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Review

Conceptual Framework of Antecedents to Trends on Permanent Magnet Synchronous Generators for Wind Energy Conversion System

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Abstract: The Wind Energy Conversion System (WECS) plays an inevitable role across the world. In particular, the attention for Permanent Magnet Synchronous Generators (PMSGs) connected with wind farm is popular. This paper deals with the literature review that describes the recent advances, progresses and innovatory trends on PMSGs for WECS. Comparison between geared and direct-driven conversion systems and the classification of electrical machines used in WECS are discussed. A detailed analysis on the design aspects considering various topologies of PMSGs are encompassed in the literature. The PMSG design and optimization problems are solved by field computation techniques and optimized by using Soft Computing (SC) techniques .The three-dimensional, finite element software platform for the analysis and design of PMSGs is discussed. This paper also deals with the interdisciplinary modeling, analysis, and optimization of PMSG using Finite Element Analysis (FEM) and SC techniques. Finally, PMSGs are reviewed and compared for further exploration.

Keywords: Permanent Magnet Synchronous Generators; Wind Energy Conversion System; Finite Element Analysis; Soft computing Techniques.

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1. Introduction

In every phase of research and development in the arena of electrical engineering, there is a well-defined need for exploring and interpreting the technical literature. The first step in research work is to conduct an extensive review on the previous related works as stated by Herbert B. Michaelson, et al. (1949) [1]. As per the stating, the review survey should comprise of specific information, detailed survey and preliminary review. This paper contains numerous indexing journals to illustrate various fields of hypothesis subjects like history of WECS, revolution of PMSG, utilization of FEM, application of SC, and advancement of Computer Aided Design (CAD). The world economy and human needs greatly rely on energy hence research in this area is highly significant [2].

In the present scenario, the needs for electric energy utilities are increasing with no bounds. Since conventional sources are fast depleting, sustainable development aspects should concentrate more on the alternative energy sources like wind, solar, biogas, hydro, and tidal wave. In the beginning of 20th century there was awareness about non-conventional energy sources, particularly in the generation of electricity using wind energy. Out of the entire renewable alternatives, wind energy has an imperative potential [2]. It is more sustainable, eco-friendly and provides energy security [10]. The below Figure 1 depicts the strategy and framework that has been followed to develop the further research.

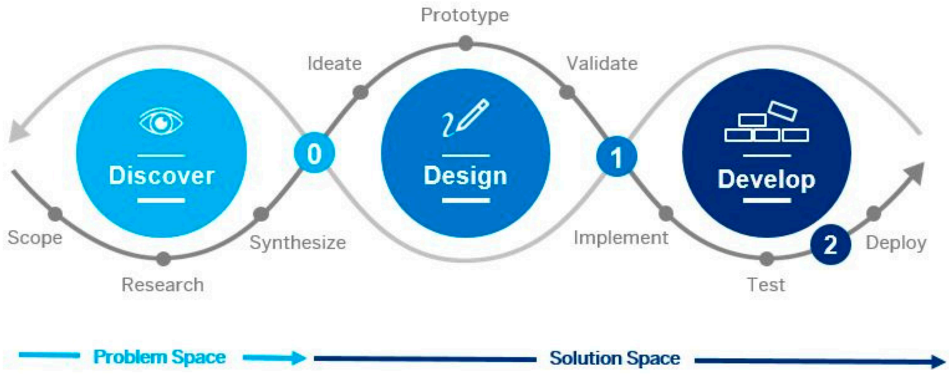

Figure 1. Strategy for design and development

2. Theory of Wind Turbine

A wind turbine is a machine that converts kinetic energy into mechanical energy. Normally, the theory of wind turbine clinches to upsurge permeation of wind energy keen on the power grid. It has overcome potential obstacles accompanying with the WECSs [11]. Basically, the wind theory is based on the principle of aerodynamic and classical momentum theory. To understand the power extraction from wind turbine, an air duct can be considered where the velocity of wind at the inlet is V_1 and the outlet is V_2. If m is the mass of the air through the imaginary duct per second, then the extracted power can be written as in (1)

$$P_k = \frac{1}{2} m \left(V_1^2 - V_2^2\right) ---------------(1)$$

If V_a, A and ρ are the velocity of the air, cross-sectional area of the duct and density of air at the turbine blades respectively, then mass flow rate of the wind can be represented as in (2)

$$P_k = \frac{1}{2} \rho A V_a \left(V_1^2 - V_2^2\right) -------------- (2)$$

Theoretically, the maximum power extracted from the wind is 0.5925 of its total kinetic power and is known as the Betz Coefficient. But, the actual mechanical power received by the generator is lesser than that due to the frictional losses in rotor bearing and inefficiencies of aerodynamic design of the turbine and can be calculated as in (3).

$$P_k = 0.5925\, X\, \frac{1}{2} \rho A\left(V_1^3\right) ------------(3)$$

In general wind pressure moves the turbine in a step-like method despite its design. In wind energy production both low (cut-in) and abundant (cut-out) wind speeds are labeled as risk potentials. Commonly, these values are called as cut-in and cut-out wind speeds, respectively. Each turbines risk potential, say are obtained based on the design parameters and size. Wind turbine yield electricity between 3 and 25 m/s, and high generation are evaluated after 10–15 m/s values. Every turbine has cut-in and cut-out values contingent on designing parameters and size [2].

3. Wind Energy installed capacity worldwide

According to Global Wind Energy Council (GWEC) wind energy supplies about 2.5 percent of global electricity consumption. Industry projections show that wind power with the right policy support will double in capacity by 2015. Thereby supplying about 8 to 12.5 percent of global electricity is supplied by wind energy. Wind power capacity is expected to reach 2,300 GW by 2030, which can meet 22% of the world's electricity demands. The Global Wind Energy Outlook 2014[3] discovers the future of the wind energy industry up to 2050. The outlook is prescribed a baseline of different settings such as New Polices Scenario, Moderate scenario and advanced scenario (Table 1).

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Table 1. Global Total Breakdown Of Cumulative Capacity upto 2030.

Global Total					
Total Capacity in MW	2013	2014	2015	2020	2030
New Polices Scenario	318128	356322	396311	610979	964465
Moderate Scenario	318128	363908	413039	712081	1479767
Advanced Scenario	318128	365962	420363	800615	1933989

The global energy demand during 2012 and 2013 was estimated as 282.5GW and 318105 MW respectively representing a strong market growth of more than 19% in 2012 and 12.5% 2013. This growth rate is lower than the annual average growth rate over the last ten years by about 22% and 21% of global electricity which is expected to increase to 8 -12% by 2020. According to the international agreements proposed on environmental commitment scenario the wind penetration level is expected to increase by 10% in the year 2016. The expected saturation level capacity by 2030-35 is $1.9x10^9$ kW.

4. Brief review of WECS

The historical background of WECS is discussed widely in literatures. In this, Ahmet Duran Sahin (2004) the literature on wind engineering and wind power meteorology with much importance to turbine and generator technology has been discussed. Also, the economics involved in wind system are evaluated [2]. R. Ramakumar, et al, (2007) insisted that wind electricity conversion is the factor growing green technology due to 1) advancement in structural design; 2) blade design and manufacture 3) power electronics based efficient power processing techniques and novel generator design for variable-speed operation [6]. G.M. Shafiullahet al. (2013) have studied the possible methodological challenges to the incorporation of large-scale wind energy into the power grid and look over in regard to current research with their obtainable alleviation techniques. Uwe S. Paulsen, et al, (2012) presented 5MW baseline design of the Deep Wind concept and Darrieus-type floating wind turbine system for depths of more than 150m. This paper covered a possible technology on existing different generator type and manufactures of large power direct drive wind turbines [234**].** Due to the technology tower & blades, the wind turbine hubs height, rotor diameter & power rating have improved from 1980-2020 as depicted in Figure 2. The most powerful wind turbine is a 7.5 MW turbine with a rotor diameter of 126 meters. According to the Global Wind 2012 Report, the largest turbine in the world is the new Alstom Haliade 6 MW turbine with a rotor diameter of 150.8 meters [3]. The future wind turbine is expected to be of capacity 20000kW with a rotor diameter of 250m.

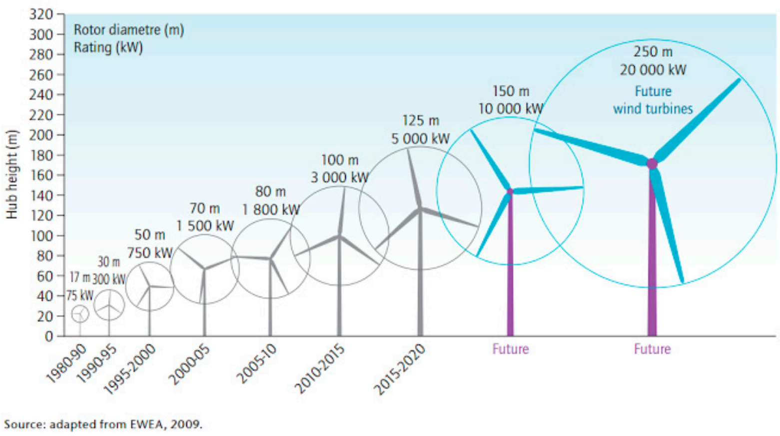

Figure 2. Growth in size of wind turbines since 1980 and prospect. KEY POINT: Scaling up turbines to lower cost has been effective so far, but it is not clear that the trend can continue forever.

The power output density function of various WECS for different operating wind regime was studied by Manish Mohanpurkar, et al (2010) using a probabilistic approach. G.M. Joselin Herbert, et al, (2007) reviewed the following information aspect of world wind energy scenario, wind turbine sizes, site selection, wind resource assessment, wind turbine aerodynamics, performance and stability of wind turbines, wake effect, difficulties related with wind turbines, wind turbine technology (Design, Loads, Blade behaviour, Generator, Transformer, Grid connection, and Control system). G.M. Joselin Herbert, et al, (2014) reviewed different aspects of significant technical issues for the wind farms such as Wind power resource assessment techniques, Environmental impacts, Grid integrations techniques, Control strategies, Off-shore wind turbine technologies, Hybrid energy techniques, Hydrogen production, Wind energy feed-in tariff, Modelling techniques on wind turbine components, Performance prediction and improvement techniques, Cost and economic of wind energy production, and Generators influences on wind energy production [5]. Sareni, et.al, (2009) investigated optimized configurations for the passive wind turbine generators that match with the behaviour of active wind turbine systems operating at optimal wind power by using an MPPT control device [231]. Arthur Bossavy, et al, (2013) present an emergent attention in short-term wind power projecting tools. Developing a prediction statistics, especially keen to ramps, is of primary interest because of both the problems that normal models have to envisage and the potential risk they represent in the management of a power system. A methodology to characterize ramps of wind power production with a derivative filtering approach derived from the edge detection literature was proposed. Then investigate the skill of numerical weather prediction outfits to make probabilistic forecasts of ramp incidence [14].

5. Wind Turbine

Wind turbine installed worldwide has undergone numerous changes in technology with significant development in wind turbine sizing. Over a period of time, wind turbine technologies have evolved resulting in the development of wind turbine concepts. The appraisals of wind generator systems have become necessary with them becoming more cost-competitive **[**142**]**. The tower supports the rotating and stationary parts. The stationary part called as the nacelle contains generator, power converter, grid side step-up transformer, and monitoring and control equipment. Wind turbines are broadly classified into two categories: horizontal axis (HAWT) and vertical axis (VAWT) wind turbines. The main rotor shaft of a HAWT rotates in the direction of the wind. The nacelle of HAWT is usually placed at the top of the tower. On the other hand, the rotation of rotor shaft of a VAWT is perpendicular to the ground and the generator, transformer, converters and other equipment are usually assembled near the ground. Due to its better aerodynamic performances compared with the VAWT, the HAWT are widely employed in large-scale offshore wind farms [18]. Md Rabiul Islam, et al, (2014) summarized the compact and lightweight wind turbine nacelle and its technical challenges with focus on HAWT [18]. Latha Sethuraman, et al, (2014) analyzed the suitability of a direct-drive radial flux permanent magnet generator as a probable drive-train runner. The fitness of the generator is tested based on the structural design (i.e., the stability of the air-gap between the rotor and stator) in accordance to PMSG is validated by FEM software to calculate the variation in flux density & force along the periphery of the rotor. A simplified analytical model is used to compute the resulting changes in flux density and force distribution along the rotor periphery. The analytical model is also validated by 2D magneto-static simulations by utilizing FEM software [236].

6. Types of Wind Turbine Generators

To convert wind energy into electricity, the Induction and Synchronous generator models are commonly used [2]. Z.Chen, et al, (2009) presented the different topologies of wind farm configurations. The Danish wind power status is also presented [12]. Jose´ Luis Domı´nguez-Garcı´a et al, (2012) classified the different schemes of wind turbine technologies. They are as follows: Direct Drive Synchronous Generator (DDSG), Doubly Fed Induction Generator(DFIG), Full Rate Converter Induction Generator (FRCIG), Full Rate Converter Wind Turbine(FRCWT), Fixed Speed Wind

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Turbine (FSWT), Fixed Speed Wind Turbine-Permanent Magnet Synchronous Generator (FSWT-PMSG), Fixed Speed Wind Turbine-Squirrel Cage Induction Generator (FSWT-SCIG), Permanent Magnet Synchronous Generator (PMSG), Squirrel Cage Induction Generator(SCIG), squirrel cage induction generator-wind turbine (SCIG-WT), Variable Speed Wind Turbine-Direct Drive Synchronous Generator (VSWT-DDSG), Variable Speed Wind Turbine-Doubly Fed Induction Generator (VSWT-DFIG), Variable Speed Wind Turbine—Full Rate Converter Induction Generator (VSWT-FRCIG) [15].

7. Types of Generator Technology

Electric generators involved in wind turbine can be classified into different types. The induction, synchronous machine and parametric (with anisotropy permanent magnets) are the main types of electrical generators. These are considered based on the principle, power level, and application. Certain concepts of generator system have been used widely spread and using commercially numerous applications. Specific new configurations have been still in the laboratory (although advanced) stages. Boldea I. (2006) explained and compared all the types of classification [147]. Generally, way of principle; there are three main types of electric generators which are: Induction, Synchronous Machines, and Parametric, with magnetic anisotropy and permanent magnets. Parametric generators have in most configurations doubly-salient magnetic circuit structures, so they may be also called doubly salient electric generators [147]. Furthermore, it can be classified based on magnetic flux penetration, PM electrical generators are categorized into three types: radial-flux, axial-flux and transversal-flux machines [147].

8. Significance of PMSGs for WECSs

A low-speed and high-torque PMSGs are highly preferred in high-power direct-driven wind power applications as they provide better efficiency [99]. PMSG is widely employed owing to the reasonable cost of Permanent Magnet (PM).PM is providing higher efficiency, high-power densities, the possibility compactness which can reduce the turbine size [2]. A PM generator claims its merits by of excluding the exciter field winding, slip rings, and brushes along with the ability to self excite making option to obtain higher power factor and efficiency.

The overloading and full torque capability of PMSG in standalone system is makes them highly competing against conventional electrical machines. It has an ability of self-excite and an attractive feature that makes it a suitable choice for operation at higher power factors and efficiencies. In addition, PM machines do have the overloading capability and full torque capability at zero and at very low speeds [17]. Particularly in the isolated areas, standalone power systems are used. This is effective inevitably competing against the conventional electrical machines.

H.Li, et al, (2009) investigated the potential site matching of the direct-drive wind turbine models based on the electromagnetic design optimization of permanent magnet (PM) generator systems. The investigation models of a three-phase radial-flux PM generator with a back-to-back power converter are presented. The study contained 45 PM generator systems designed and optimized, which are grouped as a combination of five rated rotor speeds in the range of 10–30 rpm and nine power ratings from 100 kW to 10 MW, respectively. The finest outcomes are compared in detail in terms of the generator design indexes. Subsequently, based on the design principle of the maximum wind energy capture, the rotor diameter and the rated wind speed of a direct-drive wind turbine with the optimum PM generator are determined. The Annual Energy Output (AEO) is also presented using the Weibull density function. Lastly, the maximum AEO per cost (AEOPC) of the optimized wind generator systems is evaluated at eight potential sites with the annual mean wind speeds in the range of 3–10 m/s, respectively. From the results are shown the suitable designs for the optimum site matching of the investigated PM generator systems [20].

For Anton Aleksashkin (2008) describes a complete idea about Permanent Magnet Generators Design. Geared and direct-driven permanent magnet generators are discussed. A classification of direct-driven permanent magnet generators is given. Dynamics and vibration problems of PMSG

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covered in the literature. The application of the FEM for mechanical problems solution in the field of permanent magnet generators is consistently presented. Furthermore, it is deals with different topology of design aspects and peculiarities of permanent magnet generators [9]. Tayfun Gundo˘gdu, et al. (2012) emphasized in terms of technological and economical assessment of the basic assembly and magnetic topographies of the Salient Pole Synchronous Machine and Permanent Magnet Synchronous Machine. Furthermore, an economic analysis of the designed machines has been accompanied for wind turbines [232].

9. Various aspects of comparison for PMSGs

Different perspectives of comparison were observed from the several other literatures. Güven Kömürgöz, et al, (2012) studied a general and magnetic analysis of Conventional Salient Pole Synchronous Machine (CSPSMs) and Permanent Magnet Synchronous Machines (PMSMs) using FEM. The analyses are compared in terms of topology, size, magnetic field, air-gap flux, voltage, torque, losses, weight, and efficiency. When the PM is used in machine which has the same output power while the weight of the machine reduces, the machine becomes easier to produce and its efficiency increases. Furthermore, PMSMs grow into advantages particularly in wind turbine applications considering dimensions, weight, and maintenance. Table 2 compares active material weights and cost and Table 3 matches Losses at full load [98].

Table 2. Active material weights and cost [98].

	Part of Machine	Conventional Salient Pole Machine	Permanent Magnet Synchronous Machines
Weight (kg)	Armature Copper	124.76	192.06
	Field Copper\PM	160.12	40.85
	Damper Bar Material	10.7	-
	Damper Ring Material	5.65	-
	Armature Core Steel	331.05	269.61
	Rotor Core Steel	288.93	358.29
	Total Net	921.21	860.81
Cost ($)	Total PM	-	3676.5
	Total Copper	2620.7	1671
	Total Steel	523.88	530.58
	Total Active Material	3144.58	5878.075

Table 3. Losses at full load [98].

