Effect of Grid Faults on Dominant Wind Generators for Electric Power System Integration: A Comparison and Assessment

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***Abstract* — In recent times, various types of wind generators have been linked to the power grids globally and the focus has been to control them to be more efficient and reliable. This study concisely discusses performance analysis, modeling, and assessment of different wind generators (permanent magnet synchronous generator, doubly-fed induction generator, squirrel cage induction generator), covering their benefits, drawbacks, and impact on the electric power systems. This comparison aims to guarantee that their technical and economic evaluations are comparable, allowing engineers to make a more informed decision about which generator is best suitable for their installation. Findings for the investigated wind generators lead to significant observations about their application fields, such as permanent magnet synchronous generator outperforms doubly-fed induction generator and squirrel cage induction generator, especially during grid disruptions; on the other hand, squirrel cage induction generator is simple and inexpensive.**

***Index Terms*: doubly-fed induction generator (DFIG), modeling, power system disturbance, permanent magnet synchronous generator (PMSG), squirrel cage induction generator (SCIG), wind generators.**

Abbreviations

WG - wind generator
PMSG - permanent magnet synchronous generator
DFIG - doubly-fed induction generator
SCIG - squirrel cage induction generator
RES - renewable energy sources
WT - wind turbine
NN - neural network
EST- energy storage tools
FACTS - flexible alternating current transmission system
FLC - fuzzy logic controller
WECS - wind energy conversion system
VSWG - variable-speed wind generator
FSWT - fixed-speed wind turbine
GSC - grid-side converter
VSC - voltage-source converter
IGBT - insulated-gate bipolar transistor
MSC - machine-side converter
MPPT - maximum power point tracking

I. Introduction

Renewable energy use has risen dramatically in current years all around the universe. The large-scale integration of renewable energy sources (RESs) into electrical grids has resulted in significant changes in power production technologies. This progress has been made possible by more effective management and enhancement of the electrical components, both of which have contributed to the improvement of the quality of the power delivered [1]. RESs offer a great potential to help certain regions grow sustainably while also giving a lot of socioeconomic advantages. Diversity of electricity supply, environmental sustainability, and the establishment of new industry and business possibilities are among the RES advantages [2, 3].

Due to the international agreements achieved, we might be witnessing the rupture of the link between electricity generation and CO2 emissions nowadays [4]. As seen in Fig. 1, more than a 50% increase in the global electricity demand is expected by 2030, while the amount of CO2 released by this sector remains stable. This can be a turning point since increments in electricity consumption have always been coupled with proportional rises in CO2 emissions. This switching is a consequence of the expected and necessary transformation in the electrical energy sector. Around 70% of the new electricity generation units are projected to be low-carbon technologies raising the total share of these sources to nearly 45% of overall generation by 2030 [4]. Inevitably, RESs have a central

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http://dx.doi.org/10.38028/esr.2021.03.0007
Received September 26, 2021. Revised October 11, 2021. Accepted October 23, 2021. Available online November 28, 2021.

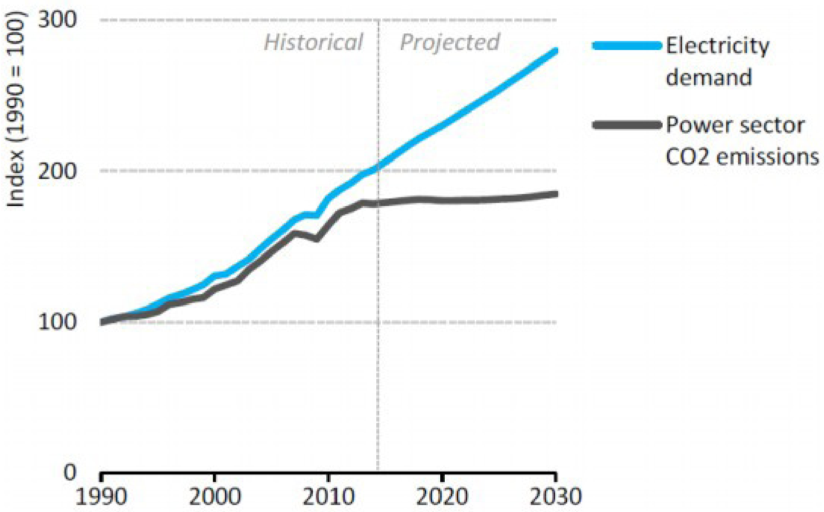


Fig. 1. Growth in world electricity demand and related CO2 emissions since 1990 [4].

