Fault Ride-Through Techniques for Permanent Magnet Synchronous Generator Wind Turbines (PMSG-WTGs): A Systematic Literature Review

Ernest F. Morgan [1], Omar Abdel-Rahim [1,2,*], Tamer F. Megahed [1,3,*], Junya Suehiro [4] and Sobhy M. Abdelkader [1,3]

1   Electrical Power Engineering, Egypt-Japan University of Science and Technology (E-JUST), New Borg El-Arab City 21934, Egypt
2   Electrical Engineering Department, Faculty of Engineering, Aswan University, Aswan 81542, Egypt
3   Electrical Engineering Department, Faculty of Engineering, Mansoura University, El-Mansoura 35516, Egypt
4   Faculty of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-Ku, Fukuoka 819-0395, Japan
*   Correspondence: omar.abdelrahim@ejust.edu.eg (O.A.-R.); tamer.megahed@ejust.edu.eg (T.F.M.)

Abstract: Global warming and rising energy demands have increased renewable energy (RE) usage globally. Wind energy has become the most technologically advanced renewable energy source. Wind turbines (WTs) must ride through faults to ensure power system stability. On the flip side, permanent magnet synchronous generators (PMSG)-based wind turbine power plants (WTPPs) are susceptible to grid voltage fluctuations and require extra regulations to maintain regular operations. Due to recent changes in grid code standards, it has become vital to explore alternate fault ride-through (FRT) methods to ensure their capabilities. This research will ensure that FRT solutions available via the Web of Science (WoS) database are vetted and compared in hardware retrofitting, internal software control changes, and hybrid techniques. In addition, a bibliometric analysis is provided, which reveals an ever-increasing volume of works dedicated to the topic. After that, a literature study of FRT techniques for PMSG WTs is carried out, demonstrating the evolution of these techniques over time. This paper concludes that additional research is required to enhance FRT capabilities in PMSG wind turbines and that further attention to topics, such as machine learning tools and the combination of FRT and wind power smoothing approaches, should arise in the following years.

1. Introduction

Climate change resulting from global warming and ever-increasing energy demands have escalated the use of renewable energy (RE) across the globe. COVID-19 restrictions implemented by nations have had little effect on renewable energy sources (RES) [1]. Renewable energy output increased by more than 3% in the first quarter of 2020 compared to the same time in 2019 [2,3]. Figure 1 depicts the production of renewable energy and its respective technologies between the years 2019 and 2021.
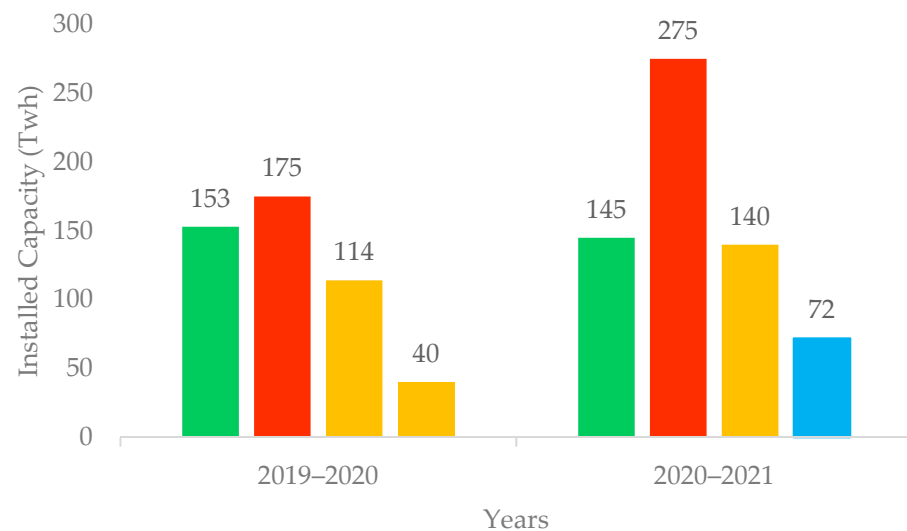
Figure 1. Renewable energy technologies in TWh with their respective years of penetration; source: authors' depiction based on IEA data [4].

As seen in Figure 1, wind energy has risen to the forefront of renewable energy sources in both capacity and technological adoption. Amidst COVID-19, the worldwide wind industry expanded by 53% in 2020, with a capacity of more than 93 GW, raising the total wind energy capacity to 743 GW, with China and the United States being the world's biggest markets, as shown in Figure 2. By 2030, the total installed wind capacity is expected to be about 1023 GW [5,6].
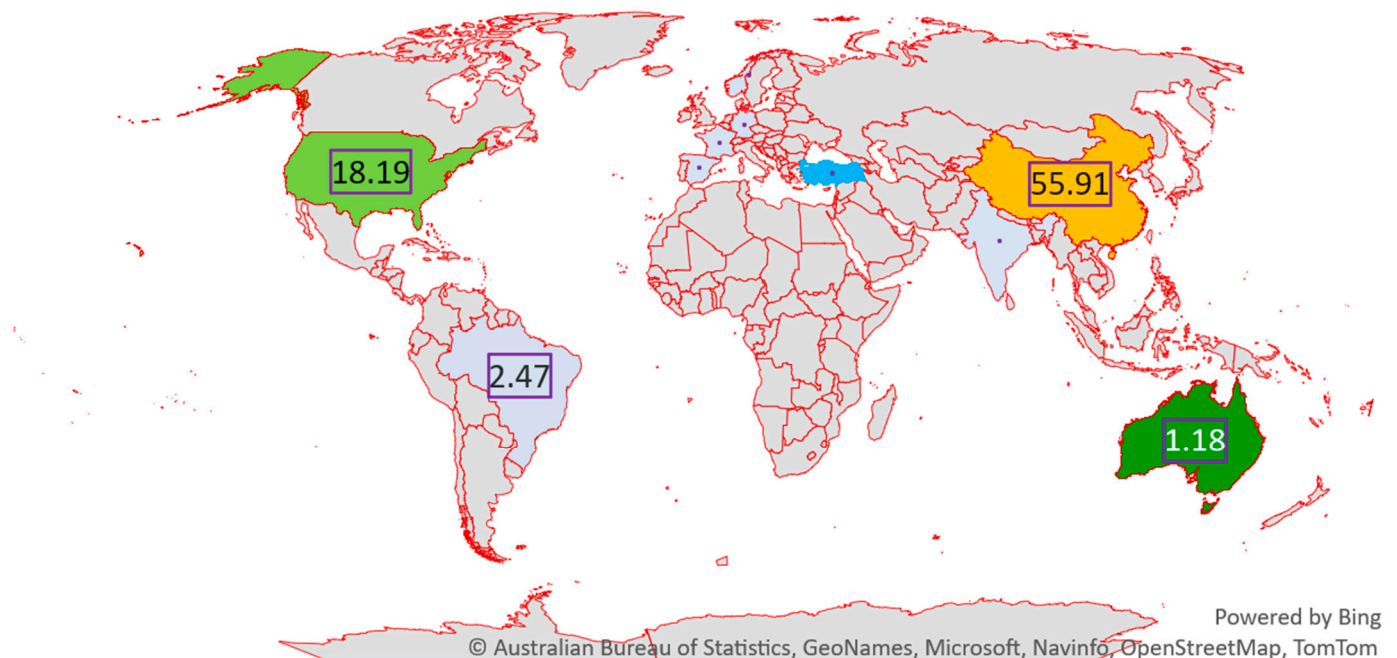
Figure 2. Global wind energy capacity and their respective countries.