Feature\Machine Type	Conventional Salient Pole Machine (CSPSM)	Permanent Magnet Synchronous Machines (PMSM's)
Iron-Core Loss (kW)	1.537	1.665
Armature Copper Loss (kW)	10.31	11
Frictional and Windage Loss (kW)	2.6	1.9
Total Field Losses* (kW)	5.9	-
Input Power (kW)	550.2	5527.4
Output Power (kW)	529.85	538.17
Efficiency (%)	96.3	97.36
Armature Current Density (A/mm^2)	5.48	4.56
Rated Torque (kN.m)	5.256	5.178
Cogging Torque (N.m)	4.23	9.74

*Total field loss consists of additional loss, field copper loss, and exciter loss

After the investigation, it has been observed that the efficiency of the CSPSM is lesser than that of the PMSM's. Still, on the improvement of magnet and semi-conductor expertise, the PMSMs may have the benefit in terms of costs. Hence, heal their strategy should be followed such as machine efficiency and the efficient use of energy while designing the electrical machines [98]. H.Li, et al, (2008) presented a synopsis of comparisons of various wind generator systems. The traditional

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wind turbines are classified based on control features, drive train types along with the pros and cons. Experiment is also conducted on the permanent magnet generators. Also presented were the quantitative evaluation and market penetration of various wind generator systems. The survey contains radial-flux (RFPM), axial-flux (AFPM) and transverse flux PM (TFPM) machine. On a conclusive note, RFPM machine with surface-mounted PM is preferred over AFPM and transverse flux PM (TFPM) machine, due to direct-drive PM generator types, simple structure, better utilization of the active materials, and lesser diameter [142]. Henk Polinder, et al, (2006) presented a comparison of five various generator models for WECS. The wind turbines prescribed are as follows: the Doubly-fed Induction Generator with three-stage Gear box (DFIG3G), the Direct Drive Synchronous Generator with electrical excitation (DDSG), the Direct-Drive Permanent-Magnet Generator (DDPMG), the Permanent-Magnet Generator with single stage Behaviour (PMG1G) and the Doubly-Fed Induction Generator with single-stage behaviour (DFIG1G). The comparative study is based on cost factor and annual energy production for a given wind climate. The DFIG3G is a feasible solution in terms of cost with the available standard components. The DFIG1G appears as the most desirable in terms of energy production divided by cost. The DDPMG has the highest energy production, despite its being cheaper than the DDSG, which is actually more costly than the generator systems with gear box [22]. Hui Li, et al, investigated a seven-variable-speed constant frequency (VSCF) wind generator system. To name, they are as follows: PMSGDD, PMSG1G, PMSG3G, DFIG3G, and DFIG1G, Electricity Excited Synchronous Generator with the direct-driven (EESG_DD), and the VSCF squirrel cage induction generator with the three-stage gear box (SCIG_3G). As per the comparative study conducted, the optimization designs were made available for various wind generator systems with the ranges of 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW, and 10MW [100]. The cost involved in the lower generator system and the increased AEP per cost have made the PMSG_DD more cost-effective over the EESG_DD system. As the wind turbine size increases, a Direct–Drive Wind generator involves lower cost. However, when the rated power increases, the PMSG_DD system performs better than the EESG_DD system. The concepts of Single–stage gear box drive train are as follows: Due to the lower generator system cost and higher AEP per cost, the DFIG_1G system seems to be more attractive alternative. Adding to that, from an AEP per cost perspective, the most cost-effective DFIG_1G system is close to 1.5-MW. In the range of 1.5 MW to 5 MW, the DFIG_1G will maintain a higher scale in the AEP per cost. The Three-stage behaviour drive-train concepts are as follows: Due to the lowest generator system cost and the highest AEP per cost, the DFIG_3G system emerges as the most sought-after choice among three wind generator systems. Added to that from an AEP per cost perspective, the PMSG_3G system is undoubtedly more interesting than the SCIG_3G system [100]. The Table 4 & Table 5 comparing five different wind generators system in different aspects with respective manufacture.

Table 4. Comparison of five different wind generator systems [142].

Generators concepts	DFIG 3G	EESG DD	PMSG DD	PMSG 1G	DFIG 1G
Stator air-gap diameter, m	0.84	5	5	3.6	3.6
Stack length, m	0.75	1.2	1.2	0.4	0.6
active material weight, ton					
Iron	4.03	32.5	18.1	4.37	8.65
Copper	1.21	12.6	4.3	1.33	2.72
PM	-	-	1.7	0.41	-
total cost, k Euro	5.25	45.1	24.1	6.11	11.37
generator active material	30	287	162	43	67
generator construction	30	160	150	50	60
Behaviour	220	-	-	120	120
Converter	40	120	120	120	40
sum of generator system cost	320	567	432	333	287
total cost (incl. margin for company costs) kWh/Euro	1870	2117	1982	1883	1837

annual energy yield, MW h	7690	7740	7890	7700	7760
annual energy yield/total cost, kW h/Euro	4.11	3.67	3.98	4.09	4.22

Table 5. Large wind turbine concepts on the market over 2 MW [142].

Wind turbine concept	Generator type	Power/rotor/diameter/speed	Manufacturer
variable speed multiple-stage concept with partial-scale power converter	DFIG	4.5 MW/120 m/14.9 rpm	Vestas
		2MW/90 m/19 rpm	Gamesa
		3.6 MW/104 m/15.3 rpm	GE Wind
		5MW/126 m/12.1 rpm	Repower
		2.5 MW/90 m/14.85 rpm	Nordex
		3MW/100 m/14.25 rpm	Ecotecnia
limited variable speed with multiple-stage behaviour	WRIG	2 MW/88 m/17 rpm	Suzlon
variable speed multiple-stage behaviour with full-scale power converter	SCIG	3.6 MW/107 m/13 rpm	Siemens Wind Power
	PMSG	2 MW/88 m/16.5 rpm	GE Wind
variable speed single-stage behaviour with full-scale power converter	PMSG	5 MW/116 m/14.8 rpm	Multibrid
		3MW/90 m/16 rpm	Winwind
		2.5 MW/93 m/15.5 rpm	Clipper Wind power
variable speed direct-drive with full-scale power converter	EESG	4.5 MW/114 m/13 rpm	Enercon
	PMSG	2 MW/71 m/23 rpm	Zephyros

The cost involved in a multibrid PM wind generator system with a single-stage behaviour is comparatively lower the direct-drive concept. The gear ratios adoption may vary widely when the wind turbine size increases. Depending on the rated power levels, the ideal gear ratio ranges from 4:1 to 10:1. As a matter of fact, for larger power ratings, higher gear ratio should be used [77]. Md Rabiul Islamn, et al, (2014) GE energy, Vestas, Gamesa, Siemens and Goldwind employ PMSGs. The PMSGs' stator is wound, where the rotor is available with a permanent magnet pole system and might have salient poles which may be cylindrical. Mostly, the low-speed synchronous machines display the salient-pole type with the prominence of many poles. A direct drive system could be obtained from a synchronous generator that has the right number of poles (a multi-pole PMSG). Some of the common types are: the radial flux machine, the axial flux machine, and the transversal flux machine. It is to be noted that the efficacy is higher in the PMSG machine over the induction machine, due to the fact that excitation is supplied without any energy supply. However, the inventory used to produce permanent magnets is expensive and difficult to manufacture as well. In addition to that, the usage of PM excitation needs the usage of a full-scale power converter so that the voltage and frequency of generation are adjusted to the voltage and the frequency of transmission, respectively, which in turn, increase the system cost involved. The advantage is that, in order to fit the current wind generation, the power can be generated at any speed. Maintenance is usually restricted to the bearing lubrication only.

The traditional issue lies in the need to maintain the rotor temperature lesser than the threshold temperature of the magnet. This again could be impacted by the Curie point of the magnetic material along with the thermal criterion of the binding material as in the case of powder metallurgy composites. The synchronous process, in turn, produces issue in relevance to start-up, synchronization, and voltage regulation [18]. Sandra Eriksson, et al, (2011), comparison is done excellently for the direct-driven PMSGs. Six different-range generators are compared with each other [38]. The considerations are taken for the fixed and variable parameters for different ranges of generators in Table 6.

Table 6. Characteristics of rated speed and power for stationary simulations [38].

Fixed parameter	Power (kW),	50					
	Current density (A/mm),	1.44					
	Slots per pole and phase,	1					
	Length to diameter ratio,	0.35-0.38					
	B airgap (T)	0.74-0.76					
	B tooth (T)	1.53-1.57					
	B yoke (T)	1.43-1.46					
	Number of cables,	2*4					
		GEN1	GEN2	GEN3	GEN4	GEN5	GEN6
Variable parameter	Line voltage (V) rms ,	134	200	286	334	400	800
	Current (A) rms,	215.4	144.3	100.9	86.4	72.2	36.1
	Electrical frequency,(Hz) ,	11	14	17	18	21	31
	Rotational speed (r/min) ,	66	64.61	63.75	63.52	63	64.13
	Number of poles ,	20	26	32	34	40	58
	Magnet width (mm) ,	95	83	72	70	62	48
	Magnet height (mm) ,	20	17	15	15	13	10
	Stator inner diameter (mm),	910	1010	1060	1090	1150	1300
	Stator outer diameter (mm),	1106	1176	1206	1228	1277	1402
	Airgap width (mm)	15.83	13.83	12	11.67	10.33	8
	Generator length (mm)	343	358	393	412	410	487
	Conductor area (mm)	150	100	70	60	50	25
	Load angle	16.1	13.2	11.1	10	9.5	7.1
	Steel weight (kg)	450	426	422	438	405	429
	Cable weight (kg)	439	368	321	299	285	227
	PM weight (kg)	102	103	107	116	105	108
	Total weight (kg)	1177	1088	1039	1057	986	960

Zuher Alnasir, et al. (2013) presented a comparison of the Geared-drive SCIG, Gearless-drive PMSG, and gearless-drive PMIG-WECS configurations. For each index, each system is assigned a number (e.g., 1, 2, or 3) to show its rank in that index with respect to the other two systems. If two systems are assigned the same number for a specific index, they are in the same rank and hence they have similar level of advantage for that index. From Table 7 remark, the geared-SCIG system is prominent in 61.5% of the indices whilst gearless-PMSG system dominates in 38.5% of the indices. Gearless-PMIG is similar to the gearless-PMSG in 60% of its advantages. Therefore, geared-SCIG system prevails in terms of a number of indices. However, gearless-PMSG dominates in three of the top priority indices, namely, duration of failure behaviour, O&M cost, and generation efficiency. Nevertheless, geared-SCIG is dominant in four of the top priority indices, namely frequency of failure, generator O&M cost, kWh production at low speed and capital cost. In order to achieve accurate results, the weight of an index, according to its order, should be considered. Gearless-drive PMSG-based and geared-drive SCIG-based systems were concluded to be the most desirable solutions among different configurations considered [235].

Table 7. Comparison of the Geared-drive SCIG, Gearless-drive PMSG and gearless-drive PMIG - WECS configurations [235].

Order of index	Index Name	Details of Index	Geared SCIG	Gear less PMSG	Gear less PMIG	Best options	Comments and justifications
1	Reliability	Duration of failure	2	1	1	PMSG and PMIG	No
2		Frequency of failure	1	2	2	SCIG	Direct-drive WECS suffers higher failure rate as fluctuation of wind rotor is directly transferred to generator and power electronics.
3	O&M cost	Gearbox	2	1	1	PMSG and PMIG	No gearbox in direct-drive turbines.
4		Generator	1	2	2	SCIG	Generator failures are costly in direct-drive turbines.
5	kWh production	Affected by cut-in, rated and cut-out wind speed	1	2	2	SCIG	Cogging torque in PM generators negatively affect the cut-in speed of the turbine and thus kWh generation.
6	Capital cost	Cost of generator and gearbox (if any)	1	3	2	SCIG	Permanent magnet machines are expensive due to magnets.
7	Efficiency	Accounts for gearbox and Generator loss	3	1	2	PMSG	Gearless PMSG has neither gearbox nor rotor copper losses. It also operates at high PF.
8	Excitation Requirements	Reactive power source	3	1	2	PMSG	SCIG is fully externally excited. PMIG is partially externally excited. PMSG is fully internally excited.
9	Magnet problems	Demagnetization and future availability	1	2	2	SCIG	SCIG has no magnets.
10	Control simplicity		1	2	3	SCIG	SCIG is simple in control while fixed magnet excitation in PM machines. Complicates their controls.
11	Construction simplicity	Number of poles, diameter size, and rotor design	1	2	3	SCIG	Direct-drive PMSG is large and heavy due to multiple-pole construction. PMIG is complicated due to double rotor design.
12	Noise level	Drive train	2	1	1	PMSG and PMIG	PMSG & PMIG have no gearbox noise.
13	Generator		1	2	2	SCIG	SCIG has no significant cogging torque.

Order of index (1–13) denotes degree of significance/priority (1: highest priority). The index (1, 2 or 3) denotes superiority (1: the best option).

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Hui Li, Zhe Chen, et al, (2009) presented the PM generator system with specified gear ratio simulations are used to optimize for each design. In this concerning investigated five different rated power levels of 750 kW, and 1.5, 3.0, 5.0, and 10.0 MW respectively. From the articles, gear ratio "1" stands for the optimized results of direct drive PM generators systems [77]. Andrea Cavagnino, et al, (2002) compared both radial flux (RF) structures and axial flux (AF) structures permanent-magnet synchronous motors. The comparison is accompanied with different motor dimensions and the number of pole influence put into confirmation. The result concluded of evidence to use the AFMs instead of RFMs [132]. Robert Rossa, et al,(2010) study deals about field-circuit method for quick computation of load characteristics for stand-alone permanent magnet synchronous generators (PMSGs) is developed with different rotor structures. The load characteristic calculations and results are compared with the practical test results. Also, defined the field-circuit method and can be used for estimating the load characteristics of PMSGs with surface-mounted, inset or interior mounted permanent magnets and with inner or outer rotors [175]. Yu-Seop Park, et.al, (2013) compared two types of PM generator, namely radial flux PM (RFPMG) generator and axial flux PM (AFPMG) generator. For the generator performance comparison during the mechanical energy storage, the output power of both RFPMG and AFPMG are measured. Table 8 and Table 9 presented the results, could be concluded that the RFPMG showed a better performance when the electrical parameters of the machines which are in very similar condition and in relatively small power applications [233].

Table 8. Measured Generator Efficiency Comparison [233].

Wind Speed and Generator Speed	Efficiency (%)	
	Radial Flux PM Generator	Axial Flux PM Generator
2.7(m/s), 80(rpm)	73.2	70.2
3.2(m/s), 100(rpm)	86.1	84.2
3.9(m/s), 120(rpm)	90.5	88.3
5.0(m/s), 150(rpm)	94.1	92.5

Table 9. Electromagnetic loss according to generator speed [233].

S.No	Wind Speed and Generator Speed	Copper Loss(W)		Core Loss(W)		Rotor Loss(W)	
		R	A	R	A	R	A
1	2.7(m/s), 80(rpm)	15.33	21.7	2.29	2.30	0.123	0.165
2	3.2(m/s), 100(rpm)	8.12	8.74	2.28	2.30	0.119	0.159
3	3.9(m/s), 120(rpm)	5.14	5.43	2.27	2.29	0.113	0.145
4	5.0(m/s), 150(rpm)	3.44	4.50	2.26	2.28	0.109	0.132

R : Radial Flux PM Generator, A : Axial Flux PM Generator

10. Different Designing Perspective.

The design of PMSG has numerous challenges which are quite different than conventional machine procedure. The slot and pole combination poses additional challenges to reduce cogging and eddy currents losses on permanent magnets concerned. Furthermore characteristic of current, induced emf, field weakening, demagnetization and THD must be studied in detail.

Generally, when designing the PMSG, optimum design must be considered several factor mandates to increase profitability and reduce the material utilization in order to decrease the weight and cost[78].Furthermore the design should be consider high Reliability, Availability, low Maintainability and Serviceability (RAMS) for the wind class TCIa[25]. In general, tend to use gearless direct drive or semi geared machines provides high reliability and efficiency requirements for wind power generator. Also, with these requirements and compactness is characterized in terms of large dimensions and weight. Moreover, when designing PMSG, the voltage waveforms and mechanical forces are important in many applications [133]. Juan A. Tapia et al. (2013) presented to maximize the apparent airgap power transferred under tangential stress constraint by using analytical optimization algorithm. The optimization processes have been modeled relevant expressions for the main design variables, operational restrictions, and external dimensions are derived to build the mathematical formulation [78]. A.E. Fitzgerald et al. (1992) offered the basic principles of electric machinery and basic concept of electromechanical energy conversion, which provides an overview of various types of machine. These are various machine types as synchronous machines, induction machines, DC machines, variable-reluctance machines, and single/two- phase machines and transformer [112]. Boldea I. (2006), presented asynchronous generator, which are covers principles of electric generators, design of high and medium power synchronous generators: topologies and steady state, synchronous generators: modelling for and transients, design of synchronous generators, testing of synchronous generators and control of synchronous generators in power systems [147]. Boldea I. (2006), wrote a book for the variable speed generators. This book covers almost all types of generators system. The Wound Rotor Induction Generators (WRIGs) Steady State, Transients Control, design and Testing methods have been discussed. Furthermore, conferred about Self-Excited Induction Generators, Stator Converter Controlled Induction Generators (SCIGs), Permanent Magnet Synchronous Generator (PMSG) Systems and Transverse Flux and Flux Reversal Permanent Magnet Generator Systems. The particular discussions are the design of PMSG, design requirements of PMSG, basic design choices, factors affecting the design of PMSG. Types based on flux path modeling of PMSG. Furthermore it presented stator modelling, types of stator winding, winding factor, mmf waves, output power coefficient and basic stator geometry, design of stator winding and stator core, armature reaction and demagnetization calculation, selection of rotor topology, rotor design, main materials selection, lamination thickness selection, influence of the permanent magnet length on the generator magnetic excitation flux, influence of the rotoric slot opening on the generator and magnetic excitation flux. Then offered performance characteristics of PMSG, saturation characteristics and various testing methods are presented [148]. J.Pyrhönen, et al, (2008) presented a design of rotating electrical machines, which is offered a in a modern way. It comprises tremendous information as follows: principal laws and methods in electrical machine design, windings of electrical machines, design of magnetic circuits, flux leakage, resistances, main dimensions of a rotating machine, design process and properties of rotating electrical machines, insulation of electrical machines, heat transfer, and thermal equivalent circuit and losses [122]. Ewald F., et al, (2008) addressed about the Power Quality in Power system and Electrical Machines. Power quality problems in the synchronous machines can be the following types of operation:

1. unbalanced load,
2. torques during faults such as short-circuits (e.g., balanced three-phase short-circuit, line-to-line short-circuit), out-of-phase synchronization, unbalanced line voltages, reclosing,
3. winding forces during abnormal operation and faults,
4. excessive saturation of iron cores,
5. excessive voltage and current harmonics,
6. harmonic torques,
7. mechanical vibrations and hunting,
8. static and dynamic rotor eccentricities,
9. bearing currents and shaft fluxes,
10. insulation stress due to nonlinear sources (e.g., inverters) and loads (e.g., rectifiers),
11. dynamic instability when connected to weak systems, and
12. premature aging of insulation material caused by cyclic operating modes as experienced by machines, for example, in pumped-storage and wind-power plants [154].

David Ginsberg, et al, (1953) dealt with a method of performance prediction by using equations concepts, and units familiar to the designer for given magnetic and electrical data of permanent-magnet generators and conventional AC generators. The calculations of design encompass the computation of the bore, axial length, optimum magnet design, and associated mechanical dimensions, with consideration to the resulting performance, cost, weight, and general production [125]. Machine design usually focuses on the magnetic and electric circuits whereas several other losses are calculated only by simple empirical equations [75]. Jiwoong Park, et al, (2010) introduced the design and development of a 3 MW class offshore wind turbine (WinDS3000). A permanent magnet generator (PMG) with fully-rated converter has been introduced for its better efficiency in partial-load operation, thus it is grid-friendly and can adapt itself to either 50 Hz or 60 Hz grid connection [25]. Weizhong Fei (2011) discussed several aspects of design and novel design of axial and radial field of Permanent Magnet Synchronous Machines. The fractional slot and concentrated winding configurations is mainly ambitious by several advantages offered by this configuration such as high-torque density, outstanding efficiency, and easy and low-cost fabrication. Also, the investigation of three main topologies of fractional-slot and concentrated winding permanent magnet synchronous machines specifically suited for particular applications. Furthermore, the cogging torque and torque ripple reduction technique based on a novel axial pole pairing scheme in two different radial-flux permanent magnet synchronous machines with fractional-slot and concentrated winding configuration are investigated [27]. Wen-Chang Tsai presented the approach to the optimal design for 5MW direct-drive permanent magnet synchronous generator based on the Taguchi method. Taguchi orthogonal array is employed to determine the optimal combination of design parameters, including: steel lamination material, applied voltage, slot number, diameter of air-gap, magnet pole materials, magnet pole depth, stator outer/inner diameter, and length of stator core under the rated rotational speeds. The concept of signal-to-noise (S/N) ratio is applied to evaluate the performance of the permanent magnet synchronous generator. Effect of these control parameters on the output power and efficiency of the generator is analyzed [30]. Kyoung-Jin, et al, (2011) investigated an outer permanent magnet rotors performance of wind power generators. The studies comprise an electromagnetic and FEM on the basis of variations in the turbine characteristics over nominal wind speeds by employing various projected systematic methods. For calculating the electrical parameters such as back EMF constant, synchronous inductance, and phase resistance on the basis of the magnetic field distribution and electromagnetic analytical method. The d-q model coordinate transformation theorem has been used for analyzing the performances of generation. Furthermore, curve fitting and FEMs have been used for core losses analysis [44]. Yao Duan (2010) dissertation has proposed a technique for the design and optimization of Surface Mount Permanent Magnet (SMPM) machines, as influenced by the energy source, mechanical loads, thermal effects, and the up-to-date developments in materials and manufacturing capabilities. It has also proposed a method for the design and optimization of cage rotor induction machines. PSO and GA have been applied to optimize the design. It is also applied for the different integrated method in terms of Electromagnetic-Thermo-Mechanical used for the design of Surface Mount Permanent Magnet (SMPM) machines [45]. Igor Stamenkovic, et al, (2013) presented an ironless brushless permanent magnet machine of the design, analysis, and graphical optimization for generator applications. The offered approach comprises comprehensive geometric dimensioning; magnetic and electrical followed by detailed 3-D finite element (FE). Furthermore, the optimal circular and rectangular designs machine configuration is compared. In addition that studied ironless stator designs configurations and its performance and material effectiveness are compared [81]. V. N. Antipov, et al, (2009) presented the wind power generators with tangential magnetic flux and stator concentric windings in the range of rotation frequencies of 75–300 rpm. Some parameters of the developed generators are presented. Intended for the investigation of synchronous generators with permanent magnets, proceed based on the fact that the problem of magnetic field distribution should be studied separately by a FEM. When developing the model, taken into account to obtain synchronous machine parameters values are varied:

1. rated parameters of the project (power, voltage, frequency of rotation, power coefficient);
2. basic geometrical sizes (active length and boring diameter of the stator);
3. winding parameters of the machine (number of poles, phase number, number of slots and turns, and the number of parallel branches of stator winding);
4. geometrical sizes of the magnets and of the design gap.