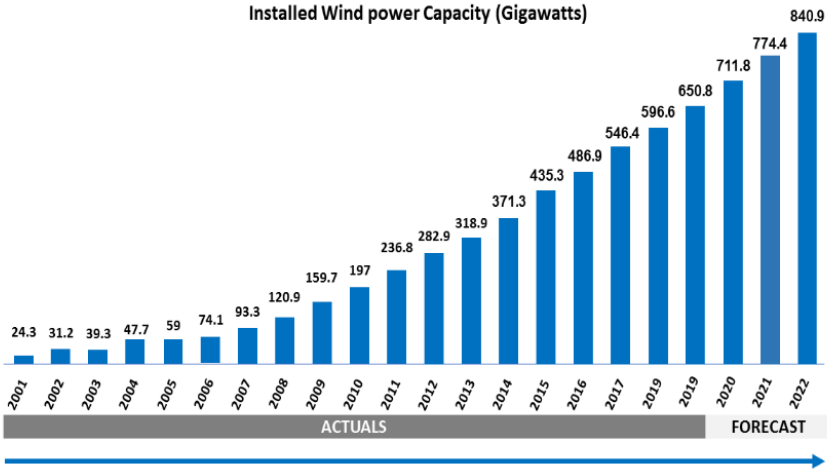


Fig. 2. Global installed wind power capacity.