Wind power facilities using squirrel cage induction generators (SCIG), doubly fed induction generators (DFIG), and permanent magnet synchronous generators (PMSG) are increasingly being added to the utility grid [7]. The impacts of wind power plants on power systems are concentrated on several problems relating to power system security, stability, and operation. Voltage control, frequency control, power control, network perturbation, and protective systems are the core aspects of enhancing power system stability [8,9].

The shutdown of large-scale wind power facilities would significantly impact the power system's transient and steady-state stability; E.ON, a German utility operator, implemented fault ride-through (FRT) standards in early 2003 to avoid the latter situation [10,11].

Direct-drive wind turbines (WTs) seldom contribute to the fault current, which could meet fault ride-through (FRT) requirements. However, they will not be able to enhance the system's voltage stability during grid voltage fluctuations. WTs must offer reactive power to the grid to keep it stable [12]. Thus, FRT is crucial for WTs in defective grid situations. WTs should tolerate grid voltage fluctuations without being disconnected from the grid. Furthermore, when the fault clears, the voltage at the point of common coupling (PCC) should reach 95% of the nominal value in 15 s and 80% in 0.5 s [6]. The FRT method is an efficient strategy for achieving the above-mentioned grid code standards regarding large-scale wind generating facilities.

The techniques of low voltage ride through (LVRT) or FRT in PMSG-based wind turbines are reviewed and compared in this research, and the remaining sections of this article are structured as follows. Section 2 discusses the literature review method. Section 3 compares WECS in brief and the mathematical modeling of PMSG-WT. Section 4 discusses modern grid codes and FRT criteria for PMSG-WTs, and Section 5 reviews various FRT methods for PMSG-based wind turbine facilities. Section 6 discusses the conclusions and observations. Figure 3 is a diagrammatic representation of the article's overall structure.
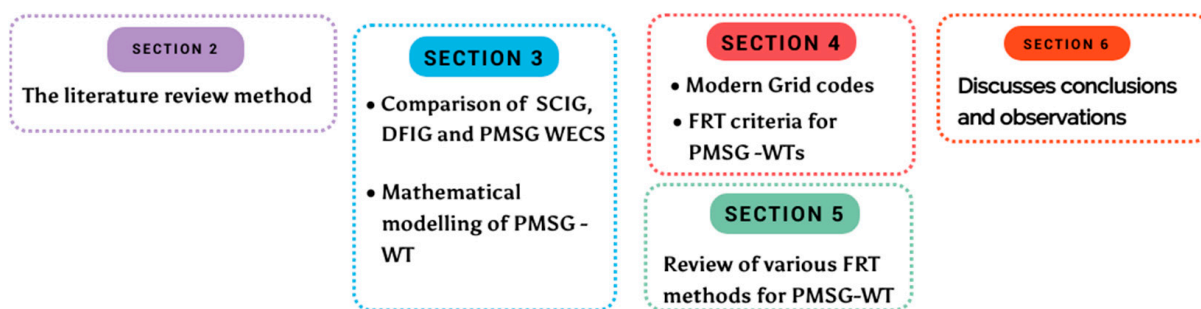

Figure 3. A diagrammatic representation of the article's overall structure.

2. Literature Review Method

In this section, a detailed bibliometric analysis is presented, and the methodology used was inspired by Barra et al. [13]. Different steps were taken throughout the study procedure. The database was chosen first. WoS [14] was selected as the database with numerous indexed impact studies in this scenario. Finally, the search equation was created with emphasis on the following keywords "LVRT" or "FRT", and "PMSG". The WOS database comprises each article's publication year, title, authors, keywords, abstract, countries, source, and affiliations. It must be stressed that only papers published in English were considered. Documents from the database are strictly limited to those that fall within the categories of review articles, articles, conference review articles, and conference articles spanning between 2018 to 2022. The VOSviewer was then used to collect the bibliometric networks once the database had been cleaned up [15]. The primary objective of these networks is to provide a quantitative analysis of the state of FRT in PMSG wind turbine generators (WTGs). An up-to-date picture of the development of FRT in PMSG WTPPs and potential directions for future study can be seen in the network of keywords. The country network depicts which nations have produced the most research in this field.

Furthermore, the most-cited sources for FRT in PMSG WTG and the nature of their co-citation relationships may be seen in the network of sources. As a result of this knowledge, a growing number of scholarly reviews have begun using these systems [16,17]. Another valuable contribution of this review study is the data included in the bibliometric analysis. Through this study, scientists in the field of FRT for PMSG WTG may locate suitable publishers for their work, establish good working relationships with colleagues from other countries, and expand their international networks.