The following parameters should be obtained as a result of mathematical simulation:

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1. efficiency and distribution of losses in a generator;
2. diagram of magnets and reserve coefficient over magnets;
3. static overloading in generators;
4. inductive scattering resistances along longitudinal and cross axes;
5. generator's parameters under loading and short circuit;
6. generator's performance (external and no load)[70].

Sorin Vlăsceanu Alecsandru Simion et al. (2012) have been analyzed and designed the PMSG by using FEM simulation software package for low speed three phase generators with external rotor topology. It is aimed to obtain sinusoidal induced voltages in the stator windings by the espoused path of magnetization and arrangement of permanent magnets in the rotor structure [180]. Parag R. Upadhyay et al. (2006) presented an axial-flux permanent magnet brushless DC (PMBLDC) motor having a stator sandwiched between two permanent magnet rotors. By using computer-aided design (CAD) procedure for designing variables such as airgap flux density, slot electric loading, winding factor, stacking factor, stator current density, slot space factor, magnet fraction, slot fraction, flux density in the stator back iron, etc., are assumed to optimize. The optimized relation of outer diameter to the inner diameter is used to derive the sizing equation [179].Vincenzo et al. (2012) deal with multiphysics approach for 10-MW doubly fed induction generator (DFIG). The analysis and an optimal design have considered for direct-drive operation of wind turbines with a reduced-size converter [87]. Zhenhong Guoet al. (2005) study comprises on PMSGs used in small wind power generation systems. The output voltage was studied by FEM under the no-load and load conditions. The effect of magnet dimensions and shapes is studied. A novel FEM study calculating outcomes revealed that the frequency of the PMSG's cogging torque is influenced by only on the number of stator slots and the number of poles. Whereas performance have been affected such factors airgap length, magnet dimension and the magnitude of the cogging torque [88].Tze-Fun Chan et al. (2010) presented the surface-inset permanent-magnet synchronous generator (PMSG) feeding an isolated load. The investigation involves for steady-state and transient performance by using a coupled-circuit, time-stepping, two-dimensional finite-element analysis. Both passive AC load and bridge rectifier DC load operating conditions are analyzed. The field and electric circuit are taken into consideration in terms of nonlinearities. Since the paper outcome of measurable analysis for voltage, current harmonics, and short-circuit performance [102]. Seyed Mohsen Hosseini et al. (2008) present the design, analysis, and prototyping of a comparatively lesser and economy axial-flux three-phase coreless permanent magnet generator. FEM approach is used to calculate inductances of the equivalent circuit. Furthermore the equivalent resistance of eddy-current loss and calculation of the end winding inductance used the classical method [110].Manuel Pinilla et al. (2012) provides a performance improvement for direct drive permanent magnet machine by means of soft magnetic composite inter poles. Also, analysis are several other factors like effective usage of material, suitable pole arc shapes, influence of magnet dimensions, labor costs and many more inferences[119].Johannes Abraham Stegmann et al. (2011) discussed design aspects of double rotor radial flux permanent-magnet wind generators in terms of electromagnetic and mechanical with non-overlap air-cored (ironless) stator windings are analyzed. The systematic model is confirmed by finite-element analysis. Subsequently the analysis shown, that electromagnetic design, determines the rotor yoke dimensions, leakage flux paths in the airgap, mass and cost of the generator [120].Yu-Seop Park et al. (2012) analyzed the performance of an axial flux PM generator using electromagnetic field for the wind turbine characteristics. The analytical approach can decrease the time required for analysis when compared with three-dimensional FEM. This can be useful for performance calculation in the preliminary design phase [127]. Ahmed Chebak, et al, (2010) developed with the optimal design of high-speed DC generation system using a slotless PM machine. The soft magnetic composite (SMC) stator yoke is used and stator winding connected with controlled rectifier [128]. E Spooner, et al, (1997) described the radial field, multi pole PMSG. The PMSG machine has been used as direct-coupled generators via grid-connected in large wind turbines with power ratings form below l00kW to more than 1 MW. However, the numbers of pole from 100 to 300 offers superb performance in terms of reactances and efficiency.

Rotor and stator section design structure have been presented the suitable for the range of power and pole number. The rotor sections use standard ferrite magnet wedges. The stator sections are E cores every carrying a single rectangular coil. A lumped-parameter magnetic model has been developed which permits rapid calculation of machine parameters [136]. E Spooner, et al, (1996) proposed that machine can be built to fit the confined space of a nacelle and its dimensions are to be commensurate with the turbine and can be used to create an electro-dynamic system for primary braking. The machine exhibits good efficiency and power factor over a wide range of operating power [138]. T. F. Chan et al. (2004) analyzed the three-phase AC generator with an inset, neodymium-iron-boron (NdFeB) permanent-magnet (PM) rotor performance. A rotor structure provides rise to an inverse saliency effect (i.e., the direct-axis synchronous reactance is less than the quadrature-axis synchronous reactance). These feature consequences in an enhancement in the voltage regulation characteristics when the generator supplies an isolated, unity-power-factor load. By solving the equations derived from the two-axis theory, it is set up that there exists, in general, two values of load current at which zero voltage regulation is attained[141]. T. F. Chan, et al, (2007) discussed about the direct-coupled an Axial Flux PMSG, which is suitable for a wind turbine system. Also, the horizontal-axis and vertical-axis wind turbine generator systems be present. An analysis with the aid of finite element software has been made the magnetic flux density distribution in the AFPMSG. The calculated results compared with practically proposed machine configuration for the output line voltage is being similar sinusoidal pattern. A prototype generator has confirmed the feasibility of the AFPMSG design [143]. Federico Caricchi, et al, (2010) present Axial-Flux Permanent-Magnet Generator for Induction Heating Gensets [144]. D.C.Hanselman (1997) & Hendershot J.R, et al, (1994) illustrated a straightforward approach to the practical design of permanent-magnet brushless machines supported by a number of analytical results. The fundamental difference between the square wave and sine wave motors details is described in terms of self-inductance, generated EMF, Torque, airgap flux density, et cetera. The stage by stage method involved in the computer-aided design of the machine is also explained, which contains the shape, torque, magnet poles and phases, poles, slots, teeth, yokes, magnetic circuit concepts, basic relationships, magnetic materials, flux linkage and inductance, influence of stator slots, tooth flux, back EMF, need for the field analysis based design FEM, energy and co-energy, series and parallel connections, cogging torque and loss modeling are presented [126] & [149]. Once the machine is assumed to have infinitely deep rectangular slots and the core of the machine operated under unsaturated condition these assumptions may not be suitable in the present day design of electrical machines with complex geometries and materials being non-linearity.

The performance of the machine must be predicted accurately solving nonlinear equations which are expressed in terms of Magnetic Vector Potential. The irregular configuration of the machine geometry makes the application of analytical methods of solution difficult. Hence, the suitable electromagnetic field computation and modelling is necessary.

11. Electromagnetic Field Computation and Modelling

Main objectives of Electromagnetic Field Computation and Modelling are to meet the design specifications with the help of field theory fundamentals. Silvester et al. (1983) [155], S.J Salon (1995) [156], Nathan Ida (1992) [157], Nicola Biyanchi (2005) [158] and Kay Hameyer et al. (1999) [159] all five books are encompasses about the Electromagnetic Field Computation and Modelling. The contents are comprises such as review of basic field theory, electric and magnetic fields, Maxwell's equations, Laplace, Poisson and Helmoltz equations, principle of energy conversion, force/torque calculation, Electro thermal formulation, Limitations of the conventional design procedure, need for the field analysis based design, problem definition, solution by analytical methods, direct integration method, variable separable method, method of images, solution by numerical methods, Finite Difference Method(FDM)and FEM, Differential/ integral functions, Variational method, Energy minimization, Discretization, Shape functions, Stiffness matrix, 1D and 2D planar and axial symmetry problem and Computation of electric and magnetic field intensities, Capacitance and

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Inductance, Force, Torque, Energy for basic configurations of electrical machines. Figure 3 is shown different methods of electromagnetic analysis. Each method has with its own strengths and weaknesses. Finite elements have proven to be very robust for general electromagnetic analysis [243].

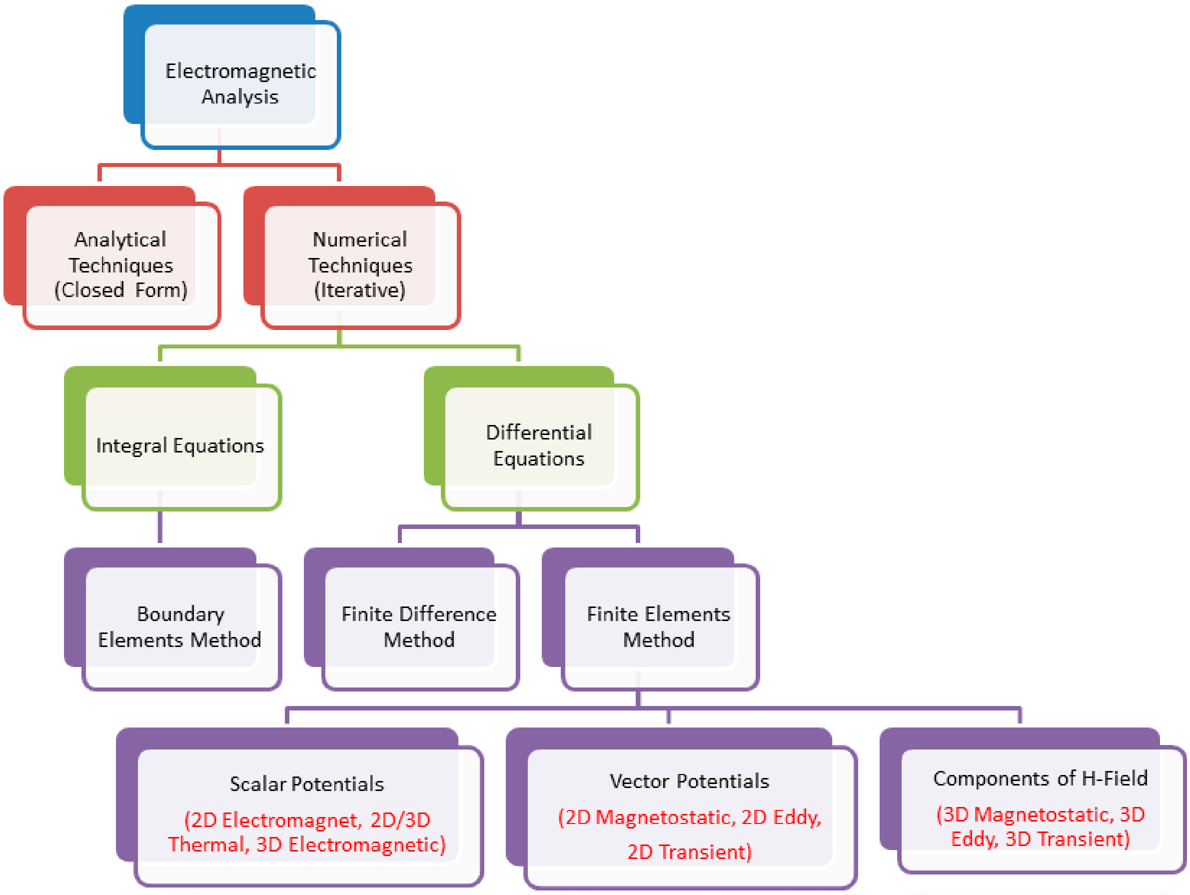

Figure 3. Different methods of electromagnetic analysis [243].

12. Finite Element Method

Finite Element Method **(**FEM) is piecewise approximation, where the solution of a complicated problem is obtained by dividing the region of interest into *small regions* (finite elements) and approximating the solution over each sub region by a *simple function* [246]. FEM is an important tool for the design highly efficient electrical machines using the computer simulation.

FEM is a versatile numerical concept. This deals litheness for forming difficult geometry, which yields steady and accurate solutions. Natural boundary conditions are implicit in the functional formulation. Also, this can handle nonlinearity and eddy currents well [156] [244] [245]. The FEMs is likely to have a more precise electro-magnetic representation of the machine. However, they have two main problems are in the computation time and large number of parameters of the electrical machine. At the same time, FEM is quite useful to accomplish acumen during the design phase of the electrical machine [48].

Shiyou Yang, et al, (2000) formulated the mathematical and computer procedures. Usually, Wavelet Galerkin method inappropriate for resolving general electromagnetic complications is a lack of exact representations of the assembly coefficients. The typical existing formulae and techniques is that the arbitrary point values of the connection coefficients, rather than the dyadic point values, can be determined. A numerical example is also given to demonstrate the feasibility of using the wavelet-Galerkin method to solve engineering field problems [169]. Janne Väänänen (1996) presents a Newton-Raphson iteration of the circuit equations. The new method is couple

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two-dimensional finite element models with circuit equations. The method is based on handling of the finite element model as a circuit theoretical multiport element. This multiport element is treated in the same way as ordinary nonlinear circuit elements within the Newton-Raphson iteration of the circuit equations. The electrical machine is modelled by the two-dimensional FEM[177].

12.1. Finite Element Analysis for PMSG related literature

Ajay Kumar, et al, (2009) discussed the FEM-software for magnetic analysis and Simulink-software for non-linear parameter identification for dynamics of a permanent magnet (PM) generator. The study encompasses mechanical dynamics and consequent starting torque curve by using COMSOL Multiphysics[17]. Huguette Tiegna et al., (2013) reviewed the state of the art of analytical modelling of PM electrical machines based on the formal solution of Maxwell's equations. To overcome some limitations with inherent methods to simplify assumptions were discussed. Recent developments in the field of analytical modelling have been described. These are classical surface mounted PM machine, hybrid excitation machine, PM flux switching machine, (check punctuation) and rotating radial flux magnetic gear[23]. Vaagn, et al, (1999) developed and implemented a mathematical model of a synchronous generator by using CAD package. The model comprises constraints based on geometric, magnetic, electrical, and economic factors. The random search method is working well in this environment due to the difficult and extremely nonlinear nature of the objective function as well as the convex specification set geometry [28]. Danhong Zhong, et al, (2010) present numerical efficient finite element solvers for synchronous machine, including a static finite element/analytical solver with accuracy of the Finite Element Analysis (FEA) yet fast enough to use in large scale dynamic simulation, and a computational efficient steady-state finite element solvers for detailed design and analysis of synchronous machines [69]. Henry M. Hämäläinen, et al, (2012) scrutinize the stator end region of the housing for 3.1 MW permanent-magnet wind generators. The significance of the additional losses has been studied. Furthermore, investigations have been done using a 3-D FEM in stator stack clamping ring and finger plate losses. Also, an analysis of the 2-D FEM stator supporting housing losses is performed. Finally, outcomes that failure to study stator end parts and stator supporting structures at the design phase can result in unsolicited additional losses and affect machine efficiency [75]. T. F. Chan, et al, (2009) presented an axial flux permanent-magnet synchronous generator without armature core by analytical method to determine the no-load and armature reaction magnetic fields. In the rectangular coordinate system Laplace's equation is solved to give the scalar magnetic potentials, using a Fourier series method. For the computation of the armature reaction field, a multi-current-sheet model is employed in order to account for the distributed nature of armature conductors in the axial direction [92]. T.F.Chan, et al,.. (2010) presented the single-sided, outer-rotor axial-flux permanent magnet synchronous generator of a magnetic field distribution and consequences based on a 3-D FEA. The benefit of the 3-D FEA methodology is that various components of flux density have been studied. Similarly, difficult core and winding geometries also deliberate. The key involvement of study is to offer on the magnetic field of the given type of machine configuration, which cannot be attained by using 2-D methods. Investigational results acquired on a small prototype AFPMSG confirmed the accuracy of the 3-D FEA computations [104].Guannan Duan, et al, (2010) presented a permanent magnet wind generator a direct drive design and electromagnetic field FEA. The simulation model is set up to study the electromagnetic field by FEM. The distribution of the magnetic field is obtained based on Maxwell electromagnetic theory. The generator characteristics are calculated in the case of no load and load transient operation. The optimization and design of the generators accomplished with supports of post processing. The proficient analysis between parallel magnetization of plane pole and radial magnetization of curved surface pole for the phase voltage rms, leakage coefficient and THD is done [105].HuiGuo et al. (2011) presented a simulation for the rating of 3.6 MW PMSG with help finite element approach such as 2D and 3D magnetic field for WECS application. From the simulation of 2D results like a no-load voltage, load voltage and current are compared with that of 3D simulation. In addition, the skew slot effect, leakage flux coefficient, and end leakage reactance are analyzed. However, the electromagnetic parameters and performance analysis are imprecise. For example, where in 2D FEA cannot consider skew slot and end effect in magnetic field simulation. Thus, it is essential to give evidence to the precision and consistency of the 2D magnetic field FEA [107]. Yoshiaki Kano, et al, (2005) presented non-linear magnetic analysis and design of surface-mounted permanent-magnet synchronous motor with aid design tool of FEA. An analysis is composed based on the equivalent magnetic circuit for the machine. An analysis is capable of calculating the flux distribution and the torque characteristics in the incidence of magnetic saturation [111]. Peter Virtiˇc, et al, (2008) modelled the systematic magnetic field and back EMF calculation in an AFPMSG without stator core. Asystematic solution of Maxwell's equations is used to calculate magnetic flux density by PMs in the midpoint of mechanical air-gap region. It offers the comparison between analytical and numerical (FEM) solutions of back EMF using Faraday's law [113]. Themistoklis Kefalas, et al, (2005) study the performance of PMSG and the rotor skew effects in PMSG. The focal effects and the reduction of the electromotive force induced, stator current harmonics and torque ripple have been discussed. The exploration is established various 2D and 3D finite element procedures [160]. Frantisek Melkes Brno (2005) presented a mathematical dealing of a planar magnetic field excited by permanent magnets. A bilateral symmetric circumstance in the analysis of magnetic fields with permanent magnets is familiarizing with to verify the distinctive existence of both the weak and the approximate solutions and also a certain error evaluation [163]. Erich Schmidt, (2004) discussed the state-of-the-art FEA of Electrical Machines and Transformers [170]. Jianyi Chen, et al, (2000) present the design and finite-element (FE) exploration of a PMSG using neodymium-iron-boron magnets for directly coupled wind turbines [172]. Marian Greconici, et al, (2011) presented an electrical machine used in wind energy conversion systems. For the analysis, design and optimization have been using 2D-FEM programme Opera 13 of Vector Fields. These examples refer to two types of synchronous generators with permanent magnets [174]. S.L.Ho, et al, (2005) presented an alteration procedure for electromagnetic field computations using an incorporation of finite element and mesh less methods [167]. S.L.Ho, et al, (2004) offered to improve the problems resolved in the generation of meshes for the FEM for solving thin skin-depth problems involving three-dimensional (3-D) eddy-currents, predominantly in cases the eddy-current region is only a fraction of the all-inclusive domain. In this paper, a new technique is proposed based on the combination of finite element and mesh less methods [168]. Konstantinos V. Tatis, et al, (2005) presented the 3-D finite elements procedure. Optimum dimensions of copper parts and solid iron slots have been investigated. And both copper and solid iron rotors geometry optimization of solid rotor eddy current constraint by using sensitivity analysis. This technique has been applied to optimize the rotor geometry of a solid rotor eddy current control used as over-speed protection in the PMSG for wind turbine [182].

