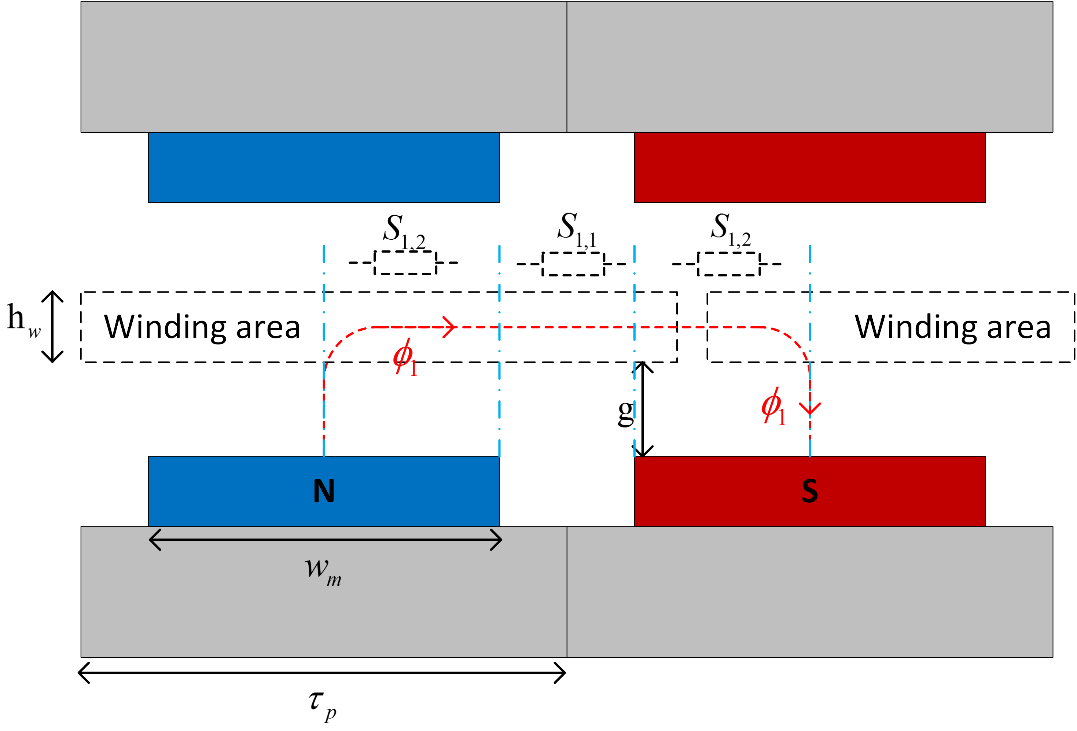


Fig. 3-10. Leakage reluctance network.

These reluctance components and resulting reluctance *S1* are calculated as follows,

 (3-19)

 (3-20)

 (3-21) In order to define fluxes and flux densities, magnetic circuit should be analysed in terms of reluctance network. Node equations at point A in Fig. 3-7 and Fig. 3-9 can be written as follows,

**** (3-22)

Equation at node B in Fig. 3-9,

 (3-23)

For the loop C in Fig. 3-9,

 (3-24)

For the loop D in Fig. 3-9,

 (3-25)

For the loop E in Fig. 3-7,

 (3-26)

from Eq. (3-23) and Eq. (3-25) ,

 (3-27)

 (3-28)

From Eq. (3-22) ,

 (3-29)

 (3-30)

From Eq. (3-24) ,

 (3-31)

From Eq. (3-26) ,

 (3-32)

where, , ,  and  are spacer flux, steel flux, permanent magnet flux and airgap flux, respectively. Left and right hand sides of the Eq. (3-31) and Eq. (3-32) can be defined as MMF matrix, reluctance matrix and flux matrix. Reluctance matrix according to combined form of loop equations given in Eq. (3-31) and Eq. (3-32) can be expressed as follows,

 (3-33)

Flux and MMF matrixes are defined according to combined form of reluctance matrix given in Eq. (3-33) as follows,

 (3-34)

To obtain the required flux values, inverse of the reluctance matrix should be multiplied with the MMF matrix. Therefore, resulting flux values are calculated as follows,

 (3-34)

Steel flux  is calculated according to Eq. (3-30). Airgap and spacer flux densities are calculated based on above flux equations as follows [70],

For air-gap flux density,

 (3-35)

For spacer flux density,

 (3-36)

For steel flux density,

 (3-37)

* **Electrical Parameters**

Since the proposed machine is a synchronous generator, electrical frequency of the machine is defined as follows [73],

 (3-38)

where *n* is the rotational speed in rpm. Mechanical speed  (rad/s) is calculated as follows,

 (3-39)

Airgap linear speed *v* (m/s)can be calculated as follows,

 (3-40)

In analytical design calculations, it is assumed that flux density in the airgap has a square waveform nature. Therefore, calculated analytical airgap flux density in previous sections, is the flat-top value of mentioned square wave. However, in reality this flux density waveforms are sinusoidal rather than square wave due to magnet shapes and leakage flux. Thus, peak value of the fundamental frequency component of the square waveform is utilized in calculations of flux linkage and induced emf [65]. In the next chapter, peak values of the fundamental component of airgap flux density in analytical calculation and finite element analysis will be compared. In Fig. 3-11, mentioned square waveform of analytical calculation and sinusoidal fundamental component of airgap flux density are shown. As can be seen from this figure, width of the square wave is related to magnet pitch-to-pole pitch ratio  .