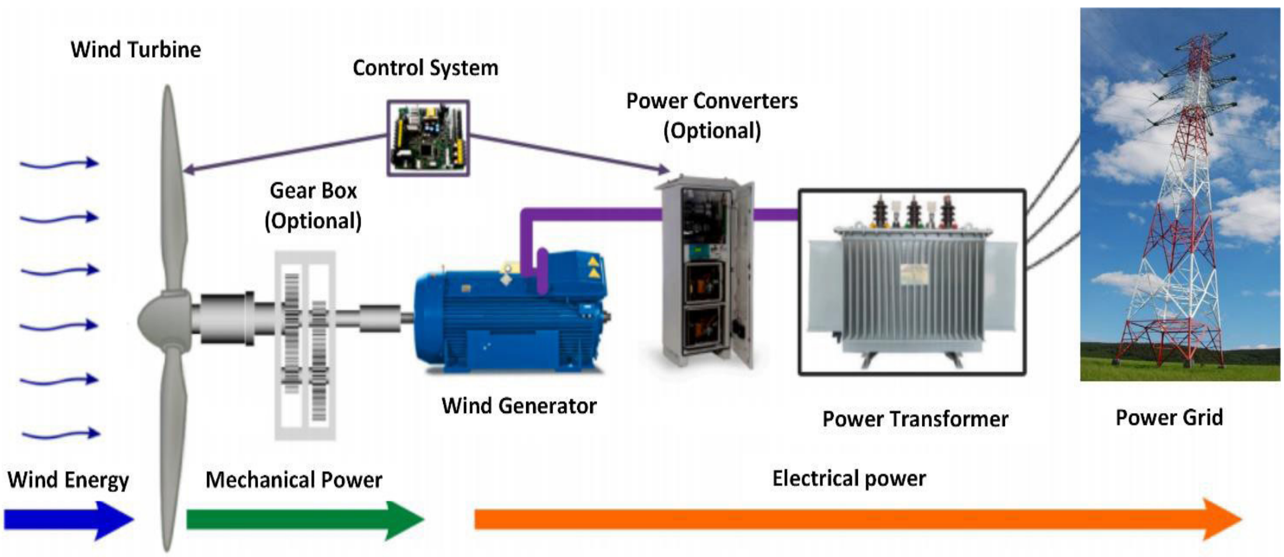


Fig. 3. General working principle of the WECS operation

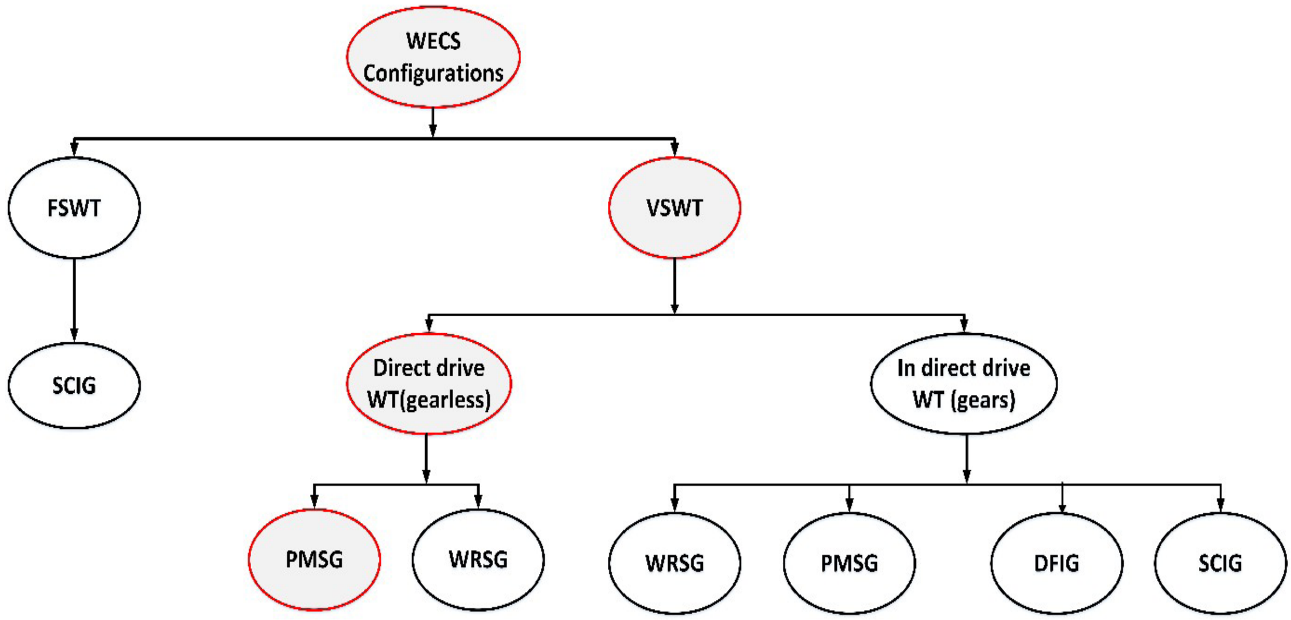


Fig. 4. Classification of WECS.

role to play here. For instance, estimations of 4 000 % and 1 000% growth in the total final energy consumption share of solar PV and wind generators (WGs), respectively, were reported in the literature [5]. Compared with other RESs, wind energy is inexpensive, produces energy with negligible environmental impacts, and is more dependable. The wind power capacity installed globally from 2001 to 2022 is shown in Fig. 2 [6].

The study of wind speed and other wind characteristics in a given location is critical for building wind turbines (WTs) on land or in the water. The Weibull is particularly useful for analyzing the data of wind velocity probability density in WT systems. In addition, data from the fluctuation of average wind speed can be obtained by applying Prandtl's law. Nevertheless, different technologies and existing WT designs should be considered to select the one that performs well in a specific application. Wind energy is a plentiful resource given by mother nature [7, 8]. Furthermore, the worldwide availability of this sort of RES makes it suitable for autonomous energy production. Old WGs operate at a fixed speed, while modern WGs can operate at variable speeds and meet the new grid requirements [6].

Various software and hardware solutions have been used for improved and efficient operation of the grid-connected WGs. The software schemes include PI-optimization methods, FLC and its modifications, and neural networks (NNs) [9, 10]. Complex nonlinear troubles can be solved using some heuristic methods with minimal computational time but with poor accuracy solutions [11, 12]. Hardware approaches are based on energy storage tools (ESTs), FACTS tools, or a hybrid of both to improve the grid integration capabilities [13].

The purpose of the study provided in this paper is to compare and evaluate the most popular WGs currently existing in the market. In addition, the influence of grid faults on various WGs has been studied, and their benefits and drawbacks are provided to aid researchers to more deeply understand their actions during grid fail. The assessment of WGs carried out in this study is to assist the researchers in selecting the most appropriate WG for their specific use.

This paper can be outlined as follows. Section 2 presents the characteristics of SCIG, DFIG, and PMSG with the operating concept of WECSs. Section 3 focuses on the mathematical model of the WT system and the aforementioned WGs. The advantages and disadvantages of WGs under investigation are discussed in Section 4, while the local grid implications on the three major WGs are summarized in Section 5. Section 6 assesses the studied WGs. The major concluding remarks are presented in Section 7.