12.2. Computer-Aided Design

Computer-Aided Design (CAD) is an expertise to model the appropriate dimension with the help of computer for the creation, modification, analysis, and optimization of a design [247]. To develop the performance and power density of the machine; the design must involve the reduction of materials used in the product design, thereby cutting down the wastage of materials. Vaagn L., et al, (1999) offereda perfect assimilates differential equations specific of an electric machine, tabled data and empirical coefficients, and geometric, electromagnetic, and economic parameters of machine design. The difficulty of the prototypical requires that the solution procedure to adopt a naive random search technique and an expert system is integrated within the package. Furthermore, synchronous generator with comb rotor mathematical model is implemented in a computer-aided design (CAD) package [184]. Z. Zhang, et al, (2011) presented the direct-driven PMSG for wind turbines an synopsis of the electromagnetic and thermal modelling. The outstanding state-of-the-art software developments are studied. It appears that some successes have been made in commercial codes in order to tackle massive, powerfully-coupled difficulties. However, combined design hassles require extremely united simulations and tools to handle large-scale, multi-physic, multi-domain, accuracy-demanding problems to be encountered. The proven

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software is usually the first choice for fundamental investigation of the machine. Though new brand software is emerging, it is to be noted that previous softwares also undergo periodic up gradation. The simulation software can be categorized into open source/free software. Moreover, different level commercialized softwares are tabulated in Table 10 [185].

Table 10. Comparison of simulation softwares [185].

Type	Advantages	Disadvantages	Examples
Open source/ free software	Small programme, use small RAM; Fast and cheap; Flexible to be driven by external environment	Limited to a small group of users and specified type of motor; Maylimited to single operating system, or Linux, or Windows; Limited capability;	Emant, FAT, FEMM, GetDP, iMOOSE, MagSolve, pdnmesh, Poisson Superfish, RillFEM, FEMG, IES
Commercialized software	Small programme, cheap	Relatively slow version-updating, insufficient tutorial; Less functionality	EMSolution, FEHT, FlexPDE, QuickField, ElectorMagneticWorks, MagneForce, MEGA, Permas, PC-FEA
Highly commercialized software	Fast version-updating, rich in supporting document and service; Versatile functionality	Require advanced support platform; Expensive	Flux, ANSYS, MagNet, Opera, COMSOL, JMAG, Fluent, SPEED, MotorCAD

Tadashi Yamaguchi (2005) developed a one of the most well-known CAD data which is created from DXF (drawing interchange file). This is making such common platforms more user-friendly [186]. G. Lacombe, et al, (2007) illustrated general finite-element simulation software. They also insisted on transforming general simulation software into a dedicated tool, easily maintainable, reusable, and extensible for innovation and development process [187].

13. Impact of Geometry Design

Geometry plays a vital role in every design. To accomplish the preferred electromagnetic performance and material usefulness, it is essential to perceive magnetic flux and comprehend how modifications in geometrical and material properties of magnetic circuits influence the back EMF co-efficient. These facts can be used to compare electric machines of analogous performance but minimizing active material. Also, a different combination and types of active material can be added for additional improvements in either performance or effectiveness. For example, loss of performance resulting from the use of less copper may be compensated by increasing the volume of the PM material [81]. The operational characteristic of air-gap flux density waveform is influenced by pole arc coefficient. When the back-EMF is maintained as a constant, a consequence flux leakage is increased between two poles due to higher coefficient. Also, when the stator teeth are small, they get saturated. It is to be noted that when pole arc coefficient is selected properly, it can decrease the torque ripple and the THD in back-EMF to a greater extent [82]. Peter Sergeant, et al, (2014) investigated the following attributes namely thickness of the magnet, material type involved in the machine and different parts of the machine geometry to arrive at a consensus with the aid of analytical models along with FEM. Some of the factors that were considered for the computation are iron loss, copper loss, magnet loss, and pulse width-modulation loss. Moreover, the risks due to demagnetization and torque ripple are observed as important parameters during the machine design. In addition, various combinations of stator slots and poles are analyzed and experimentally verified [31]. O. Danielsson, et al, (2005) took into consideration various permanent magnet sizes, shapes and stator steel geometries for the investigation. It was concluded that different magnet shapes impacted the machine performance. It was observed that the stator steel geometry is a significant contributor to the overall performance of the machine and small changes even on a millimeter scale of the same has affected the flux path and in turn the performance [53]. C. Boccaletti (2011) briefly described on Axial flux disc machines (AFDMs) to assess the total harmonic distortion (THD) of output voltage based on the permanent magnets shape and size [63]. Ghita C., et al, discussed the magnetic fields in the PMSG based on the impact of the length of permanent

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magnet length and teeth of slots upon the generator's magnetic excitation flux [64]. Ki-Chan Kim, et al (2005) presented a Spoke-Type Permanent Magnet Generator with Large Overhang with the dynamic analysis. For obtaining the optimized results of the overhang effect which is dependent on its length and rotor core material, with the aid of 2-D and 3-D FEM analysis, 2-D dynamic FEM was considered for the same [94]. Ilya Petrov, et al, (2015) present in the Tooth-Coil Winding Permanent Magnet Synchronous Machines (TCW PMSMs), 6th torque ripple harmonic is partially produced by non-symmetrical peak flux density distributions in the stator teeth, due to the interaction of the permanent magnet flux with armature flux. The 6th harmonic can be eliminated by teeth widths adjustment, whereas conventional skewing technique is not appropriate for the reduction of this harmonic. However, skewing is still favorable for the elimination of cogging torque in TCW PMSMs. The main disadvantage of the method with unequal stator teeth is that it gives the desirable results for only one working point, whereas for other loads the 6th torque ripples harmonic increases. The described methods can be used by designers, who should be aware of these local saturations in TCW PMSMs, especially when low torque ripple is one of the design targets [97]. Hyeoksoo Hong, et al, (2011) investigated the surface-mounted permanent magnet brushless synchronous machine's permanent magnets' shape with the aid of level set based topology optimization method. In order to optimize the flux linkage with the help of level set method based optimized topology, for electric machine design, this paper advises two methods namely the minimum rotor angle method and the mono-tooth method. By applying the aforesaid two methods, waveforms pertaining to back–EMF and flux linkage can successfully be matched with respect to the sine wave form which includes the torque ripple reduction as well. To obtain a fast and a reasonable solution, the optimized results derived from mono-tooth method is suggested. However, there comes a restriction where this method may be applied only to the objective of some specific design and may not be valid where design objectives are minimum cogging torque, maximize flux linkage of rotary type machines. In order to reduce the computational cost comparatively with the other conventional analysis method, minimum rotor angle analysis method is suggested despite the fact that latter involves more calculation time over mono-tooth method. However, it is to be noted that the aforesaid methods may be applied to address the multi objective design issues of electric rotor machines [106]. Vesa Ruuskanen, et al, (2011) with the aid of three-dimensional FEA, presented the impact lamination stack ends and radial that cooling channels could create the effective stator stack length, no-load voltage, and synchronous instances of a permanent-magnet synchronous machine. It is to be observed that the stack ends and the radial cooling channels are prone to decrease the equivalent electrical length of the machine, concluding that two-dimensional (2-D) approach overestimates the no-load voltage. By maintaining the rotor stack and permanent magnets longer than the relevant stator stack, the after-effects of stack ends and radial cooling channels' compensation is done on the machine length. It is proven in the case pertaining to no radial cooling channels, synchronous inductances are generally estimated beyond with the 2-D approach. However, in cases where stator structures have many or several radial cooling channels, inductances are usually estimated below using the 2-D approach [145]. Min Dai, et al, (2004) investigated torque ripple with the help of FEM. It is to be noted that various factors in motor design and construction can influence the shape of torque waveform and thereby the frequency content of the same. The key factors that determine the torque wave shape are the accuracy encountered in the skewing, the stator core's magnetic saturation, and the basic induced electromotive force (EMF) wave shape.

Figure 4 shows Bifurcated Tooth Stator Structure. The variance in reluctance could be reduced by Bifurcation, as displayed by the magnet which subsequently reduces the cogging and doubles the frequency of the cogging. In order to yield the maximum reduction in cogging torque, the bifurcated tooth structure has been optimized. From the perspective of rotor magnets, the dummy slot created due to bifurcation behaves as a true slot. In order to avoid the line-to-line induced voltage waveform as more a sinusoidal one than a trapezoidal one, a half stator slot skew is preferred to be used to lessen the cogging torque. For the convenience of manufacturing, the stator slots are maintained as straight slots and the skewing effect is applied by means of skewing the rotor magnets or the pattern of rotor magnetization [161].

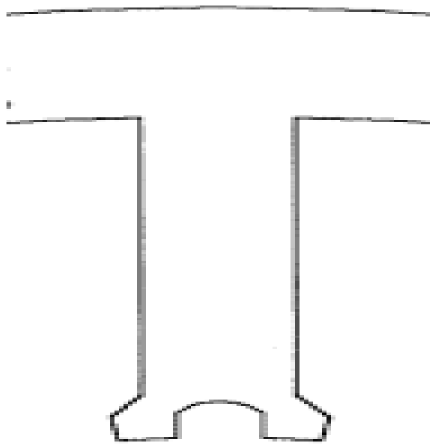

Figure 4. Bifurcated Tooth Stator Structure.

14. Influences of Winding Design

The winding design and slot number design are very important because characteristics of the back-EMF and cogging torque are varied greatly according to the number of slots [82].The essential feature of an electrical machine is the armature winding in which the back EMF is induced. The layout of an armature winding can significantly influence the back EMF shape and, hence, affect the performances of the electrical machine. Basically, the harmonic components in back EMFs can effectively be reduced by selecting appropriate winding types and coil pitches [41]. By following the below-listed regulars by the number of q, slot per pole per phase of the machine, the electrical machine's winding type could be determined: Integral (q> 1) integral-slot distributed winding, (q =1) integral-slot concentrated winding, Fractional (q> 1) fractional-slot distributed winding, and Fractional (q < 1) fractional-slot concentrated winding. As a general observation, on comparison with the concentrated windings, the distributed windings offer better usability of the stator and the rotor structure thereby decreasing the harmonics as well [41]. Anyuan Chen, et al, with the help of different winding arrangement, analyzed the back EMFs of four surface-mounted permanent magnet machines

1. 4-pole machine with integral-slot distributed winding,
2. 8-pole machine with fractional-slot distributed winding,
3. 12-pole machine with integral-slot concentrated winding,
4. 4-pole machine with fractional-slot concentrated winding.

The harmonic analysis of the back EMFs with different windings is investigated by FEA in the software of COMSOL. Finally deduced as follows

1. The integral-slot distributed winding is better than the integral-slot concentrated winding.
2. The fractional-slot distributed winding is better than the fractional-slot concentrated winding.
3. The fractional-slot distributed winding of the 8-pole machine does not effectively show the slot harmonic reduction compared with the integral-slot distributed winding of the 4-pole machine due to the relatively small slot harmonic in the machines.
4. The fractional-slot concentrated winding of the 24-pole machine is much better than the integral-slot concentrated winding of the 12-pole machine. For explaining this here, the flux leakage between the magnets in the 24-pole machine should be also taken into account.
5. When the coil pitches decrease from 180° to 120° electrical degrees, the harmonic contents in the phase EMFs of all the machines also decrease, afterwards they increase again.

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6. The prototype machines provide good opportunities for students to study the different winding concepts and the induced EMFs [41].

Kazumi Kurihara, et al, (2013) with the help of damper bars, presented an analysis that addressed the small but a high in efficacy interior permanent-magnet (IPM) synchronous generators. The damper winding that was designed was expected to ensure stable operation in the absence of a frequency controller thereby effectively reducing the increased harmonic parameters of the air-gap flux density. The investigation involved the impact the damper bars created on the stability during load exchange, output to the maximum, and the efficacy which was later proven true.

It was obvious from the results of the simulation that flux density of the PMs had little higher harmonics which was due to the damper bars that reduced the space harmonics with the means of slot ripples efficiently [66].

Nicola Bianchi, et al, (2010) performed an investigation on the losses encountered in the rotor in high-power fractional-slot PM machine and was observed that the rotor losses were predominantly because of the low order MMF harmonics. It is observed that in specific the MMF sub-harmonics possess a dominant effect. Despite deploying a conductive sheet, the rotor losses encountered by low-order harmonics did not seem to reduce. It is to be noted that single-layer winding provides MMF sub-harmonics of greater amplitude, PM machines which has similar windings will exhibit higher rotor losses. In order to predict the rotor losses which are induced by MMF harmonics, the two approaches – analytical and finite element approaches - are used. With the aid of a straight-lined model of PM machine, the rotor losses encountered due to various combinations of pole numbers and slots are compared which further proves as an efficient tool to design fractional-slot PM machines with decreased rotor loss. PM machines which have lower rotor losses are observed as per the slot/pole combinations Q/2p≈2.5 and Q/2p=1.5when double-layer winding is chosen, and Q/2p=1.5and Q/2p≈1when single-layer winding is chosen [146]. A. Di Gerlando, et al, (2007) presented the attributes pertaining to design and operation of axial flux permanent magnet synchronous machines, using armature windings alongwith concentrated coils wound around the stator teeth. The e.m.f. control depends on the difference between the windings flux linkage which is yielded by the modified the stator or rotor configuration. Alongside the deep field weakening, the aforesaid machine displays a satisfactory operation, with respect to the voltage waveform [71]. Yu. G. Bukholts, et al, (2011) determine the inductances of Permanent Magnet Machine with Single Slot Windings. The analysis of the results presented the lowest error in calculations of synchronous inductances for electric machines with single slot windings (not exceeding 9%). The analytical computation has greater error (up to 31%); however, its application is permissible for a preliminary evaluation. Consequently, the proposedmethods can be used in the design and to check calculations of similar electric machines [74]. M. Liwschitz-Garik, et al, (1956) (1958) presented a derivation of the formula to explain the harmonics of the salient-pole synchronous machine and the impact it could cause on the MMF harmonics which is produced by the armature and damper Winding. Emeka S. Obe, et Al, (2011), presented a mix of phase-variable model and winding function theory taking into consideration the effects of all mmf and permeance harmonics. In order to facilitate the comparison and observe the impact of harmonics on the performance indices, the d–q based results are also presented here. The impact of slots and winding harmonics displays that there is a notable distortion introduced in the inductances and torque [52].

Table 11 presented a permeance factor of the end windings of a synchronous machine.

Table 11. Permeance factors of the end windings of a synchronous machine [122].

Cross-section of end-winding	Non salient-pole machine		Salient-pole machine	
	λ_{lew}	λ_{w}	λ_{lew}	λ_{w}
	0.342	0.413	0.297	0.232

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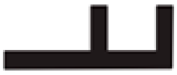
	0.380	0.130	0.324	0.215
	0.371	0.166	0.324	0.243
	0.493	0.074	0.440	0.170
	0.571	0.073	0.477	0.187
	0.605	0.028	0.518	0.138

(λ_w)-winding permeance, & (λ_{lew})-winding leakage permeance

Hae-Joong Kim, et al, (2014) described a three-phase fractional slot concentrated winding synchronous machines (FCSM). The analysis is carried out for the characteristic of winding machine with optimum turn ratio. If multiple-layer winding with optimum turn ratio is applied to three-phase FCSM, this can improve these problems. In this paper, the turn ratio in concentrated multiple-layer winding machine is proposed to be applied. Considering the turn ratio, a general formula is derived to calculate the winding factor. Using the induced formula, the winding factor changes according to the changes in the turn ratio are calculated, and the turn ratio to remove the harmonic components that the MMF has, is determined [139]. Tayfun Gundogdu, et al, (2013) presented an implementation of the fractional slot concentrated winding (FSCW) technique into large salient-pole synchronous generators (SPSGs) and the development of the generators by using additional permanent magnets (PMs). Compared to conventional synchronous generators, the FSCW technique makes it possible to achieve lighter, cheaper and higher-efficiency generators with a simpler structure. To overcome saturation of the rotor pole-body problem well known in the SPSGs, the designed FSCW SPSG has been developed by inserting PMs between the rotor-pole shoes. The insertion of PMs between rotor poles increases the generator power output while reducing magnetic saturation in the rotor pole body. Furthermore, simple theoretical expressions and detailed comparisons of performance characteristics of the designed machines are presented [237].

15. Materials in the PMSG design

The magnitude of materials utilization in the PMSG design plays a vital role. Also, the characteristics and cost of materials are significant while in the PMSG design.

15.1. Permanent-Magnet Materials

It is to be observed that the electrical machines will not limit the applications of permanent-magnet materials. Also, Permanent-Magnet (PM) materials are of different types and possess various properties and applications. When it comes to relatively lower cost, Ferrite is considered. AlNiCo (Aluminum– Nickel–Cobalt) is another type of Permanent Magnet Material. In particular, permanent magnets are typically classified pertaining to their energy product which is B H_{max}. When low energy product is considered Ferrites and AlNiCo are available whereas when it comes to higher energy product, SmCo (Samarium–Cobalt) magnets takes a lead than Ferrites and AlNiCo. From the perspective of temperature stability point of view, it is observed that SmCo produces larger magnetic fields. However, in terms of cost, SmCo is more costly when compared to Ferrites and AlNiCo. In the scenario of highest energy products, NdFeB (Neodymium–Iron–Boron) compounds have more advantages when compared over all compounds. But NdFeB's temperature stability is lower than SmCo and, in terms of cost, it is more expensive as well. The discovery of NdFeB happened in 1983 [37]. In the earlier days, generators used the Alnico magnets. With the help of high-energy rare-earth magnets such as neodymium–iron–boron (NdBFe), many designs of

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PM rotors have been presented in the recent years. However, pertaining to the cost factor, rare-earth materials like neodymium and dysprosium are expensive and dependent on China for 90% or more of the other countries world share [66]. Do Hyun Kang, et al, (2003) analyzed the principal electromagnetic aspects which have been taken into consideration in the expansion of large PM's synchronous machines rotor's magnetization. Hence, an electromagnetic design calculation pertaining to an iron core coil (magnetizing inductor) which is dedicated to the magnetization of a 1.7 MVA, 20-r/Min, synchronous wind turbine is presented. In order to expel an incorrect, strong magnetization of the neighbouring poles, an optimal arrangement for magnetizing system needs to be arranged between a rotor and the inductor [85].

15.2. Electrical Steel Grade

Electrical Steel plays a pivotal role in generator and has different materials types which exhibits various characteristics and is emerging with the technological development. Damian Kowal, et al, (2011) analyzed an analytical model for PMSG, which has been validated by FEM and is proven for its efficacy over the analysis of the impact of the electrical steel grade used with respect to the annual efficacy. In terms of optimized generator's annual efficiency and optimal pole pair number (frequency), the material M235-35A is greater when compared with M800-65A. For both of the afore-said materials, the variation between annual iron and copper energy loss is inversely proportional to the generator's mass. Whereas for the generator's fixed mass, as the number of pole pairs increases, the diameter increases with the decrease in axial length of the machine. A notable difference in the efficiency was observed between the two systems - Direct Drive PMSG Wind Turbine and Single Stage Planetary Behaviour PMSG Wind Turbine, which was due to the behaviour losses in a drive train of the latter. In spite of a lower efficiency, the latter could serve as an alternative model to the direct drive solution due to the considerable decrease in the generator's size [129].