3. Wind Energy Conversion Systems

Three kinds of generators are commonly employed in wind farms [18] as shown in Figure 4. Fixed-speed WECS are basic devices made up of an aerodynamic rotor driving a SCIG or a wound rotor induction generator (WRIG) connected by a gearbox and shaft. Fixed-speed WECS are mechanically simple, dependable, and strong. Their maintenance and electrical components are inexpensive [19]. On the contrary, mechanical stress, inadequate power quality control, and low wind energy conversion efficiency are drawbacks. The limitations of fixed-speed WECS are apparent when the scales of WECS become more prominent and the potential for wind power in the power system increases, particularly in regions with relatively weak supply grids [20]. To meet grid-code requirements, wind turbines with variable speeds are becoming common, thanks to modern power electronics converters, which link WTs to the grid. Variable-speed WECS enhance power collection, improve system efficiency, and reduce mechanical acoustic stress and noise [21]. DFIG wound-rotor induction generators are quite common in the wind sector. In DFIGs, the stator terminals are connected to the power grid, while the rotor is connected to the grid through a converter rated at about 25 to 30% of the generator's full capacity [22]. This converter separates the frequency of the electrical grid from the frequency of the mechanical rotor, allowing variable speed operation. Nonetheless, the low-speed multiple-pole used in DFIG WTs is not yet theoretically viable, making the gearbox a compulsory requirement [23]. This can lead to gear failures, resulting in low dependability and a short lifespan, making FRT requirements complex.
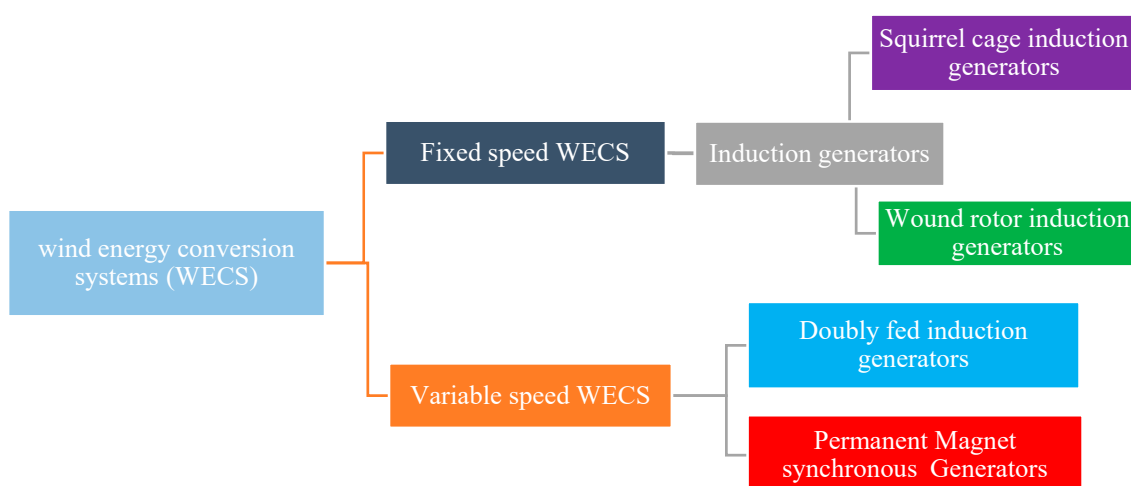
Figure 4. Types of wind turbine generators.

A PSMG is a system that does not need a gearbox as a result of using a synchronous generator that operates at a low speed yet produces high torque. A full-scale converter is also normally applied in this concept [24]. Here are some of PMSG's benefits in comparison to other types of generators:

- Due to the lack of a gearbox, maintenance costs are lower.
- Removing gears and bearings, which are the primary sources of generator failures, results in improved dependability and an increased lifespan [25].
- Lower weight.
- High energy yield and efficiency.

Because of its novel technology, it is quite expensive and less preferred.

In addition, advancements in semiconductor switching devices and enhanced reliability and efficiency are driving a surge in PMSG-based wind turbine deployment. In recent years, several global manufacturers have begun manufacturing PMSG-based wind turbines with power ratings of 1.5 and 2 MW [26]. As previously indicated, grid-side faults and

their effects on wind farm generators are some of the most significant issues requiring care in wind farms.

3.1. PMSG Wind Turbine Modeling

This section presents PMSG-based wind turbines in two parts: mechanical wind turbine features, PMSG, DC-link, and grid modeling. Figure 5 depicts a PMSG-WT scheme.
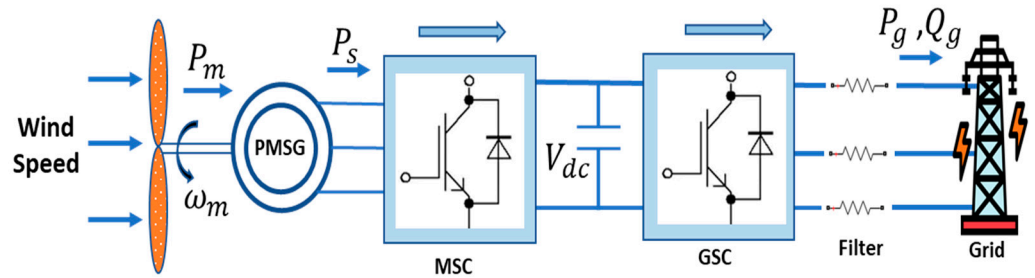
Figure 5. Schematic of a PMSG-WT.

3.2. Aerodynamic Modeling

The PMSG-WT generates mechanical power from the wind as follows [27,28]:

$$P_w = \frac{1}{2}\rho A V_W^3 C_p(\lambda, \beta) \tag{1}$$

where P_w is the captured wind power (W); C_P is the power coefficient; ρ is the air density (kg/m^3); A is the swept area (m^2); and V_w^3 is the wind velocity without rotor interference (m/s).

The wind turbine's power output characteristics are shown in Figure 6. The power coefficient of the wind turbine is associated with the ratio of the tip speed (λ) and pitch angle (β), respectively, as expressed in the following equation [29,30].

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{2}$$

where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda - 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$
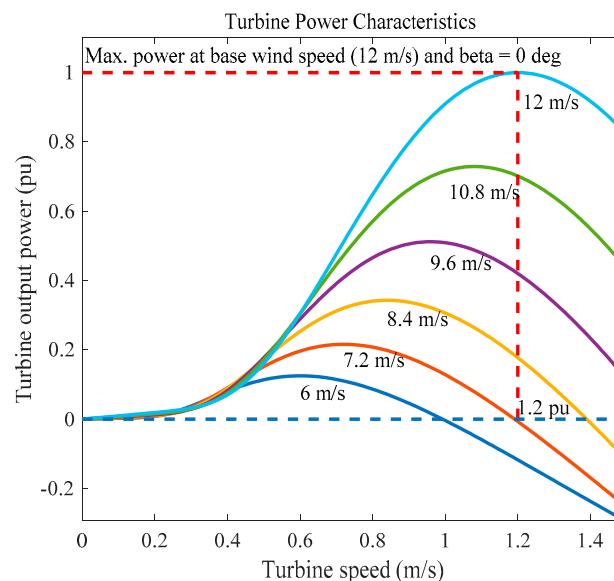
Figure 6. The turbine power characteristics curve.

In Equation (2), c_1 to c_6 are the characteristics of WT.

In the PMSG WT, the maximum power point tracking (MPPT) is associated with the rotor speed and the maximum power, as expressed in [31].

$$P_{MPPT} = \frac{1}{2}\rho A \left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 c_{popt} \tag{4}$$

where λ_{opt} is the optimal value of λ and ω_r is the rotor speed of the wind generator.