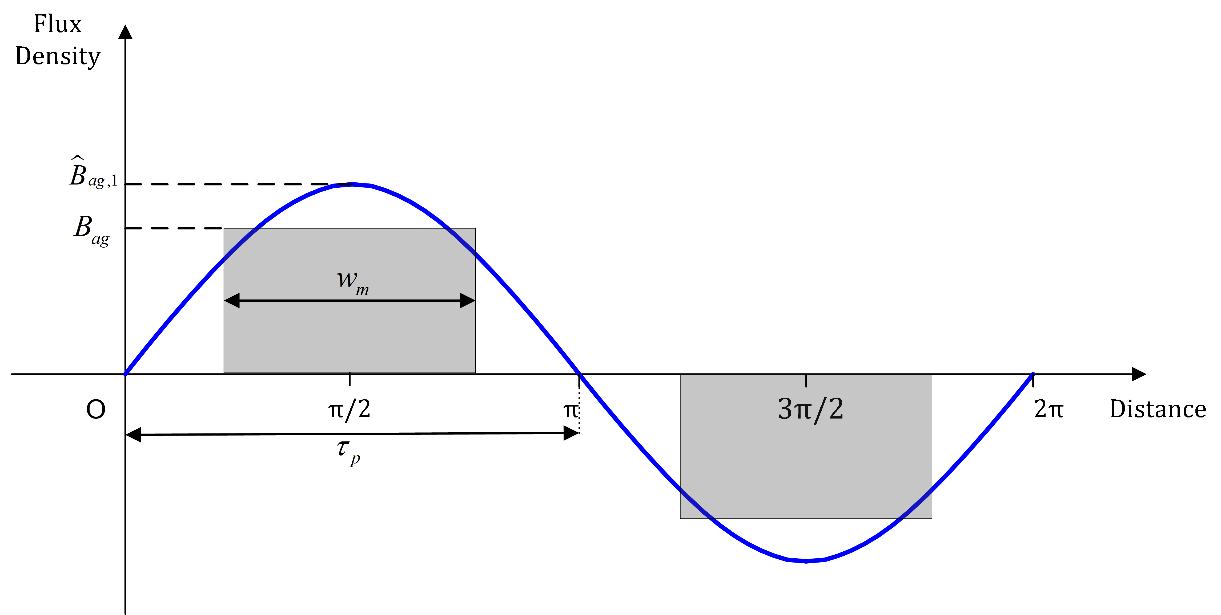


Fig. 3-11. Calculated airgap flux density square waveform (grey) and its sinusoidal fundamental frequency component (blue).

Peak value of the fundamental harmonic value of the air-gap flux density *Bag* is given as follows [65],

 (3-41)

Peak flux linkage is calculated for the proposed generator as follows [66], [74],

 (3-42)

Leakage coefficient  is selected as constant of 0.95. This value is determined according to comparison of induced emf results between analytical calculations and FEA. Induced emf *e* in one turn of coil is calculated according to Faraday’s Law by using linked peak flux as follows [66], [74],

 (3-43)

Approximate per-phase equivalent circuit and phasor representation of synchronous machine are given Fig. 3-12 and Fig. 3-13, respectively. Output rms phase voltage (terminal voltage) of a typical synchronous machine is calculated as follows [73],

 (3-44)

where,  is the induced emf rms value,  is the per phase synchronous reactance under steady state temperature and  is the rms phase current.