16. Airgab field Distribution & MMF

Almost most of the literature concerned almost discussed air-gap field distribution, MMF, and EMF. C. Boccaletti, et al, (2011) explained and derived the calculation of the following; flux density (B), the flux of an infinitesimal coil, linked flux and EMF, the equivalent inductance, the current, the equivalent resistance, and the maximum torque in detailed manner [63]. The allowable flux densities of the magnetic circuit for various standard electrical machines are shown in Table 12.

Table 12. Permitted flux densities of the magnetic circuit for various standard electrical machines [122].

	Flux density B/T			
	Asynchronous machines	Salient-pole synchronous machines	Non salient-pole synchronous machines	DC machines
Airgap	0.7–0.90 ($\hat{B}_{\delta 1}$)	0.85–1.05 ($\hat{B}_{\delta 1}$)	0.8–1.05 ($\hat{B}_{\delta 1}$)	0.6–1.1 (Bmax)
Stator yoke	1.4–1.7 (2)	1.0–1.5	1.1–1.5	1.1–1.5
Tooth (apparent maximum value)	1.4–2.1 (stator) 1.5–2.2 (rotor)	1.6–2.0	1.5–2.0	1.6–2.0 (compensating winding) 1.8–2.2 (armature winding)
Rotor yoke	1–1.6 (1.9)	1.0–1.5	1.3–1.6	1.0–1.5
Pole core		1.3–1.8	1.1–1.7	1.2–1.7
Commutating poles				1.3

16.1. Different Magnetization Patterns

Using different patterns the Permanent Magnet Machines could be magnetized. Akbar Rahideh, et al, (2013) presented the results for both internal and external rotor structures with the aid of six magnetization patterns as mentioned below:

i. Radial sine amplitude

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ii. Ideal Halbach
iii. Radial magnetization
iv. Parallel magnetization
v. 9-segment Halbach
vi. 2-segment Halbach

The aforesaid magnetization patterns have been compared by FEM and confirmed for the accuracy of the analytical expressions along with the efficiency of the analytical approach [95].

17. Significance of Cogging Torque design

Cogging torque, alongside the torque ripple which is a consequence of winding energization, has invariably become an important design consideration with respect to permanent-magnet (PM) machines, particularly on the surface-mounted PM (SPM) machines. In different dimensions, various literatures are presented in order to reduce the cogging torque such as combination of rotor pole, stator tooth number, magnet shaping, magnet shifting, magnet segmentation, pole arc optimization, tooth paring, and skewing [93]. Generally, the fractional-slot winding can reduce the cogging toque greatly [82]. Permanent magnet synchronous machines are vulnerable to significant amounts of torque ripple if they are not carefully designed. Though minimizing cogging torque can help to reduce the torque ripple, they cannot definitely give rise to a low level torque ripple [183]. Daohan Wang, et al, (2013) presented a simple solution for minimizing the cogging torque and suppressing the operation torque ripple simultaneously. The principle of that simple solution is illustrated, where a magnet with different width is used so that the flux density distribution in the machine is substantially changed. The magnet widths for minimizing cogging torque are obtained by using an analytical model. The influence of magnet widths on operation torque ripple and average operation torque is examined by using FEA which gives more preciseness to calculations. It is found that the cogging torque and the operation torque ripple can be greatly reduced, but with slight average output torque reduction. At last, the Unbalance Magnetic Pull (UMP) is examined, indicating that the presented method can substantially increase the UMP due to the asymmetric distribution of magnets [183]. Mohammad S. Widyan, et al, (2012) presented a comprehensive study of the load and no-load attributes at different rotational speeds alongside different loading conditions. In order to achieve air-gap flux density distribution very close to sinusoidal, the faces of the rotor soft magnetic pieces are curved. Comparison is done by maintaining different rotational speeds and loading conditions in order to study the steady-state characteristics. The cogging torque impacts the slotted PM electrical machines heavily. The cogging torque of the generator is forecast and comparison is done with the rated value of the machine. In order to improve the efficiency, power-to-weight ratio, operational performance and cost of active material, the windings, located at flat slots, a short end is utilized. It is possible to have a slotless configuration in radial- and axial-flux machines. Slotless topology offers a main advantage which is the absence of cogging torque because of which, the vibration and noise are minimized to a considerable extent. With the principle of virtual work which is handled better by FEM, the machine's cogging torque has been predicted. A typical Permanent Magnets' flux-MMF (Magnet Motive Force) is the difference between the instantaneous effective flux and the instantaneous MMF in a particular phase. The aforesaid parameters are critical in terms of the rotor position functioning where the flux-MMF figure is a closed trajectory upon electrical cycle. Instantaneous torque and average torque at a given current could be derived by manipulation from the flux-MMF diagram, with the help of the principle of virtual work which is $T_{Cogging} = \frac{\partial W_{PM}(\theta, i)}{\partial \theta} |i = constant|$, Where WPM (θ, i) is the instantaneous co-energy of the permanent magnet θ is the rotor position and i is the stator electrical current. The entire area represented and encircled in a flux-MMF diagram is determined by its shape in particular whereas the area embodies the average torque produced in one electrical cycle for one phase [37]. Ting LIU, et al, (2011) proposed the mathematical model of the cogging torque with the aid of Fourier analysis. In order to reduce the cogging torque, Permanent Magnet shifting method is used. By utilizing this method numerous sub-harmonics of cogging torque may be decreased [39].

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Johannes H. J. Potgieter, et al, (2012) focused the economical methods in order to mitigate the cogging torque in permanent magnet (PM) wind generators. However, there are some limitations in terms of machine design aspects like ease of Industrial manufacturing, mass, load torque ripple, and voltage quality, which should be complied with. In addition, a cheaper version of single layer PM wind generator with an irregular, parallel slotted stator is considered for analysis.

Analysis is conducted on the average and cogging torque's sensitivity over the machine dimension along with the impact created on the voltage quality and torque ripple. Various prospective methods propose areas of low cogging torque which could be identified faster during the design optimization. Another observation is the impact created over cogging torque which is done by varying the yoke heights. Using practical observation on 15-kW PM wind generator, the results are validated with simulation of Finite element method. From the result, it is noted that the average generated torque illustrates low sensitivity (±6% of rated torque) to difference in dimension in the minimum cogging torque search. By fixing the slot pitch equal to 1.0 per unit and by selecting a typical magnet pitch, the minimum cogging torque region could be obtained. Using the above, per unit slot width region, minimum cogging torque could thus be identified. On a conclusive note, it is observed that, for the final machine selection, acceptable mass, load torque ripple and THD plays a vital role [69]. J. G. Wanjiku, et al, (2011) presented the optimized techniques of minimizing cogging torque which, in turn, has marginal impact on the performance of the machine. For the analysis, three PM rotor topologies were taken into consideration as the following - a pole-arc ratio of 0.80, alternating pole-arcs of 0.61 and 0.80, and skewed PM poles with a skew one slot-pitch. During the comparative analysis between alternating pole-arcs and skewing, the former effectively minimized the cogging torque closer to 70%, whereas it was only 50% by the latter and displayed minimal impacts on the performance of the machine. In terms of the performance of the machine, the alternating pole-arcs' topology had the maximum difference and the terminal voltage alongwith efficiency at a rated load was 8% and 2.5% respectively with the pole-arc ration of 0.80 [83]. Yong Pang (2011) considered Cogging torque as a vital parameter for designing a permanent-magnet machine which in turn has been investigated over the last few decades. In the Surface-mounted PM(SPM) with two optimized PM designs by cost, the cogging torque's behaviour has been given a prime focus. The study was carried out on the influence of thickness of the magnet, split ratio, number of poles in the rotor and magnet arc angle. It is evident that in an SPM machine with any of the cost effective PM by design, decreased cogging torque could be achieved and is assured by the simulation of the finite-element which is followed by experimental result [93].

18. Issue of Total Harmonic Distortion

In the design of wind generators, the Total Harmonic Distortion (THD) is a critical factor [63]. Comparison and calculation have been performed for the harmonic content along with THD of each configuration of magnet shape (with trapezoidal, triangular, rectangular and circular magnets) [63]. Harmonic analysis of the permanent magnet machine which is classified based on Winding harmonics, Slot harmonics, and Permanent magnet harmonics [69]. The low order torque harmonics can be harmful for a variety of applications, such as direct drive wind generators, direct drive light vehicle electrical motors, and for some high precision servo applications [97]. IlyaPetrov, et al, (2015) introduce a new technique for torque ripple minimization in Tooth-Coil Winding Permanent Magnet Synchronous Machines (TCW PMSM). Also extensive research and investigation of TCWPMSMs have produced literature which deals with the torque ripple reduction and it can be assumed that at the nominal load, torque ripple appears due to two main reasons: non-ideal sinusoidal waveform of the back EMF or phase current, and synchronous inductance variation [97]. The reasons for local saturation in the stator side of TCW PMSMs are described. It is shown that these saturations, which cause asymmetrical permeability variations in the magnetic circuit, can produce some high order harmonics in the PMSM torque [97]. Fu Rong, et al, (2011) presented the harmonic suppression function of the damper windings for air-gap magnetic field of line-start permanent magnet synchronous motors (LSPMSM) with help of FEA [134].

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19. Thermal model

The Thermal model is most important consideration in the PMSG design. Generally forced air cooling has been used in direct-driven PMSG, but significantly the cooling air flow path differs because, the stator windings of the generator have produced most of the heat. And the conventional solution of blowing the cooling air axially through the generator's air gap may not be deemed as an advisable option. To attain optimum cooling, generator's stator is axially segmented to several sub-stacks where the cooling air is blown through radial cooling channels that is formed between two subsequent stator sub-stacks [99]. Janne Nerg, et al, (2012) presented an analytical and thermal model of double radial-cooled low-speed high-torque PMSGs where the thermal model is considered by lumped parameters, which are frequently used during thermal analysis of electrical machines and cooled by forced air flow through the air gap [99]. Georg Traxler-Samek, et al, (2010) proposed a thermal computation model on a different note. It was observed that during steady-state operation, rotating electrical machines is heated due to power losses. However, when the same case is considered in an air-cooled machine, the power losses are displaced by a forced cooling airflow between the active parts. The power losses, the cooling airflow, the temperatures inside the active parts (e.g., core laminations, windings) and the periphery (e.g., winding overhangs) should be considered while designing and optimizing such machine [57]. In order to manage the heating losses, Yulia Alexandrova,et al, (2014) presented a prospective compact, high-power, direct-drive permanent magnet synchronous generator (DD-PMSG) that uses direct liquid cooling (LC) of the stator windings where the main parameters of LC DD-PMSG being 8 MW, 3.3 kV, and 11 Hz. Deionized water which flows continuously in the hollow conductor of each stator tooth-coil winding is used to cool the same. The calculations from lumped-parameter thermal model were utilized to study the steady-stated and time-dependent temperature distributions of LC DD-PMSG thereby resulting in the uneven heat loss distribution in the stator conductor as well as conductor cooling system. Using FEA, liquid-cooled tooth-coil design to analyze the cooling performance of the liquid was predicted [32]. In order to investigate the thermal behaviour of Axial Flux Synchronous Permanent-Magnet Machines (AFSPMMs) using a 3-D thermal–magnetic finite-element analysis (FEA) that may provide a systematic approach to magno-thermal FEA, Fabrizio Marignetti, et al, (2008) presented a study on the same. The axial flux machine taken for study is wound on a soft magnetic compound core. The thermal source model which is yielded from a magneto-static and DC current flow model, the thermal field's computation is conducted through FEA based on a coupled thermal and fluid-dynamical model. The result from the experiment has proved that rotor core is extremely hotter than expected [40]. Jérome Legranger, et al, (2010) presented in the optimal multi physics design of machines of an Interior Permanent-Magnet Starter Generator with a blend of FE and analytical models. To forecast the stator winding and rotor magnet's temperature, a thermal model may be used which is a 3-D transient lumped-parameter network. The prospective method permits the reduction of total weight by 20 % and the magnet's weight by 60%. It has been observed that the thermal model captures the impact created by external parameters on the machine design. The thermal model is multi-faceted to compute any type of tedious magnetic shape including the double layer magnets. The archetype has temperature sensors in various key points of the stator machine. The experimental study is based on the measure of three points (i) slot temperature (145°C); (ii) end winding temperature (146°C); (iii) tooth temperature (110°C) [61]. To avoid the excessive cooling requirements, the stator windings' current density is restricted to 3–6 A/mm^2 and the current loading to 40–60 kA/m [77]. A.S.Bornschlegell, et al, (2013) presented optimized study of the thermal behaviour of a high power salient-pole electrical machine. The lost cost computational lumped method provides the thermal trend from which temperatures are calculated. In the electrical machine, presuming a fixed geometry, the predominant volumetric flow rates are bounded and subjected to a non-linear constraint.

Geometries, flow configurations and the areas of application in the machine, are presented in Table.13 [162].

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Table 13. Correlations employed and their applications [162].

Geometry	Flow configuration	Application examples
Vertical flat plate	Natural convection	Recirculation regions
Horizontal cylinder	Natural convection	Shaft at outlet
Closed cavity	Natural convection	End-windings interior
End-windings	Cross flow	End-windings exterior
Single flat plate	Parallel flow	Stator axial channel
Two parallel flat plates	Parallel flow	Stator radial channel
Stationary cylinder	Cross flow	Exciter radial surface
Rotating cylinder	No external source	Shaft at inlet
Circular tube	Internal flow	Rotor channel
Rotating disk	Parallel flow	Rotor's front at inlet
Rotating disk	No external source	Rotor's front at outlet
Rotating eccentric circular tube	Internal flow	Rotor axial channel
Rectangular channel	Internal flow	Rotor radial channel
Annular, outter static cylinder and rotating inner cylinder	Internal flow	Airgap region

20. Demagnetization, Field Weakening, and Saturation Effect

20.1. Demagnetization

Design factors should consider the effect of demagnetization, field weakening, armature reaction and saturation effects. Jordi-Roger Riba Ruiz, et al, (2010) present the impact of faults due to demagnetization that gets reflected on the PMSM's stator current spectrum, which has been analyzed using a time-frequency approach. Fast Fourier Transform (FFT) results retrieved from stator currents for a PMSM which is driven by a vector control have projected that faults in harmonics were displayed in the current spectrum. However, the faults in harmonics are unclear when the analysis if performed with the PMSM running under non-stationary speed conditions. Despite FFT finding demagnetization faults by analysis of the amplitude of harmonics in stationary signals, it may not be deemed as the best option to find failures in motor in non-stationary signal [49]. Premature demagnetization may occur due to the armature reaction which, in turn, are caused due to magnets that are sensitive to increased temperatures (only upto 150°C) [62]. Amir Khoobroo, et al, (2010) suggested Field Reconstruction Method (FiRM) to find the faults using the same. However, at an increased power rating, occurrence of demagnetization in PMSM is considered as one of the critical issues. The magnetic aging, high temperatures due to inadequate ventilation or increased short circuits could cause demagnetization. This paper presents a new dimension of the fault detection in demagnetization. Using FiRM, flux linkage of the stator phases could be calculated which plays a pivotal role in monitoring the faults.

In order to attain the maximum average torque and/or minimum torque ripple, FiRM could be linked to the optimization tools. Once the fault is detected, the optimal currents may be applied in order to improvise the output torque parameter of the machine [80].

20.2. Armature reaction

T.F.Chan, et al. (2009) published an analytical method to find the no-load and single–sided armature reaction of magnetic fields and axial flux PMSG without armature core. A multi-current-sheet model is employed in order to obtain the armature reaction field by distributed nature of armature conductors in the axial direction [92].

20.3. 20.3. Saturation Effect

Martin Jadri ´c (2010) developed a unique method for the on-line assessment of the saturated synchronous reactance of machine which is based on a detailed process for assessment of the field to armature turns ratio using steady-state operating data. Based on the d- and q-axis saturated synchronous reactances, which is found with a wide range of operating parameters; the hydro turbine generator steady-state saturation model is established in an analytical form with the help of polynomial functions of two variables [51]. When the stator yoke begins to saturate due to very high flux density, losses could be generated in the supporting structure of the stator.At a low operating frequency, losses are minor in the housing of the machine, when the peak stator yoke flux density is restricted to 1.5 T in the stator yoke [75].

Figure 5 displays a damaged stator core as a result of over excitation. In order to reduce the mmf drop in the damaged parts and to decrease the iron losses in the stator yoke, it is advised that the maximum flux densities in the rotor yoke and the stator are set to 1.2 T [77]. Katsumi Yamazaki, et al, (2011) suggested the improvisation in features of salient-pole synchronous generators by introducing more permanent magnets which are inspected from the results of finite FEM analysis and experiments conducted. It is proven that the introduction of additional permanent magnets possesses the impact of mitigating the magnetic saturation at the rotor-pole bodies along with the impact of improving the direct flux linkage of armature windings.

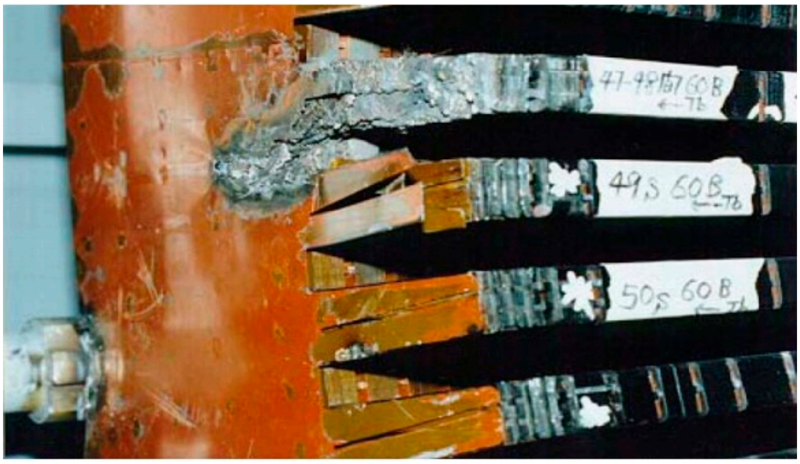

Figure 5. Stator core damaged due to over-excitation. Source: Maughan, Clyde, V., Maintenance of Turbine Drive Generator, Maughan Engineering Consultants.

Despite the fact that the maximum magneto-motive force could be improvised with the enlargement done on the filed winding's cross-sectional area, the rotor pole-bodies should be mitigated to achieve the total machine size. Due to magnetic saturation, an increased flux density and decreased permeability at the rotor-pole may be observed. Resultantly, in spite of the increased magneto-motive force, the maximum output power will not increase. Hence, the efficacy of generator decreases gradually. To attain the relevant saturation coefficient from the no-load saturation curve, the rotor-pole bodies are designed appropriately. In order to surpass the design limitation, the PMSGs development is done. The prospective generator design with the total amount of PMs is considerably reduced when compared with the full PM generators as the magneto-motive force is predominantly produced by field windings. Added to that, the output voltage by the field current's controllability is identical to that of the conventional field-winding generators. Hence, it could be re-instated so that the prospective generators should be the one of the analogous options in the various processes of electrical generators [101]. T.F.Chan, et al, (2005) with the aid of time-stepping, two-dimensional finite-element method and the inset rotor using a coupled-circuit presented a performance analysis of a PMSG. When the flux densities in the elements of the field solution region are considered, magnetic saturation is accounted. Further the load characteristics, the coupled-field circuit solution bears constructive machine information inclusive of the flux plots, components of the air-gap flux density, and the waveforms of voltages and currents [131].