3.3. PMSG Modeling

The d-q reference rotating frame for the dynamic model of the PMSG WT is expressed as in [29]:

$$\frac{d\psi_{sd}}{dt} = -V_{sd} - R_s I_{sd} - \omega_e \psi_{sq} \tag{5}$$

$$\frac{d\psi_{sd}}{dt} = -V_{sq} - R_s I_{sq} - \omega_e \psi_{sd} \tag{6}$$

From Equations (5) and (6)

$$\psi_{sd} = (L_{sd} + L_{md}) I_{sd} + \psi_m \tag{7}$$

$$\psi_{sq} = (L_{sq} + L_{mq}) I_{sq} \tag{8}$$

where V_{sd} and V_{sq} are the stator voltages; R_s is the stator resistance; I_{sd} and I_{sq} are the stator currents; ω_e is the angular velocity; ψ_{sd} and ψ_{sq} are the stator flux linkages; L_{sd} and L_{sq} are the stator leakage inductances; L_{md} and L_{mq} are the magnetizing inductances; and ψ_m is the linkage flux of the machine's permanent magnet.

Substituting Equations (7) and (8) into Equations (5) and (6), the differential equations could be obtained as:

$$L_d \frac{dI_{sd}}{dt} = -V_{sd} - R_s I_{sd} - \omega_e L_q I_{sq} \tag{9}$$

$$L_q \frac{dI_{sq}}{dt} = -V_{sq} - R_s I_{sq} - \omega_e L_d I_{sd} + \omega_e \psi_m \tag{10}$$

$$L_d = L_{sd} + L_{md} \tag{11}$$

$$L_q = L_{sq} + L_{mq} \tag{12}$$

The active and reactive powers can be estimated using the following equations:

$$P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \tag{13}$$

$$Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \tag{14}$$

The electrical torque of the generator is given as:

$$T_e = 0.5 p (\psi_m I_{sq} + (L_d - L_q) I_{sd} I_{sq}) \tag{15}$$

For the surface-seated PMSG, we can assume $L_d = L_q$, and then T_e can be written as:

$$T_e = \left(\frac{3}{2}\right) p (\psi_m I_{sq}) \tag{16}$$

4. Modern Grid Codes

Due to the widespread use of wind energy, several grid codes mandate that wind farms remain connected to the grid despite grid disruptions while maintaining system stability [10,32–34]. As far as voltage dips and spikes at the PCC are concerned, several nations have developed new grid standards for wind farm performances. Modern grid regulations mandate that wind farms have adequate LVRT capabilities. Figure 7 shows an

example of LVRT grid code curves. Under fault situations, wind farms must stay connected to the grid as long as the voltage is still in Areas A and B. Off-grid decoupling of wind farms occurs when the PCC voltage profile enters Area C.
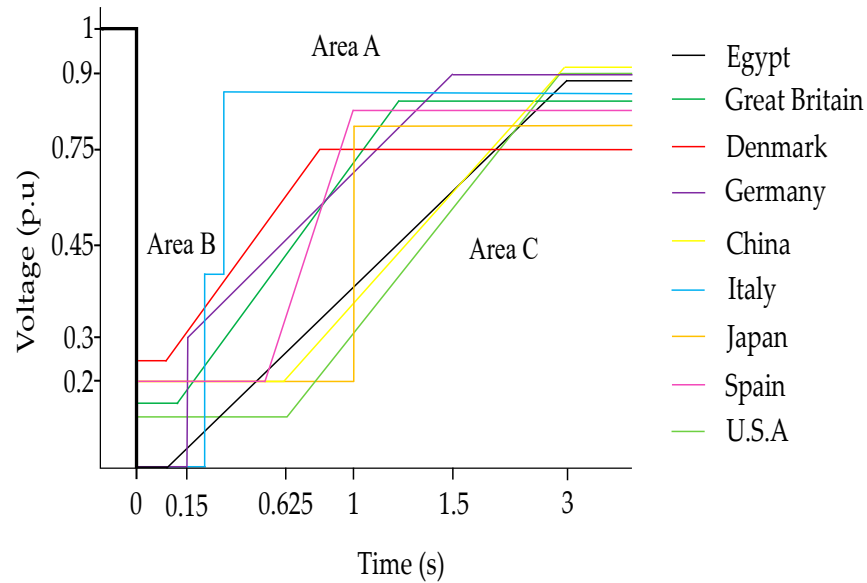
Figure 7. FRT requirements for different countries [35].

Grid codes are enforced on wind power installations to meet reactive power requirements. When the PCC voltage decreases by more than 10%, as illustrated in Figure 8, the wind farm's reactive current production should conform to the curve [36]. Equations (17) and (18) show the LVRT calculations.

$$\frac{\Delta I_o}{I_n} = K \frac{\Delta V}{V_n} \tag{17}$$

$$\Delta V = V - V_0 \tag{18}$$

where ΔI_o is the required reactive current change during the fault; I_n is the rated current; ΔV is the relevant voltage change during the fault; V_n is the rated voltage; V_0 is the pre-fault voltage; and V is the voltage during the fault.
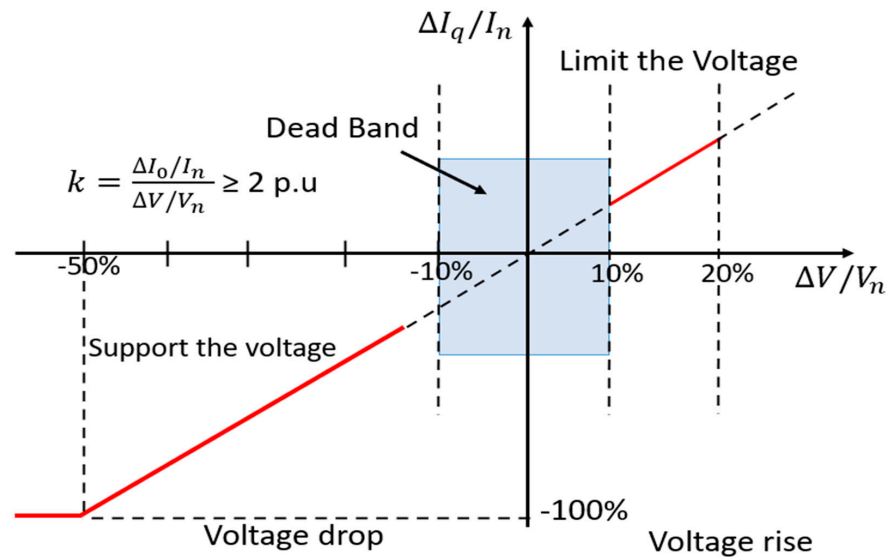
Figure 8. Dynamic reactive current regulations during the disturbance [35].