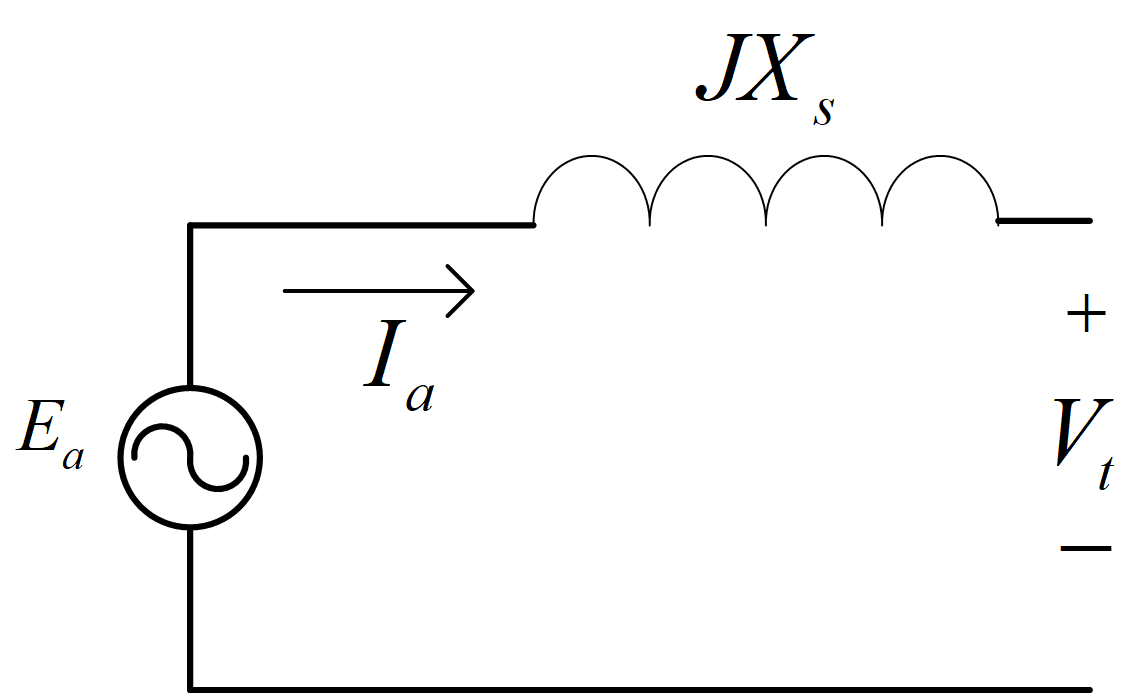


Fig. 3-12. Equivalent circuit of the synchronous machine where *Ea* is the induced emf, *Ia* is the phase current, *Xs* is the synchronous reactance and *Vt* is the phase terminal voltage [73].

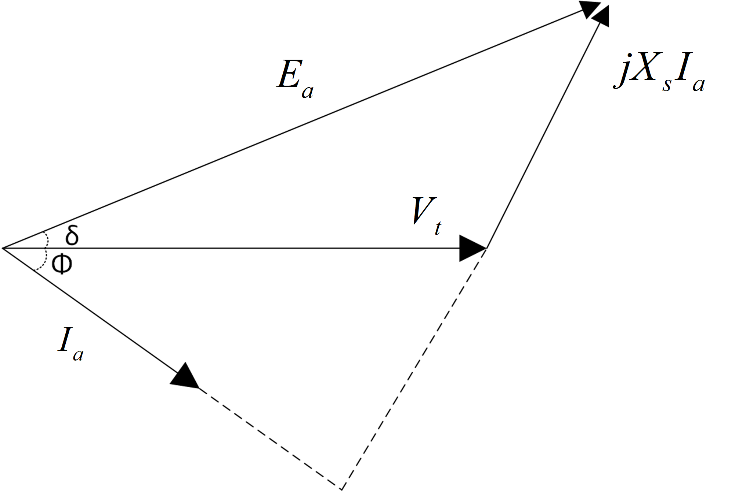


Fig. 3-13. Phasor diagram of synchronous machine where *δ* is the load angle, *Φ* is the power factor angle.

 can be calculated as follows,

 (3-45)

where *Ns* is the number of coils in series. Phase voltage rms value according phasor diagram given in Fig. 3-13, is calculated as follows,

 (3-46)

where  and  are phase resistance (which is relatively small than reactance) and phase reactance, respectively. Power factor is assumed as unity in our design. Therefore, power factor angle  is equal to zero. Because, a vector controlled power electronic stage is considered for the converter part. However, power electronic converter design is out of the scope of this thesis. Load angle  is calculated at every rotation speed in the optimization design code according to trigonometric equation given below,

 (3-47)

Effective window area of the conductors  is related with the conductor dimensions and fill factor of the design. This area value is utilized in current and resistance calculations. In Fig. 3-14, schematic representation the of the conductor in cross-sectional window of the winding is given. Effective window area can be expressed as follows,

 (3-48)

where *kfill* is the fill factor for the winding coils. Fill factor can be taken as constant between 0.6 and 0.7 during optimization process due to concentrated air cored windings in our design.

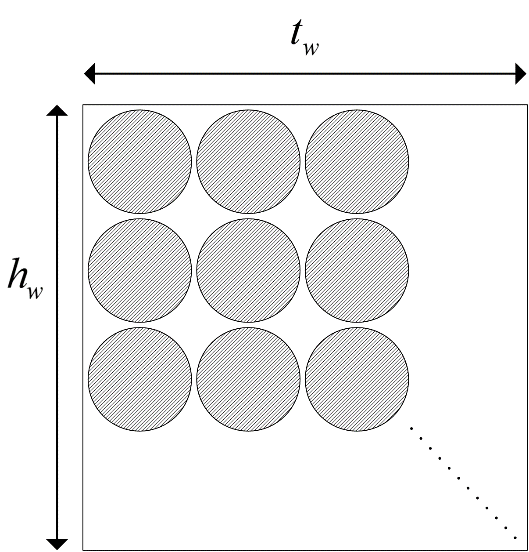


Fig. 3-14. Positions of the conductors in the winding from top view. Shaded regions represent the effective window area.

Current in one coil branch value can be expressed as follows,

 (3-49)

where *J* is the current density in A/mm2 and  is the cross-sectional area of a conductor. Current density value can be selected before the design process as a constant. However, this value is optimized in our design according to operating conditions. More detailed information about this process can be found in the next chapter. Rms value of the total current per phase () can be calculated as follows,

 (3-50)

Mean turn length for a coil *lt* is calculated as given in Eq. (3-51).