21. Consideration of Losses Calculation for PMSGs.

The calculation of Losses in the PMSGs is an important design factor. Georg Traxler-Samek, et al, (2010) presented a detailed loss computation model calculation and methods by a model with an advanced analytical loss calculation. The model details classical losses such as stator core iron losses, I^2R losses, ventilation losses, and other detailed losses like stator end region losses. As cooling is done by a separate engine, bearing friction and excitation system losses have not been considered. The loss of components that are considered are described in detail [57].

a) Iron Losses

There are eddy current and additional losses in all metallic parts except the stator and rotor windings. They can be classified by:

1. Iron losses in the stator core (teeth and yoke) including the effect of harmonics and rotating fields
2. Eddy current losses on the pole shoe surface due to tooth ripple pulsation and stator winding armature reaction magneto motive force.
3. Eddy current losses in the stator clamping plates
4. Eddy current losses in the stator clamping fingers.
5. Eddy current losses in the stator core end laminations
6. Eddy current losses in external metallic air guides.

b) Winding Losses

The winding losses include different types of losses in the stator, rotor, and damper windings

1. Stator winding copper I^2R losses
2. Rotor winding copper I^2R losses
3. Eddy current losses in the stator winding due to the tangential slot leakage field
4. Eddy current losses in the stator winding due to the radial slot leakage field
5. Circulating current and eddy current losses in the stator winding overhang due to the end leakage field
6. Damper winding losses due to tooth-ripple pulsation and the stator winding armature reaction magneto-motive force
7. Other losses computed with simplified equations based on statistic evaluations.

c) Ventilation Losses

Ventilation losses can be subdivided in the following parts:

1. Friction losses of rotating parts
2. Air friction losses of the forced cooling airflow;
3. Pressure generation losses (e.g., fan, inter polar gap, rotor rim) [57].

Sandra Eriksson, et al, (2011) conducted exemplary study on the electromagnetic losses incurred in the direct-driven PMSGs. With the help of the electromagnetic model, solutions obtained from FEM and with a MATLAB-driven model, the simulations were performed. It has been observed that the iron losses and copper losses are fairly dependent on the rated voltage and rated current. With a fixed output power, as the rated voltage increases, larger machine volume is attained. Subsequently, there is higher frequency as well as increased iron loss whereas there is decrease in rated current and reduced copper losses. During the simulations, the generator losses are analyzed at different wind speeds, thereby obtaining the loss distribution [38]. Dan M. Ionel, et al, (2007) with the improvised models for laminated steel, presented computation of core losses in electrical machines along with the comprehensive study of the material models on three models of typical steel, mathematical calculation for the extension from the frequency to time domain and

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samples of validation from electrical machine studies [54]. Yunkai Huang, et al, (2011) presented an analytical model to forecast the eddy current losses in the PMSG rotor magnets by feeding a rectifier load. The results of the eddy current loss which is achieved from time-stepping, 2-D FEM and coupled–circuit are matched and investigation was performed. E. Spooner, et al, (1997) derived losses for the model of 1MW machine design prepared with regard to the parasitic losses. These are stator beam loss, rotor eddy-current loss, stator structure cage loss, stator back-iron reluctance, stator module weld loss, rotor reluctance, rotor and stator slotting, the polygon effect, stator back-iron reluctance [135]. Floran Martin, et al, (2014) investigated the eddy current losses in permanent magnets of surface-mounted magnet synchronous machines. An original analytical method based on the magneto-dynamic problem of a conductive ring is introduced and the obtained results are compared with the ones given by 3-D FEM analysis. The analytical model considers the effect of the width on the magnet loss. The axial effect is considered through a correction coefficient. The comparison includes the induced current density, the instantaneous losses, the impact of the circumferential segmentation, and the effect of the frequency on the magnet losses. By focussing on the importance of the skin effect and the magnetic reaction due to the magnet currents, the analytical model provides an accurate determination of the magnet eddy current losses [171].

22. Modelling and Dynamic Characteristics

In general, a wind farm encompasses a number of wind turbine generators (WTGs) integrated with an internal electrical network with the operations simultaneously. M. G. Molina, Member, et al, (2010) published wind farm-related dynamic modelling and control approach with the aid of variable-speed direct-driven PMSG WTGs to perform dynamic studies in DG systems. The prospective wind farm modelling approach consolidates all WTGs that undergo similar wind velocities to a corresponding WTG model. The state-space averaging technique drives the aforesaid simplified modelling. To estimate the effect of a wind farm on the power system dynamics, a predominant problem was to develop sufficient ------ on par models that permit parameterize the individual WTGs dynamics [16]. Paul Krause, et al, focus on the principles of electro-magnetic energy conversion of static and rotating reference frames theory. The modelling of dynamic characteristics of permanent magnet and shunt DC voltage and torque equations in reference frame variables are available. Modelling and analysis of steady state operation and dynamic performance of three-phase induction machines and synchronous machines are presented. The park equations, transient stability limit, voltage equation in arbitrary reference frame and rotor reference frame voltage equation in arbitrary reference frame and rotor reference frame are discussed [73]. Nicolas Bracikowski, et al, (2012) used Lumped Models (LMs) to analyze the Multiphysics modelling with the PMSM couplings. Various disciplines of physics such as Electromagnetics, Mechanics, Thermic features and Acoustics are deployed during the design. Electrical, electronic, thermal and magnetic parts are represented by LMs and, on the other hand, analytical models represent vibro-acoustic and mechanical parts. FEM and LMS are used to perform the comparative study of flux density analysis and cogging torque. With the presence of merits such as easy implementation, lesser computing time, and a high precision FEM tool, LMs are an optimal choice [36]. Abdallah Barakat, et al, (2010) offered a holistic procedure to obtain a synchronous machine model by considering the presence of damper windings. The notable feature of the work is the comparative analysis of the equivalent circuit in the (d,q) natural reference frames and in the (d,q) stator reference frame, without altering the models' structure using a sudden short-circuit or an open-circuit test.

The particularity of this work is the analysis of the equivalent circuit in the (d,q) natural reference frames and in the (d,q) stator reference frame, also which is achieved without modifying the proper structure of the model a sudden short-circuit test or a sudden open-circuit test.

It is observed that during a sudden open-circuit, good harmonics is achieved between simulation and practical results, whereas during a sudden short-circuit, the dampers get excited and discrepancies is observed between simulation and practical results. Also, the discrepancies obtained are in relation to the assumptions and hypothesis that are supporting the damper modelling, saturation, and hysteresis phenomena [48]. S.A. Kharitonov, et al, (2008) presented the variable speed constant frequency power generation system based on a synchronous generator excited from permanent magnets and voltage inverters. The generation system block diagram and performance are considered. The results are supported by testing [56]. S.R. Holm, et al, (2007) established an analytical model for a radial-flux external-rotor permanent-magnet synchronous machine (PMSM) removing the slots in the stator iron alongwith a shielding cylinder. As a result, an airgap winding with a stator yoke which consists of stacked circular laminations is formed. The analytical model comprises the winding distribution effects on the field, which is in the airgap, and the impact of the eddy-current reaction field of the shielding cylinder.

In order to achieve the machine voltage equation, the vital machine quantities are directly derived from two-dimensional magnetic field solved in six defined machine layers. [76]. Mohammadali Abbasian, et al, (2011). presented an optimized PMSG design for a small-scale wind energy conversion system. An analytical model of a small-scale wind energy conversion system alongside grid connection is presented. Investigation is also conducted on the impacts of the design parameters of generator on the system's payback period. In order to optimize the design parameters to use in an arena with relatively low-wind speed, an optimized process based on genetic algorithm is deployed. The aim of optimization is minimizing the payback period of the initial investment on wind energy conversion systems for residential applications. It is shown that the present worth of optimal WECS with a typical 20-year lifetime is around 1.72 times of the initial investment with 6% of the annual interest rate and 3% of the annual energy inflation rate. Therefore, the payback period is around 9.9 years, which is less than half of the total lifetime [79]. C. Patsios, et al, (2010) presented an analysis for wind turbine on specific electro-magnetic field computation of permanent magnet generator. Appropriate 2-D and 3-D FEM and EMF distributions inclusive of space harmonics in real time control systems are used [90]. Precision-specific PMG modelling needs a complex electro-magnetic field analysis to account for rotor eccentricity and end-zone leakage field [90]. Akbar Rahideh, et al, (2013) presented a noteworthy comprehensive summary of the references for the various concerns on the analytical calculation of magnetic field distribution of rotary motion brushless permanent magnet machines. For the six various magnetization patterns, a holistic and analytical open-circuit magnetic field distribution of slotless brushless permanent Magnet machines with surface mounting is presented. Depending on the open-circuit flux density distribution and the configuration of machine winding, an analytical equation of back-EMF induced in every phase has been presented which, in turn, is used to derive the accurate design of slotless BLDC and BLAC motors bearing the different magnetization patterns in notice [95]. T.F. Chan, et al, (2004) analyzed and presented a study on the performance of a three-phase synchronous generator inclusive of a permanent-magnet rotor. With the aid of the two-axis model, related performance equations are developed. By analytical method, the criteria to attain zero voltage regulation, extreme factors in load characteristics and maximum power output are found. In order to quantify the saturation effects on the synchronous reactance, FEM is adopted for the computational analysis of the magnetic-field distribution [124]. Michelle L. Bash, (2012) developed a novel Magnetic Equivalent Circuit (MEC) and a solution technique to facilitate quicker calculation of the wound-rotor synchronous machines performance. The evolution of a population-based design tool which exploits the MEC is detailed [230].

23. Faults and Protection

While designing the PMSGs, fault occurrences and protection schemes are taken into consideration.

Cristian Ruschetti, et al, (2013) presented the impacts of asymmetrical magnet faults on the PMSG rotor. The common attributes leading to rotor faults are eccentricity, damage in any of the magnets, asymmetries and mechanical looseness. It is identified that uneven distribution of the air-gap - which could be static, dynamic or mixed - causes the rotor eccentricity. When static eccentricity is present, the position of the air-gap which is least, it is fixed in respect to the stator. In contradiction, for dynamic eccentricity, the rotor's centers do not coincide with the center of rotation. Hence, the position of the minimum air-gap rotates in line with the rotor. A few prominent reasons for the eccentricities may be because of load unbalances, looseness, misalignment, incorrect assembly and could even be the bending of the rotor. During the analysis, series and parallel-connected windings are considered. In order to quantify demagnetization on a single magnet, fault severity factor is defined. From the investigations carried out in this work, it could be concluded that for a generator where all the windings are connected in series, demagnetization on a single magnet produces a decrease in the induced EMF value. Similarly, if load is of resistive type, the current also tends to decrease. It becomes impossible to notice the frequency components that are associated to fault, whereas only the decreased total flux linked to the windings can be observed [21]. R.B. Rodrigues, et al, (2012), after studying the over voltages and electromagnetic transients, expresses his concern on the direct or indirect lightning strokes. The transient behaviour is described by the lightning protection of the wind turbines in an accurate way, and the restructured version of the electro-magnetic transient programme (EMTP) is used. Two interconnected wind turbines were utilized to conduct a case study, in order to consider the direct lightning stroke to the blade or the lightning strikes that occur in the soil near a tower. Also, Comprehensive computer simulations alongwith EMTP-RV are presented here [24]. Yang, Jin (2011) the analyzed fault conditions and investigated effective fault ride-through and protection schemes in the electrical systems of wind farms, for both small-scale land and large-scale offshore systems. Two variable-speed generation systems are considered. These are Doubly-fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs). The protection issues of DFIGs are discussed, with a novel protection scheme proposed. Then the analysis of protection scheme options for the fully-rated converter, direct-driven PMSGs are examined and performed with simulation comparisons [34].

G.K. Kalokiris, et al, (2007) examined progresses in magnetic materials and their influence on design of electric machine. Adding to that, possible faults were scrutinized with a fault-tolerant system design. There are two types of faults that may appear in the system, the electromagnetic faults being the first with:

1. winding open circuit;
2. winding short circuit (phase/phase);
3. winding short circuit at terminals;
4. turn-to-turn fault in a phase.

While secondly, the power converter faults are:

1. power device open circuit;
2. power device short circuit;
3. DC link capacitor failure.

If continuous operation, even under faulty condition, is the objective and a requirement, focus should be provided on designing a fault-tolerant system. Under this design, each phase should be fed by an individual single phase PWM inverter, which consists of a modular system in which every phase fault isolates the module. In case each module has a lesser electrical, magnetic and thermal interaction, the system will continue to operate without the faulty phase [65]. Jae-Woo Jung, et al, (2012), in order to reduce the mechanical stress in the core bridge, introduced FEA simulation and a rotor core design. Taking speed variation of the rotor into consideration, mechanical transient analysis is performed. In order to assure the validity of model against fatigue failure, experimental result is presented for the S-N curve (S–N curve is derived from the material test data) of rotor core material [121].

24. Damping and Oscillation

For damping and oscillation, stability issues due to PMSG in the WECs should be considered. HuaGeng, et al, (2011) offered a torque compensation strategy based on DC-link current estimation of the converters after studying the stability issues encountered in PMSG-WECS. Instability issues are generally caused when the generators are directly connected to the wind turbine where speed oscillations are caused due to the absence of damper in the design, torsional vibration. In order to reduce the oscillation amplitude and improvise the system stability, a slow generator torque controller can be used. However, as the capability is limited, it may impact the power response of the WECS. On the other hand, the torque compensation strategy, when employed to provide the positive damping of the oscillations, results in the improvisation of small signal and transient stabilities of the WECS [103]. Jose´ Luis Domı´nguez-Garcı´a et al. (2012) reflected about the impact on system oscillations due to grid-connected wind farms and focussed on the contribution or power system oscillations' damping and on inner wind turbine oscillations of the modification of several aspects of power system behaviour including stability. Power systems' stability is connected to the electro-mechanical interactions and the generator's behaviour which is connected to the grid. Hence, wind power penetration's influence over the power system becomes a vital issue to act upon. A detailed study is done on the oscillations in power system and their impact and control schemes in the wind farms for different wind turbine technologies [15]. Nicolas W. Frank, et al, (2011) threw light on Magnetic gears which is rapidly emerging with technology. Magnetic gears concept avails the merit of having inherent overload capability over the Mechanical gears. However, the torsional stiffness of Magnetic gears is lesser than that of mechanical gears which results in oscillations during transient changes in load and speed similar as in the case of damper windings used in synchronous generators to suppress oscillations due to transients [114]. A.J.G.Westlake, et al, (1996) depicted damping the power-angle oscillations of PMSG with specific reference to wind turbine applications. The generator's small pole pitch permits it to work on low speeds coupled to the wind turbine thereby maintaining a direct electrical grid connection. This paper suggests an alternative damping system where the stator is permitted to limit its rotational movement by connecting it to the wind turbine housed through a spring and a mechanical damper. This plan permits greater damping of power-angle oscillations than conventional damper windings. The generator's response to step changes in driving torque is utilized to illustrate the efficacy of the design. The generator's behaviour on synchronization and operation front when the wind differs is detailed to illustrate the viability of the new design [140].

Short Circuit

Keith W. Klontz, et al,(2011) emphasizes the prominent case of the sudden short circuit which is applied to the large Permanent Magnet Generator machines which depicts the variations in short-circuit behaviour amongst the PMG and wound-field generator. Using analytical and FEM, PMG's sub-transient reactance and time constants are calculated, and used to the typical circuit theory simulation in the short-circuit fault. FEM is utilized to evaluate the risk of loss of magnetization in magnets. The transient magnetic field is complex and hence requires transient non-linear circuit-coupled FEA in 3-D with voltage-source excitation. This paper summarizes the reviews of the different calculation methods and discussion of implications for futuristic design and application of the PMG, taking note of the attributes in relation to the application of standard tests and specifications [50].

25. Several aspects of Cost factor

Salem Alshibani, et al, (2014) addresses the high Capital Expenditure (CAPEX) which, at the start of the project, presents a hurdle for such technology especially for gearless permanent magnet synchronous generators (PMSGs). The proposed method is used to evaluate typical PMSGs designed and reported in this paper as well as others available in the technical literature. The new method's outcome is compared to that of the conventional methods. It is shown that lifetime cycle assessment (LCA) came in favor of gearless PMSGs, which has high CAPEX. It is also shown that when lifetime cost is included in the design optimization, it produces machines that provide lifetime revenues significantly higher than the extra CAPEX required [137]. The Figure 6 and Figure 7, represent CAPEX comparison of geared and gearless PMSGs at a range of power ratings with percentage.

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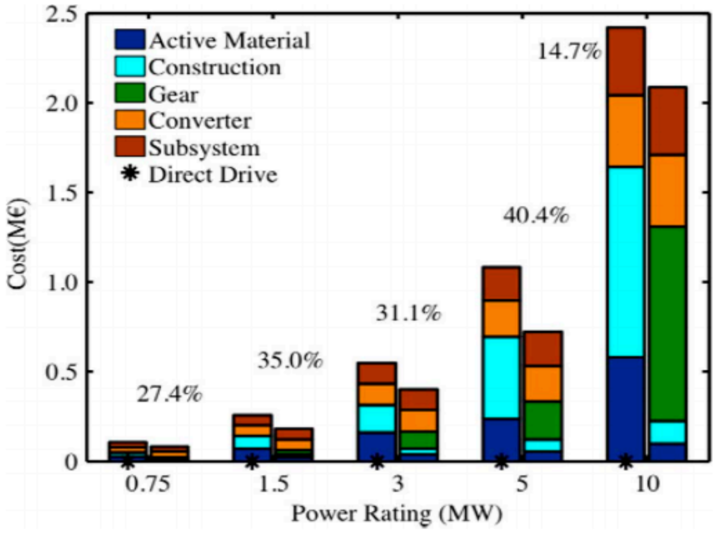

Figure 6. Depicted CAPEX comparison of geared and gearless PMSGs at a range of power ratings with percentage difference in cost shown at each power level [137].

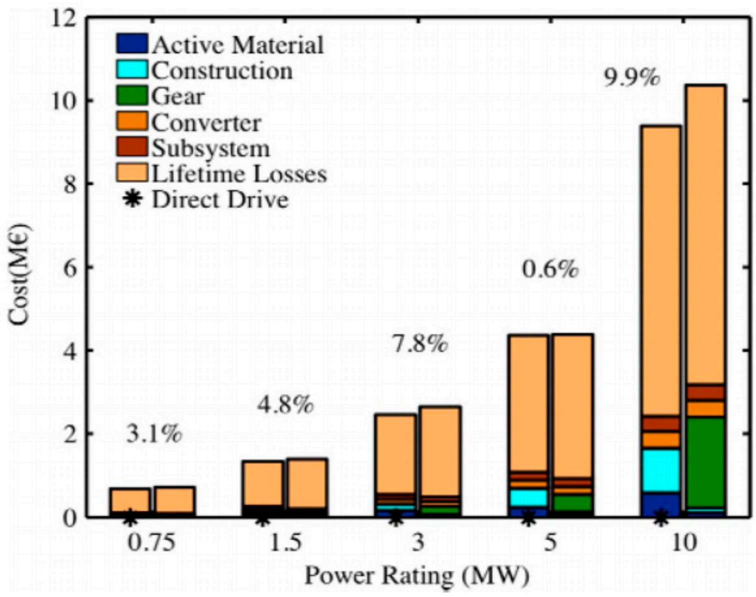

Figure 7. Cost comparisons of the machines with lifetime losses cost added and gear cost calculated twice. The percentage difference in cost is shown at each power level [137].

On a conclusive note, it is witnessed that the wind turbines which have a higher power ratings are preferred in order to reduce the construction and maintenance time to increment the energy yield [137].

A typical wind turbine contains nearly 8,000 different parts of components. The information based on a REpower MM92 turbine with 45.3 meter length blades and 100m tower [11]. The major components part of a wind turbine and their share of the overall wind energy generation cost are given in Table 14.

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Table 14. Main components of a wind turbine and their share of the overall cost [11].