PMSG-FRT Requirements

PMSG and the WT are connected directly via a machine shaft. The stator winding of PMSG is connected to the grid through a full-scale back-to-back voltage source converter (VSC) and a transformer. The grid side converter (GSC) and machine side converter (MSC) are two components of the VSC that share a common DC-link capacitor [37]. This method has the benefits of great efficiency, no additional power source for field excitation, and better reliability due to the absence of slip rings and gearboxes [38]. When the voltage at the PCC drops due to grid failures, the GSC current rises to beef up the grid power. The top limit of the GSC current is reached during a large voltage dip, and the power injected into the grid begins to decline. As a result, the GSC controller cannot support a voltage decrease at PCC, and MSC continues to transmit actual power to the DC-link capacitor. In the event of a sharp decline in the grid voltage, the grid side converter's (GSC) ability to transfer power from the DC link to the grid is limited as the converter current reaches its maximum value. Nevertheless, electricity is still produced continuously by the generators, causing generator saturation, and increasing the voltage stress on the DC link [39,40].

5. Fault Ride-Through in the Context of PMSG WTG

This section presents a review of FRT techniques for PMSG WTPP, with an emphasis on the key techniques adopted over the years, a list of publishers, their countries, and keywords used.

5.1. A Bibliometric Analysis of PMSG FRT Field

LVRT began receiving attention around 2003 when the German grid operators proposed it. Earlier research provided simpler solutions. However, more studies began considering the application of hardware and robust control techniques to enhance the FRT capabilities of PMSG WTGs. Figure 9 illustrates the statistical aggregation of publications with the terms "FRT", "LVRT", and "PMSG" in their keywords, titles, or summaries, obtained from the WOS database, as discussed in Section 2.
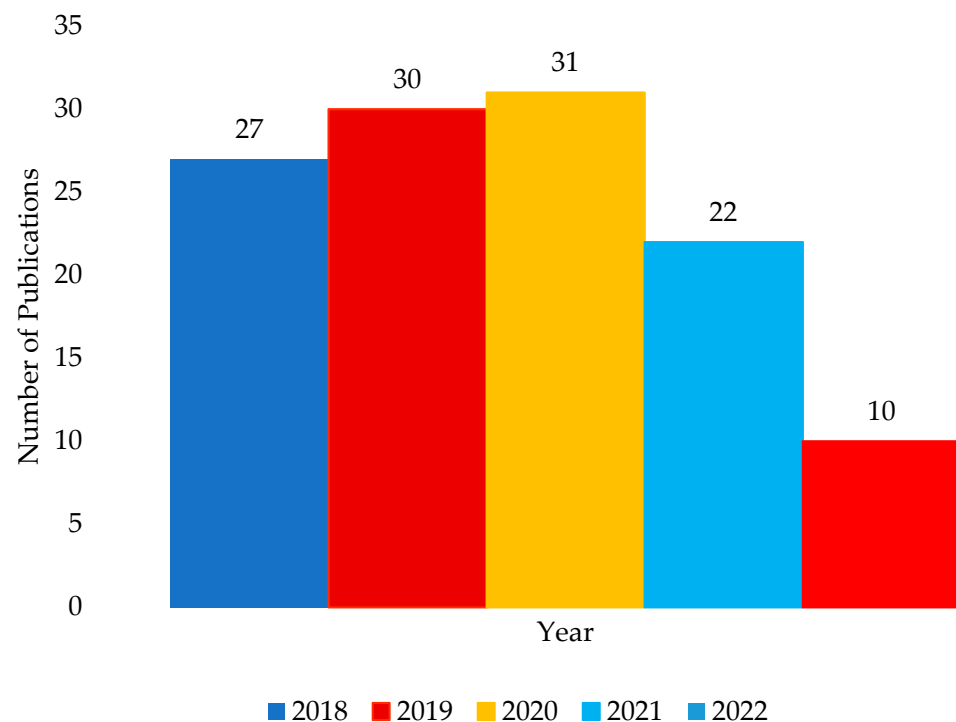

Figure 9. Publications with citations of the terms "FRT", "LVRT", and "PMSG" in the titles, keywords, or summaries. Database extracted in August 2022.

Figure 9 shows a projection in publications in the last five years based on publishers of FRT in PMSG-related articles. Moreover, 2020 was the year with the highest number of publications. Nonetheless, PMSG wind turbines are not fully developed compared to DFIG wind turbines. Therefore, more studies need to be carried out to enhance grid integration.