 (3-51)

where  ,  and  are lengths defined for end part, middle part and structural part of the coil, respectively. These lengths are calculated as follows,

 (3-52)

 (3-53)

 (3-54)

Resistance of one coil is calculated as follows,

 (3-55)

where  is resistivity coefficient of copper conductor. Resistance per phase value is based on resistance per coil branch and calculated as follows,

 (3-56)

Resistance value given in Eq. (3-48) was calculated without thermal effects. Resistance value including thermal effects can be calculated as follows.

 (3-57)

where  is the temperature coefficient of copper and  is the temperature difference between ambient and expected operating temperature. Angular frequency and inductance of a coil are calculated as follows,

 (3-58)

 (3-59)

where  is the flux linked by coil. Inductance value of the coil can be calculated as follows [73], [74],

 (3-60)

Phase reactance  value is calculated as follows,

 (3-61)

Phase impedance *Zph* can be calculated using phase resistance and reactance values as follows,

 (3-62)

## Structural Deflection

Structural deflection is related to mechanical stability. Since proposed design has air-cored stator, there will be no attraction force between stator and rotor [71]. However, C cores try to close the airgap against each other and result in deflection in the air gap clearance. Main reason of this deflection is strong magnetic attraction forces between magnets in the air gap clearance. Ratio of this deflection with respect to airgap clearance is significant parameter in terms of structural modelling of the generator [70]. This type of deflection is shown in Fig. 3-15. In literature, air gap deflection is generally allowed between 10-20% [70], [75]–[77]. It is desired to keep this ratio below reasonable ratio of 10% in our design.

To model the structural deflection at 2D, beam model is employed [78]. Normally C cores are exist on the web module. Therefore, length of the beam  is limited as sum of the magnet length  and magnet to steel web clearance. Right hand side of the beam is modelled as stationary wall to show the steel web part. Beam model is given in Fig. 3-16. Normal stress *q* due to airgap flux density is calculated with Maxwell stress tensor as follows [66],

 (3-63)

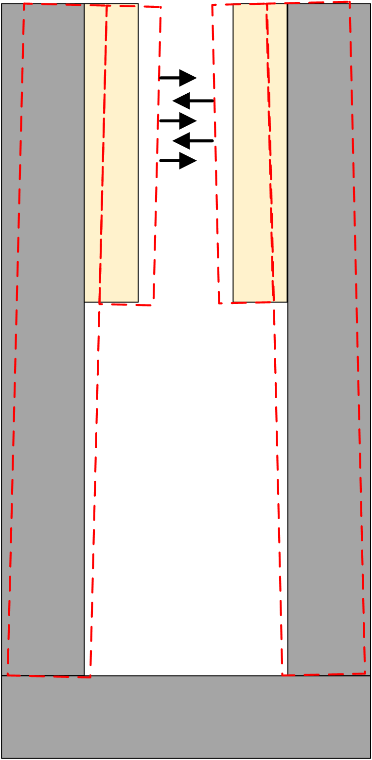


Fig. 3-15. C-core deflection due to attraction forces, deflected cores are shown with red dashed lines.



Fig. 3-16. a) Beam model for the C core deflection. b) Model for uniformly distributed load () is applied at *a=0* c) Model for uniformly distributed load () is applied at limited *a* units along the beam [70].

Uniformly distributed load  is calculated as follows,

 (3-64)

Total deflection *y* is calculated by summing the two sub-models as shown in Fig. 3-16. First sub-model demonstrates the deflection *y1* when a=0 and the second one demonstrates the deflection *y2* when *a*=. As mentioned before, beam length is calculated as follows,

 (3-65)

Two beam deflections (*y1* and *y2*) and resulting total deflection *y* are calculated as follows [79],

 for  (3-66)

 for  (3-67)

 (3-68)

where *E* and *I* are the Young’s Modulus of steel and the second moment of inertia of steel cross-section, respectively. Young’s Modulus is taken as constant as 200x109 Pa for structural steel. Second moment of inertia is calculated as follows,

 (3-69)

## Thermal Considerations

Main heat resources in proposed generator are copper losses of the windings and eddy losses. However, eddy losses are relatively very low with respect to copper losses because of low speed and low electrical frequency operation [66]. Therefore, current density control is the main focus of this design. When insulation class of windings (F class-155oC [80]) and operational thermal limits of permanent magnets (N50-type magnet-80oC [81]) are taken into account, forced cooling methods are more reasonable rather than natural cooling methods for such a MW-level generator. Cooling of the machine is chosen as forced air cooling in order to improve electrical loading performance. Additionally, forced air cooing improves the magnet thermal performance and prevents them from demagnetization at extreme conditions such as short circuit faults [82]. In this study, thermal network of the machine is neglected. However, this disadvantage is compensated by forcing the optimization algorithm to converge for higher efficiency ratings. Therefore, we can determine a reference current density (A/mm2) value at 100o C operating temperature according to chosen cooling technique. Then, calculation of the temperature rise for windings  can be found by using a rational relationship between “I2R” losses and current density given as follows,

 (3-70)

where reference current density  is selected as 7A/mm2 [54], [83], [84].Resulting operating temperature can be found by summing the temperature rise value given above and ambient temperature , which can be assumed as 20o C. In the optimization process, operating temperature value is calculated at every different operating speed with respect to related current density values. Other constants and reference values will be explained in the next chapter.