S.No	Name of Component Part	Percentage	S.No	Name of Component Part	Percentage
1	Tower	26.6%	10	**Generator**	**3.44%**
2	Rotor blades	22.2%	11	Yaw system	1.25%
3	Rotor hup	1.37%	12	Pitch system	2.66%
4	Rotor bearing	1.22%	13	Power converter	5.01%
5	Main shaft	1.91%	14	Transformer	3.59%
6	Main frame	2.80%	15	Brake system	1.32%
7	Cable	0.96%	16	Nacelle housing	1.35%
8	Screw	1.04%	17	Other	10.37%
9	Gear box	12.91%			

26. Soft Computing Techniques-based Optimization used PMSGs.

Optimal design of electrical machine, when FEM is used, is impacted by two critical issues: FEM simulation's computation time and the large number of parameters of the electrical machine [211]. Present-day, the Soft Computing techniques based optimization used for PMSGs. LaureneV.Fausett(2008) [238], Timothy J.Ross (2010) [239], George J.Klir and Bo Yuan,(1995) [240], David E.Goldberg, (2009) [241], W.T.Miller,, et al, (1996) [242], and many more soft computing books are incorporating contents based on such review and fundamentals of neural network, artificial neural network , fuzzy set theory, Neuro fuzzy, Genetic Algorithm and Tabu Search, Ant-colony Optimization and Particle Swarm Optimization methods are used for several applications [238]-[242]. S. Giurgea, H., et al, (2007) with the help of statistical multiple correlation coefficients (R2) analysis and moving least squares (MLS) approximation proposed an alternative model to be compatible with electrical machines. In general, optimization process involves a large number of computations which strongly depend on the parameters; the computation effort is negligible compared to the time that could be saved. This method is evaluated by the application of the same to the optimal design of a Synchronous machine. The results showcase the increase in torque per weight ratio by 13% on comparison with the results from classical optimization methods [211]. Ajay Kumar, et al, (2010) with the aid of FEM and Fuzzy method investigated the comparison involved in leakage field analysis in generator. In order to carry out the leakage field analysis, the generator's fuzzy model is developed with the adaptive neuro-fuzzy inference system (ANFIS). A comparative evaluation is performed on FEM model and fuzzy model and it is observed that good correlation has been achieved between them, [165]. Rajkumar Roy, et al, (2008) found the latest approaches in order to automate the manual optimization process and the challenges on the implementation in the engineering community. Depending on the design evaluation effort and the degrees of freedom view points, classification is done on Engineering design optimization. A holistic view on the various approaches for the optimization of design is presented. Scalability is identified as the major challenge for the design optimization techniques by the study. The Large–scale optimization needs considerable computing power and the effective algorithms like the swarm intelligence [212]. G. Tsekouras, et al, (2001) presented an approach on neural network on comparison with the sensitivity analysis based on the FET to optimize the permanent magnet generators [173]. Manuel Pinilla, et al, (2012) brought to light the challenges encountered during optimization of a design, either to minimize or maximize the fitness function which, in turn, will determine the purpose of the design. Genetic algorithm which is included in the population-based optimized technique lacks the other matters such as the raw active material, magnet, copper and magnetic laminations. The very intention of minimizing the fitness function is based on the energy cost generated by the system that accounts for the uncertain variables [19]. H. Li, et al, (2009) experimented with the direct-drive PM wind generation system optimum design models where the PM is developed using an improvised genetic algorithm alongwith a 500 kW direct drive PM generator for the minimized generator active material cost to illustrate the effectiveness of design optimization [20]. Julien Fontchastagner, et al, (2007) offered a new approach in electrical rotating machines design. A perfect combination of analytical model and exact global optimization algorithms results in rational solution of predesign. As a caution, before designing the extensive prototype, the aforesaid solutions need to be validated by a numerical tool using FEM. The intent of the paper is to extend the accurate global optimization algorithm by introducing the direct use of the automatic numeric tool. This new technique enables in solving the design problems in a rational way. A few numerical examples evaluate the effectiveness of the new approach [29]. Chunhua Liu, et al, (2008) implemented a new 36/24 – pole outer –rotor permanent magnet (PM) hybrid machine for directly-coupled wind power generation. In order to provide effective flux control, hybridization of two excitations (PMs and DC field windings) in the double-layer stator is used. As a result, constant output with varying wide range of speeds and loads is observed [115]. Frédéric Messine, et al, (2006) detailed on the multi-airgap cylindrical concentric machine. In order to combat the inverse problem linked to the electrical machine design, a reformulation solution is required. Hence, focus should be to solve the new mixed-constrained global optimization issue. From a mathematical perspective, the bigger issue is due to the variation in the number of variables and constraints during resolution which is dependent on the number of the air-gaps taken into the consideration. Moreover, the process involves extended analytical models which have been used for permanent-magnet machines. This paper employs the numerical tests conducted for concentric rotor machines with one, two, and three (in one case) mechanical air-gaps which permit evaluation of this methodology of design [178]. Yiu-Wing Leung, et al, (2001) offered a genetic algorithm known as the orthogonal genetic algorithm alongwith quantization/quantification for global numerical optimization using continuous variables. In addition to that, we can apply the quantization technique and orthogonal design to develop a new crossover operator, so that the crossover operator will generate a little but representative sample points as that of the potential offspring. This proposed algorithm is used to solve the 15 benchmark problems with 30 or 100 dimensions and bigger numbers that belong to local minima [193]. Rafal Kicinger, et al,(2005) summarizes many of the promising areas in new research of evolutionary computation which is currently trending as an upcoming engineering computational paradigm and is rapidly developing and is exciting new dimensions. K.M. Saridakis, et al,(2008) details on the soft computing (SC) techniques in the field of the engineering design. By inspecting the competence of the soft computing methods and techniques, in order to address the high complexity design tasks and issues, Fuzzy logic (FL), Genetic Algorithms (GA), and artificial neural networks (ANN) are reviewed [191]. NorfadzlanYusup, et al, (2012) presented an overview and the comparative study of the researches conducted in the recent five years which is used for the evolutionary optimization techniques in order to optimize the machining process parameterization of conventional and modern machining. The most considered five techniques are genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO), ant colony optimization (ACO) and artificial bee colony (ABC) algorithm. Amongst all, GA has been widely applied by researchers to optimize the machining process parameters according to the literature [189].

Weicai Zhong, et al, (2004) offered a new solution namely multi-agent genetic algorithm (MAGA), obtained by integrating the multi-agent systems and genetic algorithms to solve the global numerical optimization problem [192]. Shahryar Rahnamayan, et al, (2008) offered an disagreement versus randomness in SC techniques.

R. Ba˜nos, et al, (2011) presented a review of the cutting-edge research developments regarding the use of soft computing used to optimize the different segment for design, planning, and control problems in the field of renewable and sustainable energy. Also, numerous soft computing methods presented and reviewed about the current state of the art in computational optimization methods applied to renewable and sustainable energy, proposing a vibrant visualization of the state-of-the-art research progresses in this field [8].

Random numbers should be generated by Soft computing methods so that the random numbers could either be used during the initial estimation or at the time of learning and searching process. On a comparison between simultaneous consideration of randomness and opposition and pure randomness, the former is proved to be more advantageous states the recent results from evolutionary algorithms, reinforcement learning and neural networks. In order to accelerate the soft computing algorithms, it is evident that opposition-based learning provides an elevated effect. It is also proved mathematically and experimentally that SC has the merits when applied to accelerate the differential evolution (DE). Despite lack of prior knowledge about the solution, with the advantage of random numbers and their opposites, search or learning process in SC techniques could be enhanced [194]. YoungjunAhn et al. (2010) presented the application of memetic algorithm with GA (Genetic Algorithm) and MADS (Mesh Adaptive Direct Search) in optimal design methodology of electric machine. To obtain the effective optimal design of an electric machine with many local optima and longer computation time, hybrid algorithm has been developed to obtain the global optimum. In order to maximize the Annual Energy Production (AEP), the prospective algorithm has been referred for the optimal design of a direct-driven PM wind generator which is facilitated by FEA. The Figure 8 is exemplifies regarding conventional and non-conventional optimization tools and techniques (Mukherjee & Ray, 2006) [189].

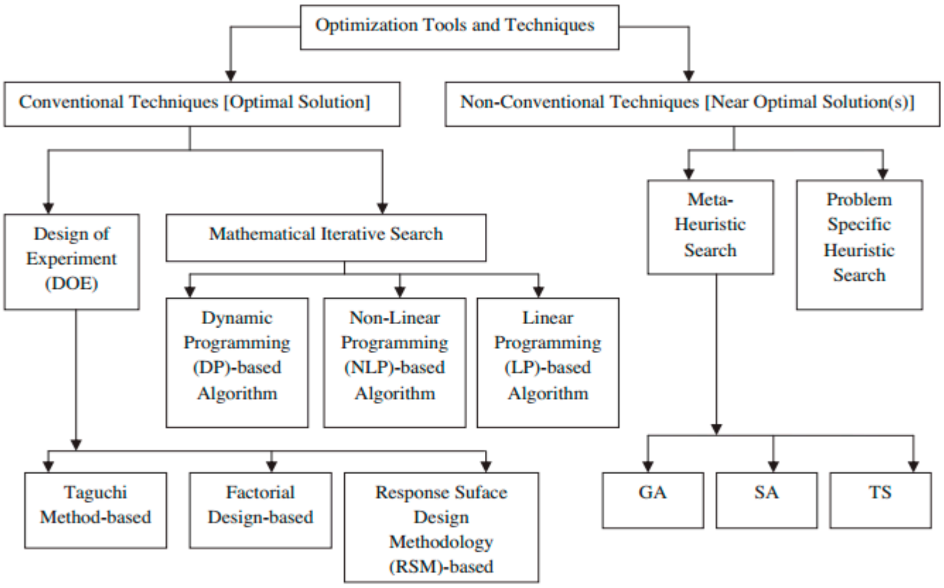

Figure 8. Conventional and non-conventional optimization tools and techniques (Mukherjee & Ray, 2006) [189].

To conclude, the effective reduction of computation time for the optimal design of a PM wind generator, MADS combined with GA is preferred over the purposely developed GA implemented with the parallel computing method [195]. Brian H. Dennis, et al, (2001) offered an issue of multidisciplinary design and optimization (MDO) of a diffuser for a steady, incompressible magneto-hydrodynamic (MHD). The encountered design problem is resolved by using Genetic Algorithm-based optimized programme coupled with Finite element-based MHD simulation programme for which least-square FEM (LSFEM) based programme has been developed for the latter [196]. Alexandre H., et al, (2002) presented the non-dominated sorting genetic algorithm (NSGA) to resolve this class of problems and the performance is analyzed by comparing results of the same with the results from the other four algorithms. Discussion is also done on the solutioning of the Multi-objective optimization process by evolutionary algorithms. The results derived from analytical and electro-magnetic problems indicate its effectiveness [197]. S. Kiartzis, A, et al, (2001) presented an approach for the PM generator design for wind power applications. This approach consists of two stages: preliminary design stage with a standard formulae and an optimization stage comprising of a two-dimensional FEM deploying deterministic and artificial intelligence approaches [198]. Swagatam Das, et al, (2008) inspected Particle Swarm Optimization (POS) and Differential Evolution (DE) Algorithms: technical analysis, applications along with hybrid perspectives [199]. Artificial Bee Colony (ABC) algorithm is the innovative swarm optimization algorithm with fine numerical optimization results. Xiaojun Bi et al. (2011) presented an improvised algorithm known as fast mutation artificial bee colony algorithm (FMABC). While choosing the

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food sources, the onlookers prefer the sensitivity model in Free Search algorithm in order to replace the conventional roulette wheel selection model. Also, instead of behaviour of scouts, a mutation strategy which is based on the opposition-based learning was proposed. By applying the improved ABC algorithm on seven benchmark optimization functions, displays a notable improvisation in the performance over the conventional ABC [200]. Bilal Babayigit, et al, (2012) presented an altered ABC algorithm for numerical optimization issues to improvise the ABC algorithm's exploitation capability. A varying probability function and an alternate search mechanism were proposed. Seven numerical optimization problems were used for testing the modified ABC algorithm [205]. Naghi Rostami, M et al. (2012) used genetic algorithm (GA) to achieve an optimal design for an axial –flux PMSG (AFPMSG) hence identifying the condition required for the minimum active material cost. A proposal is done on the results obtained from GA using computer aided procedure. During the design procedure, consideration is done on the practical and performance characteristics due to the limitations for the object function in the optimization algorithm [201]. Chonghui Song, et al, (2009) based on numerical optimization algorithm, presented a generalized receding horizon control of fuzzy systems. In order to resolve the optimal control problem for generic fuzzy dynamic systems, a numerical method was developed namely direct finite difference with sigmoidal transformation. A more comprehensive numerical algorithm, namely fine optimization, is developed by considering the previous optimized results same as the initial results [202]. S.L. Ho, et al, (2005) efficiently reinforced radial basis function (CS-RBF) which is upgraded and used to design a new response surface model. As the main objective is to decrease the numerous function calls which usually involve the computationally-heavy procedures like the repetitive use of FEA which is usually required in solving inverse problems, a fast and effective global optimal design strategy is developed using the incorporation of the model into stochastic global optimal methods [203]. Devendra K. Chaturvedi, (2008) book delivers a thoughtful understanding of the soft computation techniques for application in Electrical Engineering field along with integrated pseudo-code operational summaries and Matlab codes [204]. Fei Peng, Ke Tang, et al, (2010) having the delivery of the solution within a given time budget, consider a scenario where population-based algorithm is applied to a numerical optimization problem. Despite an elaborative study on wide range of population-based algorithms like evolutionary algorithms, particle swarm optimizers and differential evolution, the algorithm's performance is prone to vary considerably from problem to problem [206].

At times, search problems are difficult to compute due to high dimensionality of search spaces. Until appropriate approaches are employed, search process could take a toll of time and effectiveness. With the help of nature and its many complex systems, such difficulties could be tackled. For instance, to increase the mutual survivability in Fish schools, a large number of constituent individuals is deployed [207]. Carmelo J. A. Bastos Filho, et al, (2008) introduced a novel method to search high dimensional spaces considering the account behaviours obtained from fish schools. The derived algorithm – Fish-School Search (FSS) mainly comprises three operators: feeding, swimming, and breeding. Cumulatively, these operators afford the evoked computation: (i) wide-ranging search abilities, (ii) automatic capability to switch between exploration and exploitation, and (iii) self-adaptable global guidance for the search process. The novel algorithm is detailed in this paper. With respect to high dimensional searches, the simulations presented include FSS algorithm which when compared, in some cases, outstands well established intelligent algorithms like Particle SWARM optimization [207].

S.L. Ho, et al, (2006) presented the enhancement feat to particle swarm optimization (PSO) methods. The presentation includes, an age variable for the anew strategies to figure the optimum solutions of the particle and its associated neighbor, the design of a original formula for velocity updating, the integration of an intensified search phase alongwith an improved PSO method. Results derived from experiments imply that the proposed method's refined pinpointing search ability and the global search ability have considerably improvised in comparison to the traditional PSOs [208]. Dragan Matic, et al, (2012) offered a support vector machine classifier to detect the broken ba electrical induction machine. A relative analysis of linear, Gaussian and quadratic kernel

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function versus error rate and the number of support vectors is carried out. The suggested classifier has very successfully detected the broken bar in many operational situations and is precise, fast, and robust to load changes, which qualifies for the right use in real-time online applications used in industrial drives [209]. S.L.HO, Shiyou, et al, (2002) in order to find the Pareto solutions of multi objective optimal design problems, proposed a tabu-search algorithm, from which the contact theorem is utilized to assess the former. When the iteration cycle is begun so as to recognize the new current points, ranking selection approach and the fitness sharing function are introduced. Elaborate numerical results are presented here to showcase the proposed algorithm's power so as to ensure the uniform sampling, thereby yielding the Pareto optimal front of the multi-objective design problems. An effective strategy of executing the proposed algorithm is also detailed [210]. Rhythm S. Wadhwa, et al, (2011) presented the Improved Discrete Particle Swarm Optimization (IDPSO) searching technique that is applied on an electromagnet head on the shape and magnetic field gradient optimization. COMSOL is used for computation on magnetic field and forces. The objective of the optimization is the refined search of an optimal pole shape geometry resulting in homogeneous magnetic field distribution alongwith the desired holding force in the region of interest [213]. A. A. Arkadan, et al, (2007) offered an innovative recursive fuzzy logic categorizing (R-FL-C) strategy for the PM generators design approach which is used to void the search space and to expel the local minima in the due course of the optimization process. Finite Element State Space models are used to explore the space database with the knowledge obtained off-line from them [214]. Guoqiang Li, et al, (2012) to assess the numerical functional optimization, investigated an artificial bee colony algorithm (ABC) which derives its inspiration from the honey bee swarm's foraging behaviour, which is a classic epitome of biological-inspired optimization. Also, ABS's efficacy stands tall on a comparison with genetic algorithm (GA), particle swarm optimization (PSO), and ant colony optimization (ACO). However, while ABC is appreciative at exploration, its exploitation capacities were poor alongwith its convergence speed issues in a few instances. To address the issues, improved ABC algorithm (I-ABC) is introduced. To refine the search process, inertia weight and acceleration co-efficients are presented in the thus far best solution, I-ABC. Inertia weight and acceleration are marked as the fitness functions [216]. Ingo Hahn, et al, (2012) offered a heuristic structural optimization for the Surface Mounted PMSG. Structural optimization, usually a process to identify the optimal material distribution of a machine part, is very prevalent in the discipline of Mechanical Engineering. Likewise, in the discipline of electrical engineering, very few dedicated applications of Structural optimization are used. In contrast to the other reported methods which deploy continuous models to elaborate the material properties with a delayed homogenization process, a promising solution to the Structural optimization issue is given by a Heuristic Search Algorithm [217]. Annette Muetze (2008) offered a deterministic global mathematical optimization which later became a vital tool in design processes. The multi-faceted design problems could be handled by various optimization techniques and mathematical models.

In Figure 9 is shown a typical requirement consideration for optimization [215].

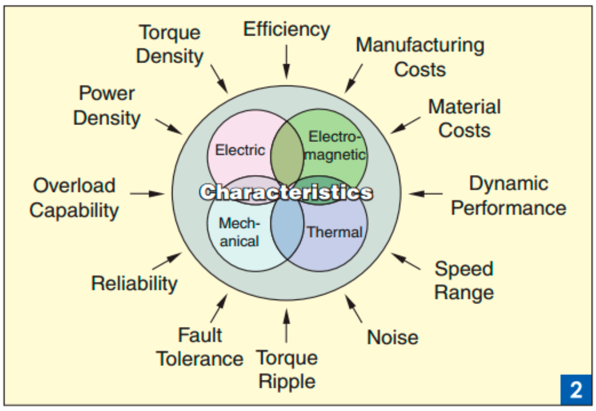

Figure 9. Typical requirements consideration for optimization [215].