Regarding the research trends in PMSG FRT techniques, the most frequently used keywords in articles that include the phrases "FRT", "LVRT", or "PMSG" in their abstracts, keywords, or titles are shown in Figure 10. This map was created using VOSviewer. To be captured, a keyword must have appeared on this map at least five times. The size of the circle representing a term is related to the number of times the keyword occurred in the article. Furthermore, the thickness of the lines joining the circles represents the frequency with which the terms were used together. Finally, the color of each circle represents the average publication year of papers that utilized the keywords. As shown in Figure 10, the available data can be used to provide a visual representation of PMSG FRT techniques. This map allows users to compare the average year researchers employed a certain technology. Thus, it can be observed that energy storage systems, fault current limiters, and coordinated controls are among the techniques currently explored.
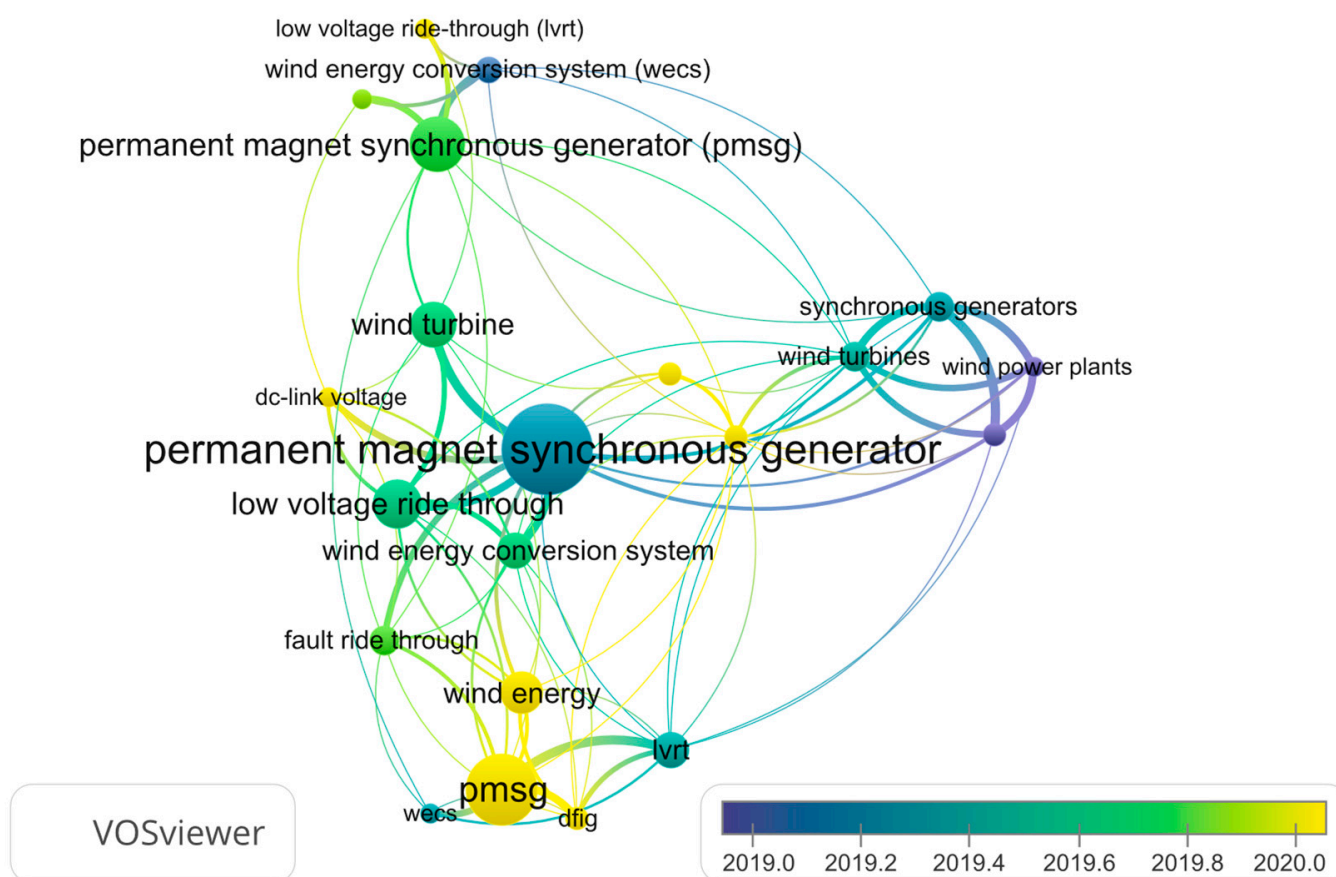
Figure 10. Keyword map of the PMSG FRT technique over time.

In Figure 11, the sizes of the circles relate to the number of publications per nation, and the colors show the average publication year. Regarding overall publications, China is well ahead of its nearest competitors, i.e., Egypt, and Saudi Arabia. More current works are from China and Egypt. Japan, South Korea, Australia, and Turkey are budding research nations with recent publications on this subject. Lastly, this study may be useful for collaborations and partnerships.
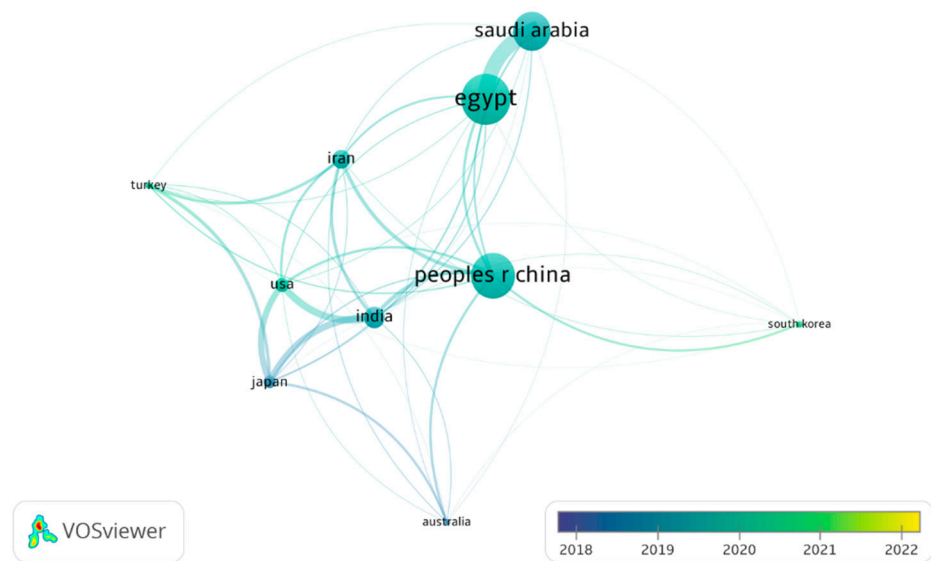
Figure 11. Countries' collaborative network on PMSG FRT considering the existing publications.

The bibliometric study also reveals the most relevant journals in the field of FRT in PMSG WTGs. Figure 12 shows the most referenced journals in this discipline. In this map, a journal's circle size shows its co-citations with other journals. Thus, the sizes of the circles are proportional to the number of times that papers published in certain journals referenced publications from other journals. Journals are linked together symbolically by the lines that run between them. Another way in which articles are connected is by the number of times their writers cite other journal papers in their works; this makes the line connecting them bigger. The journal's cluster determines the circle's color, which depends on citation behavior. The primary goal of Figure 12 is to provide researchers with access to a data-driven depiction of the leading publishers in the area of PMSG FRT approaches. Some of the journals in this map may be review publications, in which case, a disproportionately high number of citations is anticipated. However, researchers can utilize this map to locate suitable publishers for their study results.
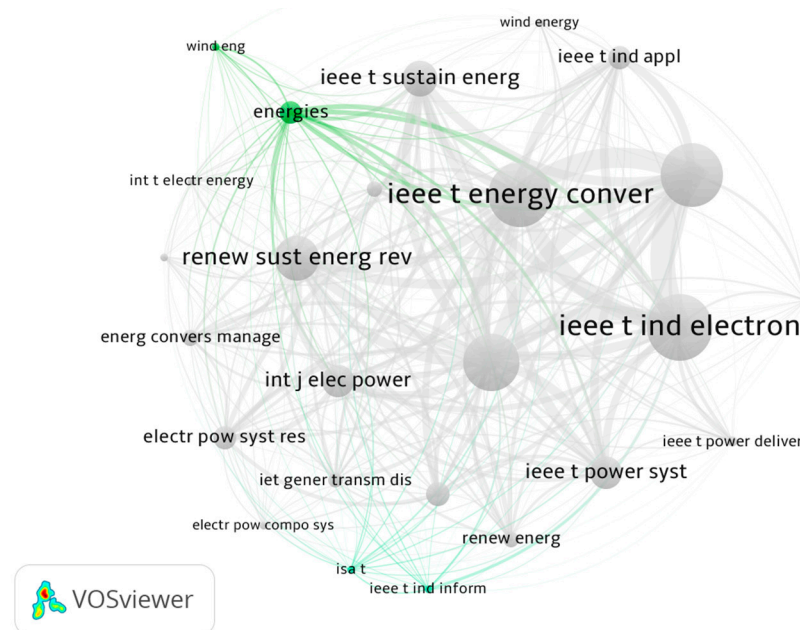
Figure 12. Co-citation map with the most cited journals regarding FRT in PMSG WTGs.