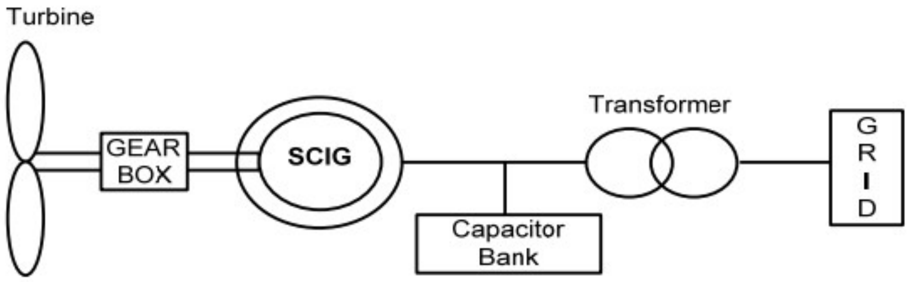
II. Configurations of dominant wind generators

Advanced technologies are being applied to WECSs to make them more effective and achieve the grid necessities. This study concerns the three most common WGs, which are SCIG, DFIG, and PMSG.

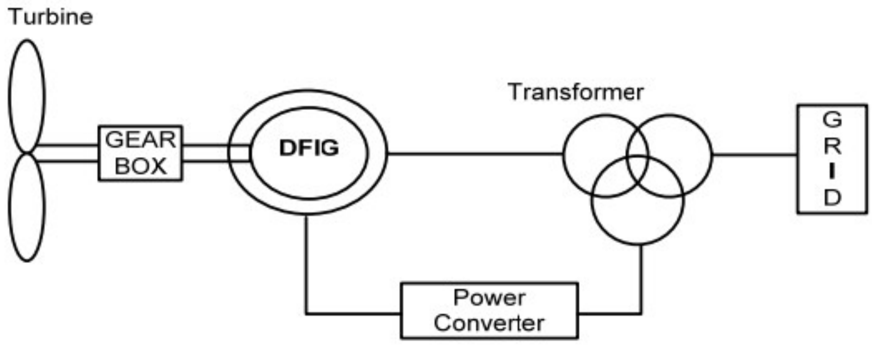
1) *Working principle of WECS*

The working principle of the WECS involves two stages. In the first stage, the kinetic energy in the wind is being captured and converted into mechanical energy through the blades of the aerodynamic WT rotor. The second stage is electromechanical power conversion, which employs an electrical generator that converts mechanical energy into electrical energy to be transmitted to an electrical power grid [14]. This is the general principle of operation, and it is shown schematically in Fig. 3.

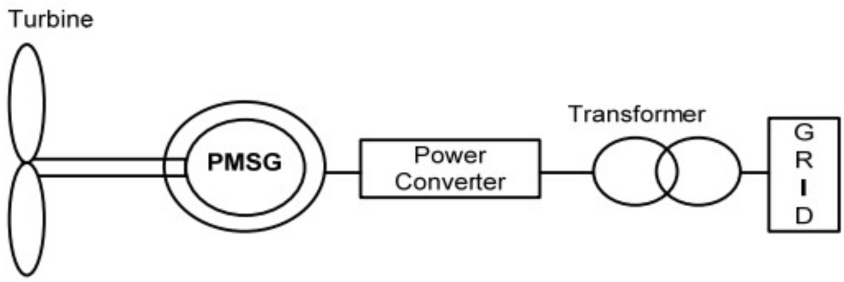
2) *Classification of WECS*



(a)



(b)



(c)

Fig. 5. Generating systems used in WECSs: (a) SCIG, (b) DFIG, and (c) PMSG.

Based on their operational speed, WECSs can be classified into two main categories: fixed speed WTs and variable speed WTs. Moreover, they can also be subdivided into many different types based on their ability, reliability, efficiency, performance, and minimal cost [14]. Fig. 4 shows the classifications of WECSs. As regards the construction of their generating system, almost all of the currently mounted WTs use one of the configurations shown in Fig. 5.

a) SCIG technology

SCIG is the first electrical generator used to generate electrical power by capturing the power of the wind. The output of SCIG is used to be directly connected to the power grid through a power transformer, which results in its rotor speed varying slightly according to the amount of power needed by the grid. However, these variations are as small as 1 to 2% of its rated speed. Accordingly, it is often called a constant speed or FSWT. Impressively by altering the number of pole pairs of its stator winding, the SCIGs, equipped with WTs, can run at two completely different (but constant) speeds. SCIG needs a continuous supply of reactive power for its operation, which is undesirable, especially when it connects large WTs to weakened grids. Thus, capacitors play a significant part for SCIG by supplying fully or partially the amount of reactive power needed for the generator to achieve unity or near-unity power factor. There are considerable hazards related to this generator, i.e., the power captured from the wind is