## Volume and Mass Equations

Total mass of the generator consists of two main categories: active mass and structural mass. Active mass includes the materials which affect the electromagnetic performance of the machine directly while structural mass components generally provided mechanical stability to generator via non-magnetic materials. However, as the machine diameters and power ratings increase, structural mass contribution in total mass become dominant [70], [76], [85], [86]. Since large diameter direct-driven generator concept is chosen in our design, similar structural mass dominance exists. Main duty of the structural mass parts of the machine can be summarized as transmission of the torque between shaft and air gap and maintain air gap by providing structural support against magnetic forces [70], [76], [85]–[88]. Total mass contribution to proposed generator is included in designed system by cost optimization. Mass components of the proposed AFPM generator can be listed as follows,

* Active mass: Steel mass, Copper mass, Permanent magnet mass.
* Structural mass: Shaft, Stator cylinder structure, Rotor torque structure, Steel band, Epoxy.

## Active Mass Calculation

Total steel mass  consists of three main parts: outer limb mass, inner limb mass and web mass. These mass values are calculated as follows,

 (3-71)

Total magnet mass  is calculated as follows,

 (3-72)

Total copper mass is calculated as follows,

 (3-73)

In order to include number of parallel machines into calculation, number of layers of each component should be multiplied with related single layer mass of component as given in Eq. (3-82). A sample view of 3-stage (number of parallel machine is three) axially stacked generator is given in Fig. 3-17. As it can be seen on this figure, number of outer limbs is always two (2), regardless of the stack number of generators. Number of inner limb is always one less than that of the stack number (-1). Number of permanent magnets  is always double that of the stack number (2). Number of steel web is same as number of stacks (). In addition, thickness of the outer limbs are always more than that of the inner limbs due to the single-sided magnetic forces. These unbalanced forces are shown in Fig.3-18.



Fig. 3-17. Proposed axial flux PM generator side view with three axial stacks [66].

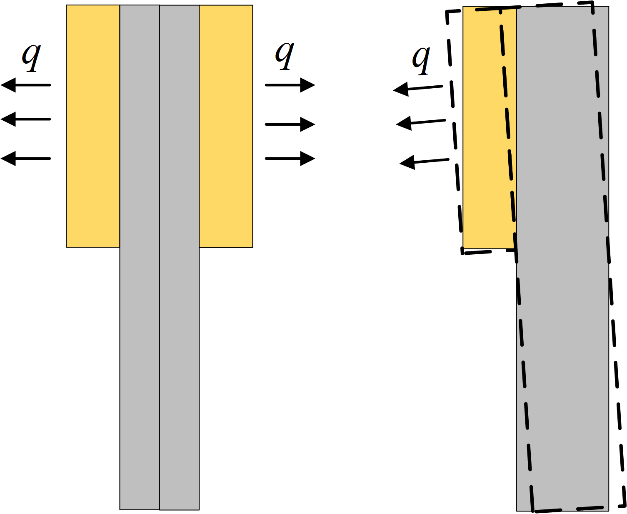


Fig. 3-18. Balanced and unbalanced forces of c-core limbs, left: inner limb case,

right: outer limb case.

## Structural Mass Calculation

Total structural mass of the generator can be defined as the sum of the shaft mass, stator torque structure mass, rotor torque structure mass, steel band mass and epoxy resin mass [15], [66].

Shaft can be modelled as a hollow cylinder. Therefore total shaft mass can be calculated as follows,

 (3-74)

where  ,  and  are shaft outer radius, shaft inner radius and shaft length, respectively. Shaft radius values can be selected as a ratio of outer radius of machine [70]. However, these values are used as constant in the design process since mean radius hence outer radius is allowed to change in a limited range in the optimization stage. For the convenience, shaft length is selected as the 5/4 times that of the machine total axial length. Total stator mass consist of a stator cylinder mass  and two times of the stator torque arm structure mass  . Formula of this mass is given as follows,

 (3-75)

Stator cylinder provides stiff supportive mechanism to the stator windings and mass of this structure  can be calculated as follows [66],

 (3-76)

Stator torque structure holds the stator cylinder mechanism stable and consists of torque arms [70]. These arms are formed of rectangle steel hollow bars as can be seen on Fig. 3-19. Top view of steel hollow bars with dimensions are also shown in same figure. Stator torque arm structure mass is calculated as follows,

 (3-77)

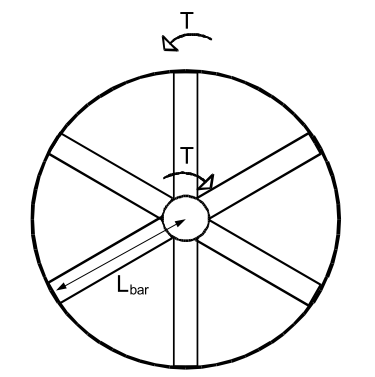
 

Fig. 3-19. Torque arm structure with 6 arms and Top view of steel hollow bar dimensions [66].

where  and  are the number of stator torque arms in a single structure and length of stator torque arms, respectively. Length of a torque arm is generally half of the stator outer diameter of the machine. *b, d, bi,* and *di* are the cross-sectional distances of steel hollow bars. Dimensions used in the calculations of these values should be suitable in terms of hollow bar view. In [70], author arbitrarily selected hollow torque arm dimension for radial-flux variant, considering arm deflection cases. Torque arm dimensions can be expressed in a similar approach as follows,