Several techniques have been proposed in the literature by different academics on ways of enhancing FRT in PMSG wind turbines [25,41–43]. The categorization of various LVRT techniques utilized by PMSG-based wind power turbines is shown in Figure 13. The subsections below describe some of the most frequently utilized LVRT capability techniques for PMSG-based WECS.
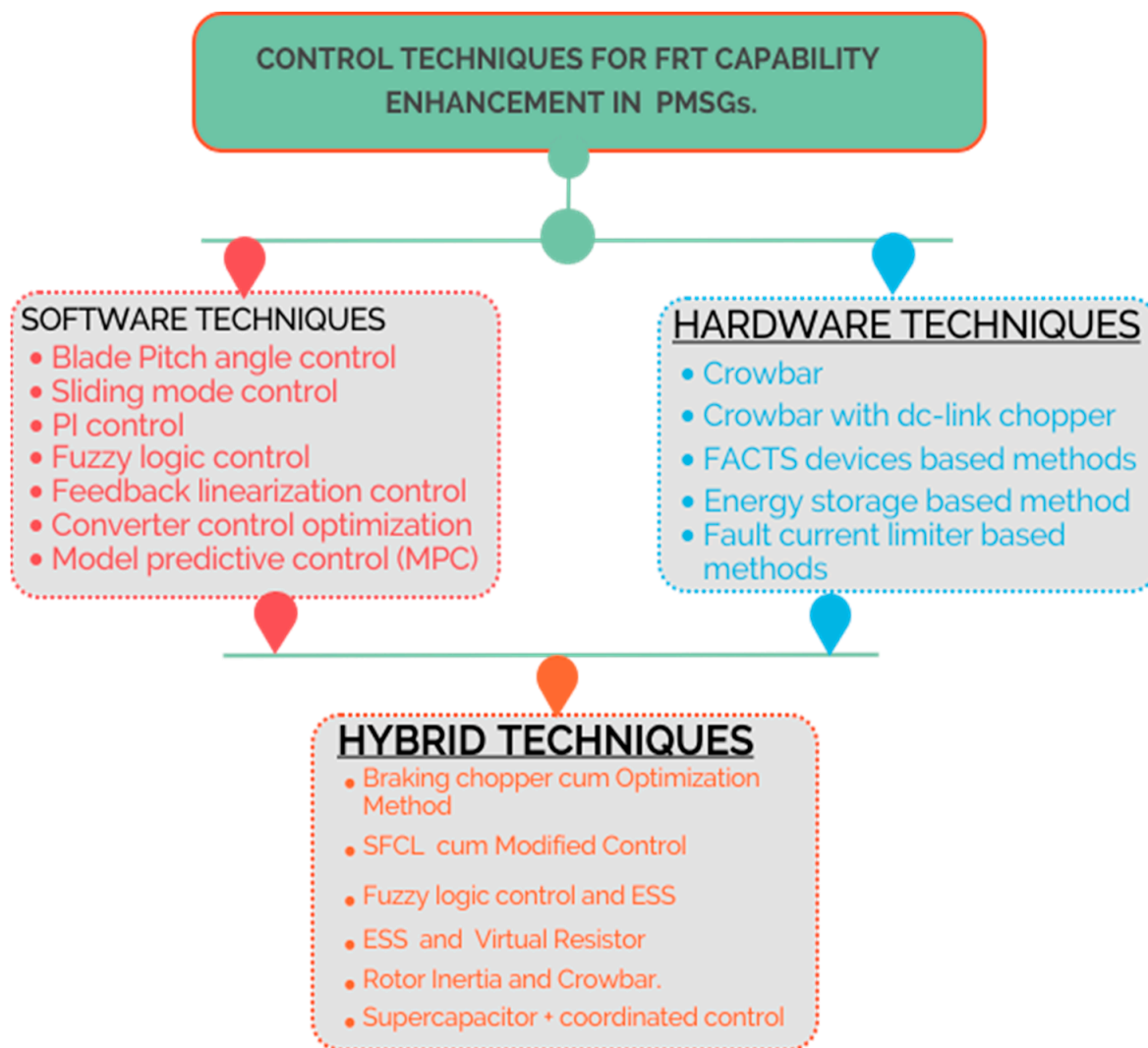
Figure 13. Classification of FRT techniques for PMSG.

PMSG-LVRT has been the subject of many studies. In general, the solutions are divided into the following categories:

- Using a software-based FRT technique with internal control changes, increasing system complexity.
- The hardware-based FRT approach necessitates the purchase of extra hardware, increasing the system's cost.
- A hybrid solution integrates FRT techniques from the hardware and software.

Between 2018 and 2022, the Web of Science database revealed 120 articles, of which, three were review articles that focused on PMSG-FRT techniques. Figure 14 shows the breakdown of the 117 FRT articles.
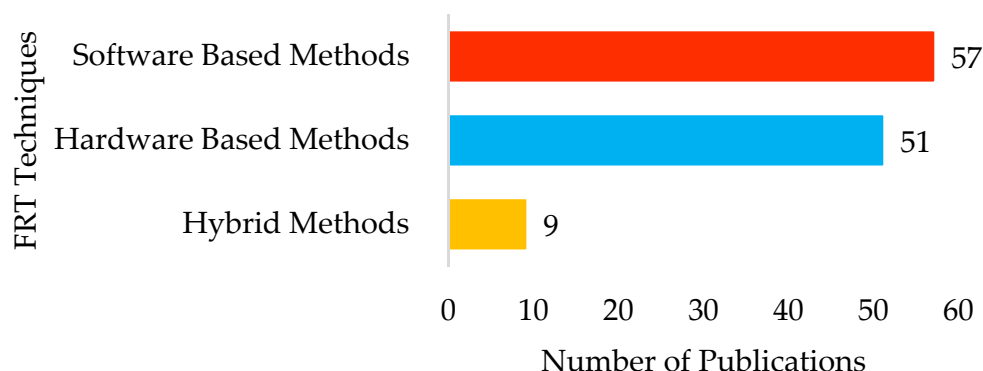
Figure 14. Subdivision of FRT articles in PMSG-based wind turbines.