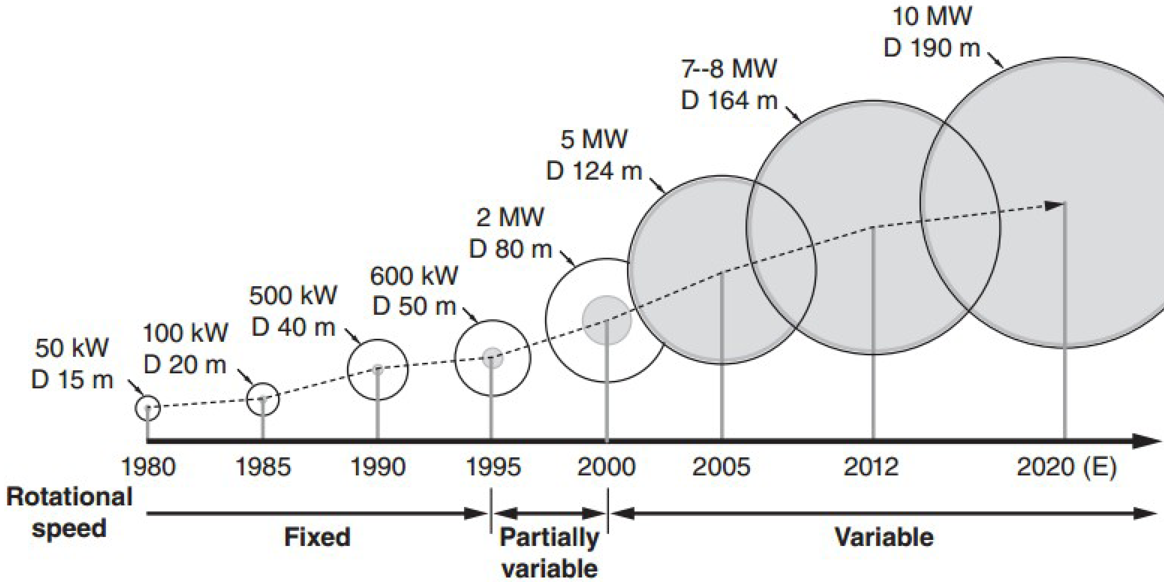


Fig. 6. State-of-the-art development – wind generators.

sub-optimal, it is exposed to danger due to self-excitation for the period of the power grid interruption, and reactive power compensation is required [15].

b) DFIG technology

DFIG is viewed as a starting point for the VSWG because its mechanical rotor speed can be easily decoupled from the power frequency of the electrical power grid. This can be achieved by using a power electronic converter to feed 3-phase power to the DFIG rotor windings, as shown in Fig.5. In this way, the mechanical and electrical frequencies of the rotor can be decoupled, and consequently, the electrical frequency of the rotor could be aligned to its stator counterpart and independently of the rotor's mechanical speed. Change in the DFIG's rotor resistance can result in a shift of the torque/speed characteristics of the generator and an increase in transient rotor speed of about 10% of the nominal rotor speed [15].

c) PMSG technology

PMSG is the first generator to make a complete benefit of the power electronic converters to be decoupled from the power grid. The used GSC is a VSC, i.e., IGBT bridge. The MSC can be either a VSC for a large scale, in MW, or a diode rectifier for a small scale, in kW. It is characterized by self-excitation, simple structure, high power density, low maintenance, absence of gears, good controllability, and full-scale power electronics interface. It is one of the most attractive and promising WGs due to its reported merits [12, 16].

SCIG, DFIG, and PMSG represent about 97% of generators in the market these days. It is clear from Fig. 6 that before 1995, WGs had been based on FSWTs due to their simplicity and low cost, but their main drawback is the need for reactive power to assist voltage support. In 1995–2000, DFIG became the dominant sector due to its merits like reduced cost and the presence of power electronic converter. Due to the problems with the earlier two WGs, PMSG is currently the major WG that can meet MPPT and new grid code requirements. The main cause of the rapid growth of VSWTs is the advance in power converters technology [17, 18].