 (3-78)

 (3-79)

 (3-80)

 (3-81)

In this thesis, arm deflections are not included in calculations. Because primary aim of the structural components is to maintain air gap clearance stable. For this purpose, core limb deflections are already calculated and kept under limited ranges with optimization. Duty of rotor torque arms is to maintain stability to C-shaped cores of rotor. Total mass of rotor torque arms () is calculated in a very similar way that of stator torque arm calculation:

 (3-82)

where  and  are number of rotor torque arms and length of the rotor torque arm, respectively. Calculations and definitions for steel hollow torque arms for rotor are same as stator torque arm calculations. Therefore, Fig. 3-11 is valid for rotor torque arm structure. Length of rotor torque arm bar is equal to web radius . It can be optional to use supporting steel discs instead of rotor torque arms as shown in Fig. 3-10. However, torque arm is selected for rotor support in our design due to its simple design equations. In our proposed design 8 rotor bars and 6 stator bars are used [70]. Function of the steel band is to give mechanical support to coils and fix them to the stator structure. A sample steel band used in proposed generator is given in Fig. 3-20. Total steel band mass is calculated as follows,

 (3-83)

where  and  are the height and width of the steel band, respectively. These sizing values of the steel band can be determined as constant during optimization.

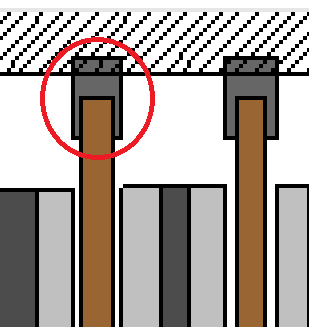


Fig. 3-20. Steel band [66].

Epoxy resin is used to fill the free space around coils and to give mechanical support and insulation for winding [37]. Its total mass  in our proposed design is calculated as follows,

 (3-84)

where  and  are the mass density of epoxy resin and pitch of the coil former. Main duty of the coil former is the give mechanical support to the coils from inner side [37]. Representation of sample trapezoidal winding with distances including the pitch of the coil former is given in Fig. 3- 21. A commercial coil former which has open slots structure, is given in [89]. Mean pitch of the coil former  can be calculated as follows,

 (3-85)

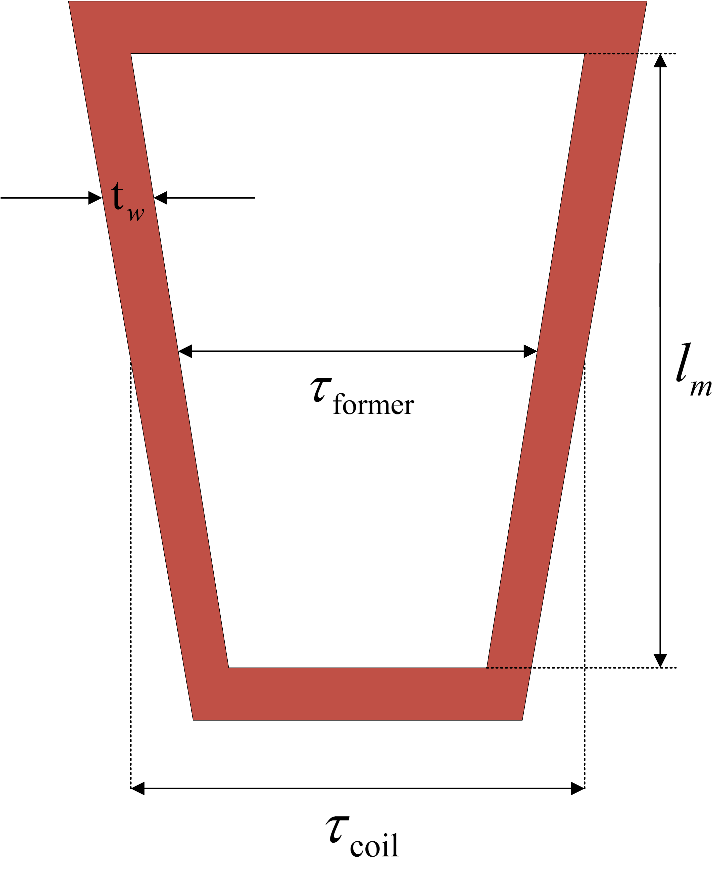


Fig. 3-21. Trapezoidal winding distances.

## Losses

Total energy loss in the generator is sum of the core losses and the copper losses.