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Dragan Matic, et al,(2012) recommended simulations on annealing algorithm for electromagnetic devices' multi objective optimizations in order to obtain the Pareto solutions in a considerable relative manner which is dependent on the Pareto set successful introductions alongwith the parameter and objective space strings. The proposed method interrogates the new rank formula, fitness sharing functions, stop criterion and other improvisations. In order to validate the robustness of the method proposed, two numerical examples are validated [218]. S.L. Ho (2001) offered an improvised tabu-search algorithm to apply practically so as to find the electro-magnetic devices' optimal designs. Simultaneously, mathematical test function and team workshops were conducted. The numerical results obtained from them unearthed that the iteration number of the method proposed is less significant on a comparison with other algorithms like simulated annealing [219]. Li Liu, et al, (2008) to identify parametrically with non-linear model structure, proposed a new methodology with particle swarm optimization (PSO) as the reference. The aforesaid method is also applied to PMSM's dq-model for the parameter identification. The disturbed load torque and the motor stator resistance are recognized for the PMSM variable-frequency drive system application. To interrogate the efficacy of the identification method, simulation and experimental results have been provided. Good precision on time-varying parameters has been observed with the help of PSO algorithm [220]. Shiyou Yang, et al, (2000) presented a self-learnable simulated annealing algorithm which is built by blending the simulation annealing and domain elimination method's characteristics. Standard mathematical function is used for evaluating the algorithm alongwith the optimization of power transformer practical end region [221]. Scott D. Sudhoff, et al, (2005) established a PMSM with rotor feedback using a Genetic Algorithm demonstrating both single and multi-objective optimizations. The extended version of this artifact is incorporation of core losses which can be sited using Steinmetz approach. Other up-front improvisations will be the amendment of the tooth shape (specifically the base), inclusion of voltage constraints and the volume expression modification for the inclusiveness of the end turns [222]. S.L. Ho, et al, (2005) suggested the improved Ant Colony Optimization Algorithm and its use in Electro-magnetic Devices Designs. The algorithm is experimented on an inverse problem and a mathematical function, where its resultant performances are compared with the other better-designed methods [223]. Dervis Karaboga, et al, (2007) performed a comparative study of the ABCs performance on numerical function optimization with GA, PSO, and Particle Swarm Inspired Evolutionary Algorithm (PS-EA) which are also swarm intelligence and population-based algorithms. Five high dimensional benchmark functions which possess multi-modality are deployed to explore the performance. The simulation results strongly recommended that the algorithm that was proposed has the ability to expel the local minimum and could effectively be deployed in multi-variable, multi-modal function optimization. The scope for the futuristic studies is a compelling factor, to name some is the investigation of control parameters' impact on the ABC algorithm's convergence speed and performance [224]. Dervis Karaboga, et al, (2009) did a comparative study on the ABC algorithm's performance with DE, PSO, GA and Evolution Strategy (ES) with the aid of a large set of unconstrained test functions. The results concluded that ABC algorithm's performance is on a scale higher than the relevant algorithms despite the fact that less-control parameters were used, thereby effectively solving multi-modal and multi-dimensional optimization problems [226]. The results confirmed that the ABC algorithm's performance is better than those of relevant algorithms. Despite this, Hany M. Hasanien, et al, (2012) presented a beneficial design procedure for controller used in the frequency converter of a variable speed wind turbine (VSWT) driven PMSG with Genetic Algorithms and response surface methodology (RSM) [227]. S.L. Ho, et al, (2004) recommended a mesh less technique centered on connection with radial basis functions (RBFs) and wavelets. This proposed method avails the full advantage of RBFs and wavelets. In the context of consistency and linear independence, the bridging scales are used in order to preserve the mathematical properties. To validate this proposed method, a numerical example is utilized [228]. Chang-Hwan Im, et al, (2003) proposed a hybrid genetic algorithm (GA) for the optimization of electromagnetic topology. A two-dimensional (2-D) encoding technique taking into consideration the geometrical topology is firstly applied to electro-magnetics. Later for the crossover operator, a 2-D geographic crossover is

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used. To improvise the convergence characteristics, an innovative local optimization algorithm called as on/off sensitivity method, hybridized with the 2-D encoded GA is used. The results have been published after verifying the algorithm to the various case studies [229].

27. Novel Topology Development in PMSGs.

Johannes H.J. Potgieter discussed the evaluation of low maintenance slip-synchronous permanent magnet wind generator, which is based on the concept of a permanent magnet induction generator. The permanent magnet induction generator (PMIG) concept on which the slip-synchronous permanent magnet generator (SS-PMG) is based upon was first introduced by Punga & Schon (1926). This generator consists of a conventional stator winding and induction machine cage-rotor, with a second free-rotating PM-rotor added to the design. This second PM-rotor runs at synchronous speed, with the cage-rotor operating at a relative slip speed with regard to the PM rotor and rotating synchronous stator field. This generator is a gearless, directly grid connected wind turbine generator, which means that no behaviour or power electronic converter is needed in the drive train. Md Rabiul Islamn, et al, (2014) summarized large-size wind turbines which are able to generate more electricity at lower cost compared to the smaller turbines. This is because the set-up costs and maintenance costs do not depend on the size of the machine. Due to this, the output power of today's wind generators has exceeded 7 MW. For example, since 2011, Enercon has been producing a wind turbine E-126/7500 with a power capacity of 7.5 MW. Currently, Sway Turbine and Windtec Solutions are developing 10 MW wind turbine generators, which are expected to be commercially available by 2015[18]. In Table 15 exemplify for voltage ratings of generators.

Table 15. Summarizes the voltage ratings of a few common wind turbine generators [18].

Turbine Power (MW)	Voltage (V)	Model	Manufacturer
1.50	575	1.5SLE	GE Energy
1.65	690	Wt1650	Windtec
2.05	575	MM92	Repower
3.00	400	E-82 E3	ENERCON
5.00	690	Brad 5.0	Bard Engineering
5.50	690	Wt5500	Windtec
10.00	690	SeaTitan	Windtec

Ying Chen, et al, (2011) proposed an innovative model of Surface-Inserted Permanent Magnets Synchronous Generator, with adjustable air slots in the rotor. This model improves the PMSGs predominant disadvantage of fluctuating regulating voltage [181]. On a comparative analysis done between superconducting machines and conventional machines, the former have advantages such as lighter, compact, efficient and supports significantly stable operation in power system over the latter [35]. El Hadj Ailam (2007), used eccentricity topology which promises an increased power density, and is used for the design, construction and testing on an eight pole superconducting rotating machine. Also, estimation derived from Magnetic scalar potential from a Coulomb formulation by Markov Chain Monte Carlo (MCMC) method and the calculation of the flux density with the help of derivation from regularization method is discussed. In order to minimize the computation time, MCMC method is employed which, in turn, enables the magnetic scalar potential calculations in selective regions of discrete geometry. With the use of YBaCuO high-temperature superconducting (HTS) bulk plates, low temperature superconducting NbTi wires are used for generating a high magnetic field. To enhance the cooling operation, the superconducting machine possesses a stationary superconducting inductor and a rotating armature which is wound with copper wires [35]. Mohammad S. Widyan (2012), detailed on the difference between construction and arrangement of active materials for transversal-flux machines from radial and axial ones. Lower stator copper losses are attained by increase in windings space without impacting the available space for flux in the transversal flux. Due to the sophisticated electromagnetic structure, transversal-flux machines are actually expensive [37]. Suhail Zaki Farooqui, et al, (2012), proposed a unique low-fare methodology introduced for making wind turbine electric generator from the burnt-out squirrel cage induction motors. The general properties required for a wind turbine generator are firstly discussed and the methodology of its workability, multi-pole, low-speed, PMG is discussed later. A comparative analysis on cost and performance is performed with the test results obtained from a 500W generator at 900 RPM and a 1,500W generator at 650 RPM [42]. Estanislao Echenique Subiabre, et al, (2011) with the help of Finite Elements and Equivalent Circuit Modelling, estimated the efficacy of an Air-Cored PMSG. Air-cored machines in wind energy are an emerging trend. Iron is not present in the stator instead the magnets which is held by rotor is made up of mild steel. At zero load, the two-sided axial-flux air-cored machine's flux path could be viewed as a constant magnetic flux crossing axially from a magnet on one rotor to the opposite rotor's facing magnet. The coil which is held by the stator is held on a plane in between the 2 sets of magnets [43]. Salem Alshibani, et al, (2012) proposed an alternative viable solution to the conventional PMSGs at MW level in the direct-drive wind turbine applications via Halbach array. In order to yield the maximum benefits of the Halbach array, machine dimensions should be optimized. This paper provides an insight into the Halbach array application's calculation by analytical equations prevalent in the technical literature. Superior performance was also attained by permitting specific modifications of an existing PMSG design where the magnet volume is maintained a constant. Conventional array is valued more than the Halbach array when critical rotor radius is taken into consideration. To shift in the critical radius to larger sizes was made possible by increasing the number of poles thereby permitting a positive utilization of the Halbach array at a MW level. The analytical equation findings are verified by the FEA simulation. Jae-Seok Choi, et al, (2008) by utilizing the numerical optimization method which is based on Finite element analysis, a Halbach magnet array is designed. Each element's magnetization direction is defined as the design variable. To increase the attractive, repulsive, and tangential magnetic forces between magnetic layers, the optimal magnet arrays which are composed of two and three linear magnet layers are investigated. A torsional spring comprised of two and three magnet rings accepts the tangential force that is maximized by the magnet array. Some optimization techniques, such as Sequential linear programmeming and the adjoint variable methods, are employed in the two dimensional finite-element analysis [225]. In [53] (who?) presented a study done theoretically of the magnetic circuit for a longitudinal flux PM synchronous linear generator. To analyze the performance of the machine, a coupled field and circuit model solved by a time-stepping finite-element technique is used [53]. Stéphane Brisset, et al, (2008) presented a comparative study of various configurations of an axial-flux nine-phase concentrated-winding PMSG for direct-drive wind turbine [61]. Johannes H.J. Potgieter, et al, (2012) interrogated on different prototypes. One such prototype decisively states that the slip PMG unit's active mass in a SS-PMG which could be curtailed considerably. Evaluation is also done on various slip-PMG concepts. In particular, a considerable minimization in active and PM mass is feasible for the novel brushless –DC winding slip-PMG as contrast to the non-overlap winding configurations. Also, it is exhibited that Aluminium can substitute copper, thereby not increasing the slip-PMG's mass without impacting the performance along with the machine cost [58]. SorinVlăsceanu Alecsandru Simion, et al, (2012) considered the low-speed three-phase generator with external rotor topology for the study. In order to obtain the sinusoidal induced voltages in the windings of the stator, the PMs in the rotor structure and adopted direction of magnetization are arranged appropriately [62]. JIN Wan-bing, et al, (2006) presented an insight into the basis of a conventional PMSG's construction, a new breed of Hybrid Excitation Permanent Magnet Synchronous Generator (HEPMSG) is presented by inserting exciting winding in rotor or stator [67]. D S More et al (2008) presented the Flux Reversal Machine (FRM) with a doubly-salient stator permanent magnet machine with flux linkage reversal present in the stator concentrated winding. Comparative analysis is conducted on Full pitch winding flux reversal machine (FPFRM) and conventional concentrated stator pole winding FRM (CSPFRM) on the design which reveals that the former has a higher power density than the latter. To replace the standard claw pole alternator, single-phase FRM was firstly introduced by Deodhar, et al, (1997) in an automobile application with its advantages being simple in construction, low in inertia, and high

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power density. Wang, et al, (1999) introduced three-phase FRM [68]. The distributed winding for flux reversal machine (FRM) was studied and proposed by D.S.More, et al, (2010).

FPFRM provides a high-power density and improves the efficacy. The Flux reversal machine (FRM) has the merits of both Switched Reluctance Machine and Permanent Magnet (PM) machine. FRM is a doubly-salient PM machine with concentrated windings. To obtain the induced EMF, flux linkages and winding inductances, FEM analysis is carried out. Both the machines' inductance is received by winding function strategy and comparison is done with FEM results. Based on the fictitious 'electrical gear', power density comparison of CSPFRM and FPFRM with PMSM is made. For different FRM configurations, gear ratios are provided. It is observed that FPFRM topology is appropriate for low speed low power applications as the Power density of compensated CSPFRM is 1.236 times higher than PMSM, but the power density of compensated FPFRM is 2.45 times higher than PMSM which shown in Table 16 [130].

Table 16. Comparison of CSPFRM, FPFRM and PMSM.

	CSPFRM	FPFRM	PMSM
KVA	1.92	2.88	1.4
copper weight, kg	4.9	11.6	4.4
core weight, kg	37.51	37.51	41
PM weight, kg	1.1	1.1	1.1
compensating capacitor, kVAr	3.183	10.32	0.91

A.B. Zakharenko et al (2007) presented low-revolution magneto-electric generators which are specially designed for use in wind power engineering. The most effective way to reduce own drag torque, with an insignificant decrease in the EMF and the preservation of the magneto electric machine design's adaptability to manufacturing, is to implement a rake of magnets. The optimal alternative is the one in which the rake of the magnets situated outside and inside of the rotor inductors is approximately equal to the width of spline way slots found inside and outside of the stator[72]. Xikai Sun, et al, (2009) proposed an optimal design method of a double-layer permanent magnet (PM) Dual mechanical port (DMP) machine for wind power application with random low-wind turbine speed input and constant high synchronous speed output, compared torque between outer-rotor and inner-rotor. Also, comparison is done for the variations of THD with pole arc co-efficient for inner-rotor and stator winding [82]. In order to address the potential challenges of dimension, reliability and cost, Shao Zhang, et al, (2011) recommended a multi-generator architecture. It is suggested that 2 PMSGs must be shared with one shaft which is driven by the turbine. From the 2 PMSGs, outputs are obtained, rectified to be connected in series and intermediate DC chopper and back-end inverter are supplied with the same [84]. T.F. Chan, et al, (2012) presented a study on the new form of transvers and axial-flux PMSG's magnetic field. In an unique machine configuration, like the rotation, the main flux flows in the transverse direction [86]. Jiangui Li, et al, (2010) came up with a new Outer Rotor–Permanent –Magnet (PM) Vernier (OR-PMV) machine for direct-driven wind power generation, which offers operation at low speed so as wind power could directly captured and enabling the high speed rotating field design so as to maximize the power density [89]. Juan A., et al, (2003) presented Consequent-Pole Permanent-Magnet Machine's (CPPM) operating principle. Alongwith that sizing analysis, Finite element analysis and results derived from the experiment pertaining to a prototype machine are addressed. CPPM machine possesses various advantages with the main one being controlling the air-gap flux level without the risk of the demagnetization from the magnetic pieces. On the low-reluctance iron poles, control action could be performed. Alongwith the low field AT requirement, a broader spectrum of air-gap flux control is also yielded which could be utilized to increase or decrease the air-gap flux [91]. Alberto Tessarolo, et al, (2012) with the aid of the winding functional theory, detailed to figure out the multi-phase synchronous machine's inductance, furnished with a PM or a wound field rotor. The solution offered by the three magneto-static simulations conducted on simplified machine geometrical models enables in the accurate determination of the permeance

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function. The aforesaid method is used for the stator phase inductances, phase-to-field inductances and PM flux linkage calculations. For the appropriate implementation in numerical machine models pertaining to dynamic simulations, machine inductances relevant Fourier-series expansion is proposed [109]. Weimin Wang, et al,- (2011) presented an innovative interpolating strategy for air-gaps through antiperiodic boundary condition when applied to AFPMSG. By using coupled-circuit, time-stepping, element analysis, AFPMSG's performance is studied at isolated load. Investigation is also performed on short-circuit's performance. To yield accurate analysis result, the second-order serendipity quadrilateral elements are used [116]. Ying Fan, et al, (2006) offered a novel three-phase 12/8-pole doubly-salient permanent-magnet (DSPM) machine for use of wind power generation which, in turn, is used to design and investigate the recommended DSPM generator, namely, the design of a new machine structure so that high power density, high robustness and high efficiency is attained in the device of system operation. FEM has been used the proposed generator's static characteristics are obtained [117]. Johannes H. J. Potgieter, et al, (2012) handled the modelling, design, and the construction of a new idea slip-synchronous permanent magnet (PM) wind generator for the direct-drive direct-grid connection. The proposed generator is a variation from the conventional PM induction generator perception as derived from the literature, where the usage of non-overlap winding is proposed for the first time for the type of generator proposed. For the effective design of the generator, a blend of analytical, finite element calculation and optimized design methods are employed. In the design optimization, the critical design parameters like Load torque ripple and no-load cogging torque should be minimized to the absolute minimum. Verification of modelling and the design is done using measurements on a 15-kW wind generator system prototype [118].

Thierry Lubin, et al, (2007) under linear condition conducted a comparison of the prediction of the following two methods to calculate the electro-magnetic torque with inductances of a synchronous reluctance machine.

1 Winding function analysis (WFA)
2 Finite-element analysis (FEA).

Rotor geometry, stator slot effects and the stator winding connections are taken into consideration in the aforesaid methods. WFA simulation results are compared with the two dimensional FEA and provides the same results. The winding function method extends considerable simplicity, lesser computational costs, and is faster in case of magnetic linear condition [164]. Fu Xinghe, et al, (2009) offered the analyses conducted on Hybrid Exciting Synchronous Generator (HESG) along with specific structure and operating principles. A PM generator takes needed upkeep for the main output whereas a homo-planar inductor alternator works on regulating the terminal voltage. 3-D FEM is used to perform the EMF computation and performance analysis of HESG [166].

28. Control Mechanism for WECSs.

WECS employs multiple control mechanism. Control system, statistical wind distribution, and aerodynamic efficacy are vital parameters to be considered during a generator's design as it is a decisive factor to assess the performance. In this particular application, high overload capacity generators are considered for the study. It has been concluded that to attain a high overload capability, the generator should be optimized for losses that are minimal [38]. Karin Thorburn, et al, (2006) offered Time-stepping FEA pertaining to variable speed synchronous generator along with a rectifier. This model keeps up the speeds of the bi-directional alternator speeds, since the application is a linear generator with respect to the ocean wave energy conversion [176]. The predominant objective of the wind power generation systems is to excerpt the maximum amount of wind energy and its conversion of electric energy. This could be attained by placing the needed control structure that permits the operation range and the right algorithm of the stable system with Maximum Power Point Tracking (MPPT). The MPPT's objective lies in excerpting the maximum energy by adjusting the system's operating point which is then controlled so that the fullest power

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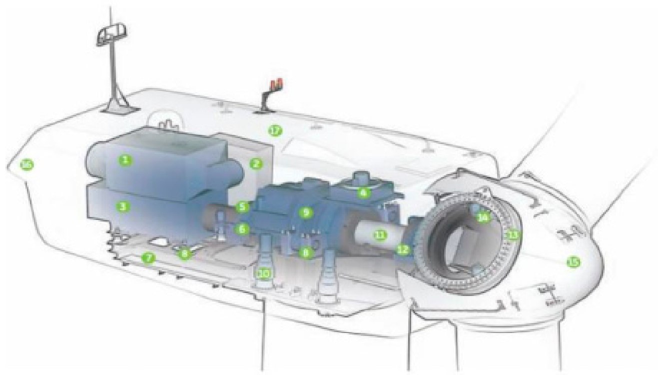
is obtainable from the wind [96]. Sadegh Ghani Varzaneh, et al, (2014) proposed the output power fluctuations of the wind farm, which causes many problems in the power system. The fluctuations of the output power are compared with the conventional schemes and influence the proposed schemes. However, in the proposed scheme, the optimal rotational speed is tracked in such a way that the output power is smoothed . The conventional vector control has been replaced with a fuzzy PID controller and as a result, the optimal rotational speed of the turbine has been tracked and the output power of the wind farm has been smoothed [33]. Keyuan Huang, et al, (2009) introduced the modelling of the system design and control approaches for a 2 MW direct-driven PMSG which is fed by means of parallel-connected full power back–to-back PWM converters. It is imperative that optimal generator design and electromagnetic FE analysis are performed for the application with respect to wind generation [46]. O.Carranza, et al, (2013) offered a control structure pertaining to wind energy systems which is based on the PMSG. In order to improvise the robustness and reliability the best structure is determined by speed and torque control which is obtained by the analysis of the conventional control structures using variable speed and fixed pitch wind energy generation systems [96]. Duc-Hoan Tran, et al, (2010) offered a detailed design and experimental approach of a completely passive wind turbine system excluding the active electronic part (power and control). The devices' efficacy largely depends on a rigid condition where the design parameters of the system are reciprocally adapted by means of an integrated optimal design methodology, which targets parallel optimizing the extraction of wind power and the losses due to the global system for a provided wind speed profile, thereby decreasing the wind turbine generator's weight. Optimal PMSG for passive wind turbines critical features like geometric and energetic features are obtained by the aforesaid approach [188].

In Figure 10, the illustration describes the general scheme of a typical variable-speed direct-driven PMSG wind turbine connected to the grid distribution.



Source: ReGen Powertech [262]

Figure 10. Typical variable-speed direct-driven PMSG wind turbine

29. Conclusions

In this review paper presented, several comparisons with current literature and approaches have been discussed. The conceptual framework is outlining the research challenges that will now drive the proposed work of design and analysis of PMSGs for WECSs. Its expected impact and preliminary results will spearhead the progress beyond the state-of-the-art envisioned research. The literature encompasses the history of WECSs, classification of wind turbine and generators schemes, and types of PMSGs technologies. The application of the FEM is integrated with electric and magnetic phenomenon. The PMSG's designs and optimization problems can be solved by a solution in the field computation techniques which have been discussed. The same which could be obtained using Soft Computing (SC) techniques are applied for the optimal design methodologies of the PMSGs are reviewed. The three-dimensional CAD software package for the analysis and design of PMSGs have been discussed, also bearing the cost factor in mind. To retrospect, the literature exploration has identified myriad problems in the developmental perspective way forward.

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