III. Modeling of dominant wind generators

1) WT model

The WT model can be articulated as follows [12, 13]:

$$Cp(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\exp^{-\frac{21}{\lambda_i}} + 0.0068\lambda\,,$$

$$\lambda = \frac{\omega_r R}{V_W},$$

$$T_m = \frac{P_m}{\omega_r},$$

$$T_m = J_{eq}\frac{d\omega_r}{dt} + B_{eq}\omega_r + T_e\,,$$

where, Cp, λ, ω_r, J_{eq}, B_{eq}, T_e, T_m are the studied WT parameters defined in [12].

2) PMSG model

The PMSG's concept is fully defined in [12] and can be represented as follows:

$$V_{ds} = R_s I_d + \lambda_d - \omega_e \psi_q,$$
$$V_{qs} = R_s I_q + \lambda_q - \omega_e \psi_d.$$

The stator flux connection components can be written as:

$$\psi_d = L_d I_d + \psi_{pm},$$
$$\psi_q = L_q I_q,$$
$$\lambda_d = L_d I_d + \psi_{pm}.$$

The T_e can really be defined in the following way:

$$T_e = \frac{3}{2} n_p \left(\lambda_d I_q - \psi_q I_d \right) = \frac{3}{2} n_p \left(\psi_{pm} I_q + I_d I_q \left(L_d - L_q \right) \right).$$

For the surface-mounted PMs sort, ($L_q = L_d$). So, T_e can be written as tracks:

$$T_e = \frac{3}{2} n_p \left(\psi_{pm} I_q \right).$$

3) DFIG model

The DFIG concept is discussed and defined in [19] and can be exemplified as follows:

$$V_{ds} = R_s I_{ds} - \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs},$$

$$V_{qs} = R_s I_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds},$$

$$V_{dr} = R_r I_{dr} + \frac{d\psi_{dr}}{dt} - \left(\omega_s - \omega_r \right) \psi_{qr},$$

$$V_{qr} = R_r I_{qr} + \frac{d\psi_{qr}}{dt} + \left(\omega_s - \omega_r \right) \psi_{dr},$$

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr},$$
$$\psi_{qs} = L_s I_{qs} + L_m I_{qs},$$
$$\psi_{dr} = L_r I_{dr} + L_m I_{dr},$$
$$\psi_{qr} = L_r I_{qr} + L_m I_{qs},$$

$$T_e = \frac{3}{2} P \left(\psi_{ds} I_{qs} - \psi_{qs} I_{ds} \right).$$

4) SCIG model

The dynamic behavior of the SCIG-WG is given as follows [20]:

$$V_{qs} = R_s I_{qs} + P\lambda_{qs} + \omega\lambda_{ds},$$
$$V_{ds} = R_s I_{ds} + P\lambda_{ds} - \omega\lambda_{qs},$$
$$V_{qr} = R_r I_{qr} + P\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} = 0,$$
$$V_{dr} = R_r I_{dr} + P\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} = 0,$$

$$\begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} = \frac{1}{D_1} \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix},$$

$$\lambda_{ds} = (V_{ds} - R_s I_{ds} + \omega\lambda_{qs})/S,$$
$$\lambda_{qs} = (V_{qs} - R_s I_{qs} - \omega\lambda_{ds})/S,$$
$$\lambda_{dr} = (V_{dr} - R_r I_{dr} + (\omega - \omega_r)\lambda_{qr})/S,$$
$$\lambda_{qr} = (V_{qr} - R_r I_{qr} - (\omega - \omega_r)\lambda_{dr})/S,$$
$$D_1 = L_s L_r - (L_m)^2,$$
$$T_e = 1.5P(I_{qs}\lambda_{ds} - I_{ds}\lambda_{qs}).$$

IV. Benefits and drawbacks of the compared wind generators

Table 1 shows a comparative analysis of the three types of generators discussed in this study. The benefits and drawbacks of these generating systems are compared against each other and listed concisely in the Table.

V. Local grid impacts on the common wind generators

High wind power penetration has resulted in some noticeable local impacts on the power system, including changes in node voltage, fault currents, harmonics, and flicker [21, 22]. A comparison of these impacts and their effects on the three WGs are stated briefly in Table 2.