 (3-86)

Copper losses  are calculated as follows,

 (3-87)

Core losses  consists of eddy losses both on coils and magnet surface. These losses are calculated as given below [73], [90], [91],

 (3-88)

 (3-89)

 (3-90)

where ,  are coil and magnet components of eddy current losses, respectively.  and  are thickness and height of the copper conductor, respectively. *Bag* is the airgap flux density, *keddy* is the eddy loss coefficient used in calculating magnet eddy loss, *Nc* is the number of coils. Eddy loss coefficient is taken as constant of 18 kW/m3 for rated speed (12 rpm) from FEA eddy loss simulations and it will be changed during the optimization according to operating frequency of generator. Number of coils can be calculated as follows,

 (3-91)

Number of coils per phase (*Nc,ph*) is calculated by dividing *Nc* value by 3. Height and thickness of the coil can be expressed as follows,

 (3-92)

 (3-93)

where  and  are thickness of epoxy and number of turns per strand, respectively. Epoxy thickness value can be taken as constant (1 mm) during the design process. Number of turns per strand value is calculated as follows,

 (3-94)

where  is the number of strand and taken as 1 in our design. Coil area including the insulation part is calculated as follows,

 (3-95)

## Electromagnetic FEA vs Analytical Evaluation For Sample Dimensions

In electrical machine design, airgap magnetic flux density is a key parameter to estimate. Because the airgap magnetic flux density affects the induced emf on stator windings via airgap flux calculations. Besides, airgap flux affects the core magnetic saturation characteristics. Hence core dimensions should be determined properly for normal flux distributions among the machine structure. Due to the reasons aforementioned above, it’s important to calculate the airgap flux density parameter correctly before machine production. Finite element modelling and analysis techniques are preferred especially when the machine geometry is hard to model and calculate analytically. In this subsection, some of the machine analytic equations described earlier in this chapter and the finite element modelling results will be compared in order to verify the design equations and techniques used in this thesis. Finite element modelling results are obtained from Ansys Maxwell 3D FEA analysis software.

To verify the design equations and techniques used in this study, airgap flux density and induced emf per phase values are chosen for the comparison. For this purpose, a 50 kW sample generator design is considered and evaluated in the optimization problem. Detailed information about optimization parameters and optimization process will be given in the next chapter. However, essential design parameters of the 50kW sample generator, which are achieved by the genetic algorithm optimization, are given in the Table 3-4.

Table 3-4. Optimized design parameters of the sample 50 kW generator.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Rotational speed () | 60 rpm |
| Mean radius () | 0.7 m |
| Phase current () | 5.3 A |
| Airgap clearance (*g*) | 2 mm |
| Voltage per phase | 977 V |
| Induced emf per phase rms (*Eph,rms*) | 1058 V |
| Induced emf per phase peak () | 1496 V |
| Number of turns (*Nt*) | 146 |
| Number of poles (*Np*) | 96 |
| Output power (-per stack) | 15,396 W |
| Phase resistance () | 14.92 Ω |
| Current density (*J*) | 4 A/mm2 |
| Steel web clearance (*lc*) | 16 mm |
| Fundamental airgap flux density peak value () | 0.67 T |
| Airgap Flux Density (flat-top) | 0.57 T |
| Height of the winding () | 13 mm |
| Winding thickness/Coil pitch ratio  () | 0.369 |
| Fill factor (*kfill*) | 0.65 |
| Height of the magnet (*hm*) | 10 mm |
| Length of the magnet (*l*m) | 87 mm |
| Magnet pitch-to-pole pitch ratio () | 0.76 |
| Number of parallel branches () | 1 |
| Number of parallel machines () | 3 |
| Efficiency () | 92.38 % |
| Total mass (active + structural) | 1024 kg |

The peak value of the fundamental harmonic of the airgap flux density  is calculated according to Eq. (3-41). As it can be seen on the Table (3-4), this value is calculated as 0.67 T in our optimization process by using genetic algorithms. In the finite element analysis side, this peak flux density value is found as 0.65 T. For simplicity of the analysis 4 pole symmetric model is used in the analysis. Airgap flux density vector variation is recorded along the line which is shown in Fig. 3-22. This sinusoidal variation is shown in Fig. 3-23. Also in this figure, analytically calculated airgap flux densities are shown. As can be seen from the figures, the peak value of the flux density is 0.65 T. Therefore it can be said that analytic equation results and finite element analysis results show good agreement in terms of airgap flux density.