VI. Assessment of wind generators

Both technological and economic considerations should be addressed while selecting the kind of WG for specific conditions and applications. According to previous research, the SCIG voltage decreases most after a three-phase failure, requiring more time to recover while also using reactive power. Stator voltage and rotor speed instability may occur as a result of this. On the other hand, when a PMSG is subjected to a 3-phase fault, the

Table 1. Benefits and drawbacks of the more used generating systems.

Generator	SCIG	DFIG	PMSG
Advantages	Simple and robust	Less mechanical stress	Negligible mechanical stress
	Less expensive	Small converter	Absence of gearbox
	Electrically efficient	Aerodynamically Efficient	Aerodynamically Efficient
	Standard WG	Standard WG	Standard WG
	———	MPPT operation	MPPT operation
	———	Variable speed	Variable speed (0–100%)
Disadvantages	Achieves grid codes using costly hardware solutions only	Achieves grid codes using hardware solutions only	Achieves grid codes using either hardware or software solutions
	Aerodynamically less efficient	Electrically less efficient and affected by the grid disturbances	Heavy and large
	Gearbox is essential	Gearbox is essential	Power converter is a must
	Mechanical stresses	High cost	———
	Noise and vibration	Complex control	———
	Necessity of large and expensive compensation units	Speed varies about 30% of rated speed only	———

Table 2. Effects of grid's local impacts on the three dominant wind generators.

Local impact	SCIG	DFIG	PMSG
Changes in grid voltage	Compensation is a must, using FACTS tools or storage systems	Compensation is feasible, however, it is contingent on the converter's rating	Compensation is possible, however, it is conditional on the converter's rating
Harmonics	Hot point of research and interest, and a major issue	Less interest, and is not a major issue	Least interest, and is not a major issue
Flicker	Important, due to absence of power converters	Important, due to partial scaling of power converters	Unimportant, due to high system inertia and full scaling of power converters
Fault current sharing	Large share, due to direct connection to power grid	Small share, due to partial existence of power converters	No share, due to power converter's fault current blocking capability

grid voltage is higher than that with DFIG used. The employment of power converter units allows the regulation of reactive power during breakdowns, which helps to reduce voltage fluctuations.

Previously, if severe difficulties arose, WGs linked to the grid were typically just unplugged. Nowadays, many nations have mandated that WGs should not only stay attached but also help in the event of a severe grid outage. PMSG and DFIG are superior to SCIG in terms of meeting this criterion. PMSG can supply more reactive power to the grid during or after a failure than DFIG, and PMSG meets the additional standards better than DFIG.

Existing WGs are meant to operate for 120 000 hours through the course of their 20-year life span. The expenditures of operation and maintenance can make up 10-20% of the overall cost of a WG system. The cost of operations is determined by the number of jobs given and the size of the wind project, not by the kind of WG [23].

Since direct drive (PMSG) systems do not include a gearbox, their maintenance costs are different from those of other systems. The repair cost is higher for WGs that employ gearboxes because they have more rotating components (gearboxes) and wearing points necessitating more repair. As a result, the cost of maintaining WGs incorporating gearboxes is often 1% greater than that of PMSG systems.

As the size of WGs has grown, it becomes challenging to develop dependable gearboxes that can resist the massive pressures they must endure. As per a current survey, some WGs in a five-year-old wind farm are now on their second or third gearbox retrofit. In regions with high wind instability, such as mountainous terrain, a gearbox is more prone to wearout. For example, if a 1.5 MW WG gearbox is rebuilt at a local repair shop in the United States, it will cost between \$150 000 and \$200 000, accounting for 10% to 15% of the entire project capital cost. However, with the gearbox to be delivered and repaired outside of the United States, an additional 80% of the cost must be paid [24].

PMSG systems do not have a gearbox, therefore, this problem never arises. In this example, the overall project cost of employing these technologies is less than that of using a gearbox system. Nevertheless, if the PMSG-WG systems fail, their repair costs will also be appreciable because their primary shaft, bearings, and rotor are usually incorporated into one framework, and their scale is large.

VII. Conclusions

Wind energy is becoming more widely used globally, and several technological advances are being used to design new WGs. The three major WGs have been modeled, with grid implications studied and assessed herein in this paper. In addition, their benefits and drawbacks have been discussed. Since SCIG-WGs lack reactive power management, they are utilized only by tiny wind farms. Although DFIGs require smaller initial capital and have been deployed more widely than PMSGs, PMSGs can maintain grid voltage better than DFIGs during failures. When maintenance is factored in, all turbine models have equal long-term costs.

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