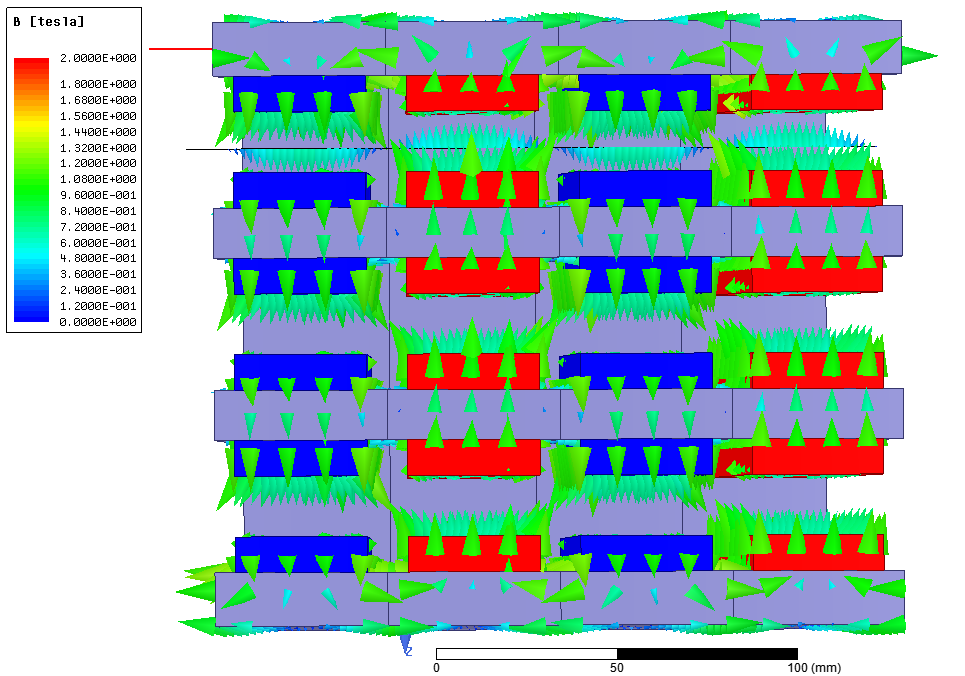


Fig. 3-22. Airgap flux density vectors for the sample 50 kW design.

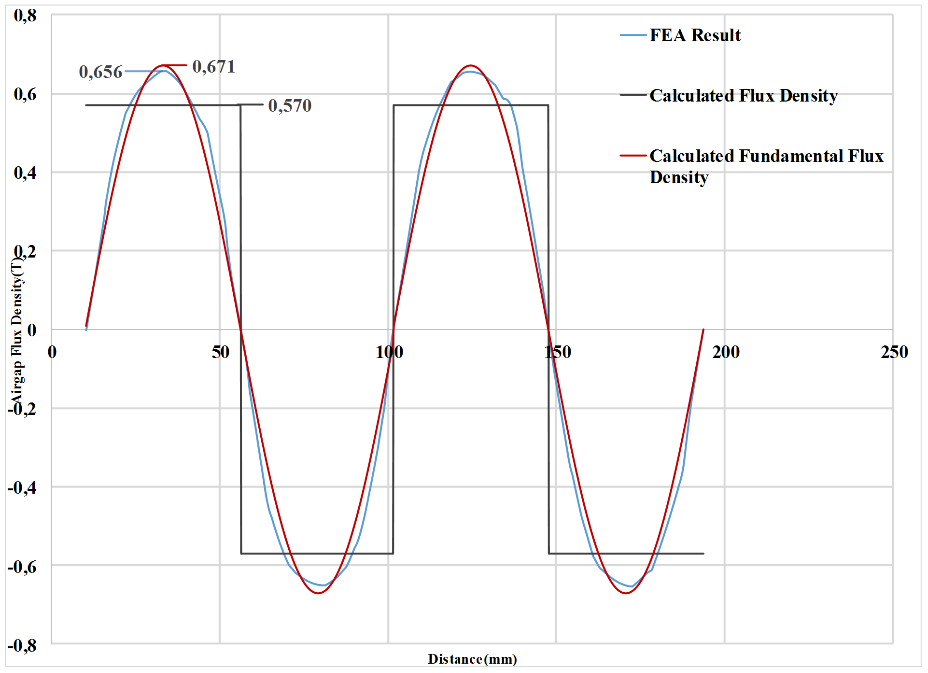


Fig. 3-23. Airgap flux density graph with analytical results for the sample 50 kW design.

Sinusoidal flux density variation induces sinusoidal voltages on windings. In our analytical design equations, induced emf (peak) per phase is calculated via Eq. (3-45). As it can be seen on Table 3-4, this value is calculated as 1496 V. Induced emf per phase peak value of the finite element analysis is given in Fig. 3-24. This graph is obtained for three phase at rated speed of 60 rpm. All three phases are balanced (120o phase difference) in time domain and they all have peak magnitude of nearly 1600 V. Therefore, it can be inferred that analytic equation results and finite element analysis results show good agreement in terms of induced emf. In Table 3-5, comparison of flux density and induced emf values of both analytical calculations and FEA results are given with related error rates.



Fig. 3-24. Induced emf per phase graph for the sample 50 kW design.

Table 3-5. Comparison of the critical parameters of analytical and FEA results for the sample AFPM design.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Analytical | FEA | Error |
| Peak airgap flux density () | 0.67 T | 0.65 T | 3% |
| Peak induced emf (*Eph,peak*) | 1496 V | 1600 V | 6.5% |

## Conclusion

In this chapter, analytical design equations of the proposed AFPM generator are described. In the first section, mechanical and electrical parameters of the proposed generator are covered with related graphics and mathematical expressions. These design equations are mainly consist of; fundamental generator equations, geometrical and structural equations, phase turns, resistance and flux density equations, thermal equations, reluctance network and related equations, volume and mass equations and finally power and efficiency calculations. During the design of the proposed generator leakage fluxes are taken into consideration. Unity power factor is assumed for the phasor equations due to selection of vector control in the power electronic stage. These design equations are very important as their results will be used in the optimization process and finite element design. In the second section of the chapter, comparison of the results of the design equations and the finite element analysis is given for a sample 50 kW AFPM generator in order to verify the design method followed in this thesis study. For this purpose, airgap flux density and induced emf per phase parameters are chosen since they’ve been used widely in the design of electrical machines as key parameters [73]. It is concluded that the results of the analytical equations and the results of the finite element analysis are in good agreement. Therefore, these analytical equations can be used in the optimization for the proposed AFPM generator design.

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