5.2. Software Solutions

According to [39,44–47], PMSG control settings greatly influence their performance. Ref. [45] suggested that the amount of active power needed for PMSG-LVRT depends on the control settings. The tuning of conventional proportional–integral (PI) controllers influences the FRT capability of PMSG-WT [48]. Several software control techniques that satisfy LVRT requirements are listed in Table 1. The suggested solutions are verified experimentally or via simulations. To improve PMSG-WTG LVRT, a grey wolf optimizer is recommended for both MSC and GSC [49]. At the same time, the sum of integral squared errors (ISE) of the DC-link voltage, generated power, root mean square (RMS) voltage at the machine side, and RMS voltage at the PCC between GSI and the grid is employed as a fitness function because of the nonlinearity of the modeled system. Four PI controllers are in each cascaded control of the MSC and the GSC, totaling eight PI controllers. As a result, sixteen parameters should be adjusted for improved LVRT performance. When the grey wolf optimization (GWO), the simplex, and the genetic algorithm (GA) were compared, the GWO gave the lowest ISE and superior LVRT capability performances. Mitigating the power imbalance during faults is suggested in [50]. The surplus power generated due to the fault is converted to the rotor kinetic energy by the model predictive controller (MPC), avoiding an abrupt rise in the DC-link voltage. Moreover, during low voltage, the grid code requirement of the compensating reactive current to the grid is satisfied. An LVRT scheme employing a proportional resonant (PR) controller is proposed in Reference [51]. The simulation results show that the suggested techniques can help improve the FRT capabilities of PMSG WTGs, with reduced costs. However, none of them could completely ride through significant voltage dips at high rotor speeds, making it difficult to meet the stringent grid code requirements discussed previously.

Table 1. Control approaches to enhance PMSG-LVRT.

Reference	Solution
[52–55]	Stored rotor kinetic energy technique
[56]	Whale optimization technique
[57]	Least mean and square root of exponential (LMSRE) algorithm
[45,58]	Sliding mode control
[59]	Artificial intelligence
[60,61]	Machine parameters varying technique
[62]	Linear active disturbance rejection control
[49,63]	A grey wolf optimization of conventional PI controllers
[64–66]	Feedback linearization-based controller
[67–71]	A fuzzy controller
[72–76]	Pitch angle control
[39,50,77–79]	Model predictive controller
[80,81]	A fast reactive current controller

Table 1. *Cont*.

Reference	Solution
[82]	PI control of speed (Ω) and torque (T)
[83]	Optimized PI-controller parameters based ant lion optimizer (ALO)
[84]	Torsional active damping controller
[85,86]	Adaptive DC-link voltage control
[87]	Lyapunov and passivity theories
[80,88]	Torque control
[89]	Extended Kalman filter state estimation technique
[72,90]	Virtual synchronous machine technique
[51]	Proportional resonant (PR) controller
[40]	Peak current limiter
[91,92]	Active power priority control strategy
[93]	Dynamic current feed-forward mechanism
[94]	Exchange of converter roles
[95]	Advanced nonlinear backstepping control
[96]	De-loading droop technique
[97,98]	Virtual automatic voltage regulator
[99,100]	Reconfigurable parallel wind power converters
[101]	Current oscillation cancellation scheme
[102]	Interval type-2 fuzzy logic control (IT-2 FLC) method

5.3. Hardware Solutions

According to Babagharbani et al. [77], as cited by Nasiri et al. [40], the discrepancy in real power raises the DC-link voltage during grid malfunctions in PMSG WPPs, possibly destroying capacitors, causing generator saturation, and imposing voltage stress on the grid and mechanical side converters. Hence, without protective hardware, PMSG would not withstand significant voltage dips. This section discusses the most common techniques first, then the supplementary literature suggestions.

5.3.1. Crowbar Method

A PMSG-based wind turbine is shown with an active crowbar topology in Figure 15. This topology is a well-known protection circuit-based method for isolating MSC [103]. It is linked across the rotor windings terminals and used only when there is a problem in safeguarding the MSC by dissipating excess power using an IGBT-based crowbar [55,104]. Because the crowbar resistor's impedance is lower than that of the DC-link capacitor under DC circumstances, any surplus power is diverted to the crowbar and dissipated [20]. The crowbar technique has several drawbacks, including the need for a huge resistor bank to dissipate megawatts of power, a cooling system to disperse the heat produced by the crowbar, and its inability to meet grid reactive power requirements [55]. Xing et al. [55] proposed a compositive control method to convert surplus power from PMSG to rotor energy; the PMSG's power is controlled by the GSC. A crowbar circuit prevents the DC-link overvoltage before the MSC reacts to the grid fault. Moreover, the authors of [105] investigated the dead-band management of a crowbar duty ratio to preserve the DC-link voltage.
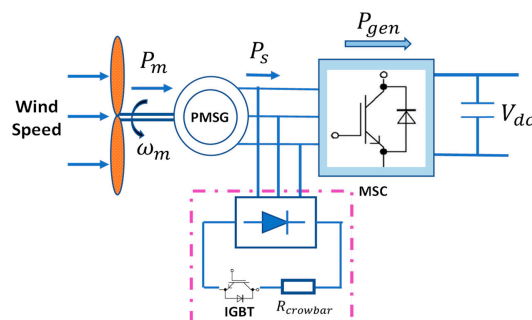

Figure 15. An active crowbar circuit [106].

Zhou et al. [107] utilized a hybrid method in which a lower-rated crowbar is combined with a stored energy in rotor inertia (SEIRI) strategy to decrease the DC-link overvoltage produced by transient power differences between the stator and grid, thus increasing the power-delivering capacity.

5.3.2. DC-Link Chopper Method

The braking chopper consists of an active crowbar circuit with a high-power resistor and a switch linked in parallel with the PMSG's DC link. In a chopper circuit, IGBTs are often employed as switches. It offers the benefits of a simple control structure and cheap costs [108]. The braking chopper mechanism is shown in Figure 16 to minimize the DC-link voltage spike produced by imbalanced energy [109]. The surplus power (P_{bc}) from the mismatch between the generated power (P_g) and grid power (P_{grid}) is dissipated by a controlled braking chopper, with the duty ratio (D) calculated in Equation (19).

$$D = \frac{\text{braking resistance } (R_{bc})}{\text{DC} - \text{link voltage } (V_{dc})^2} \times \left(P_g - P_{grid}\right) \tag{19}$$
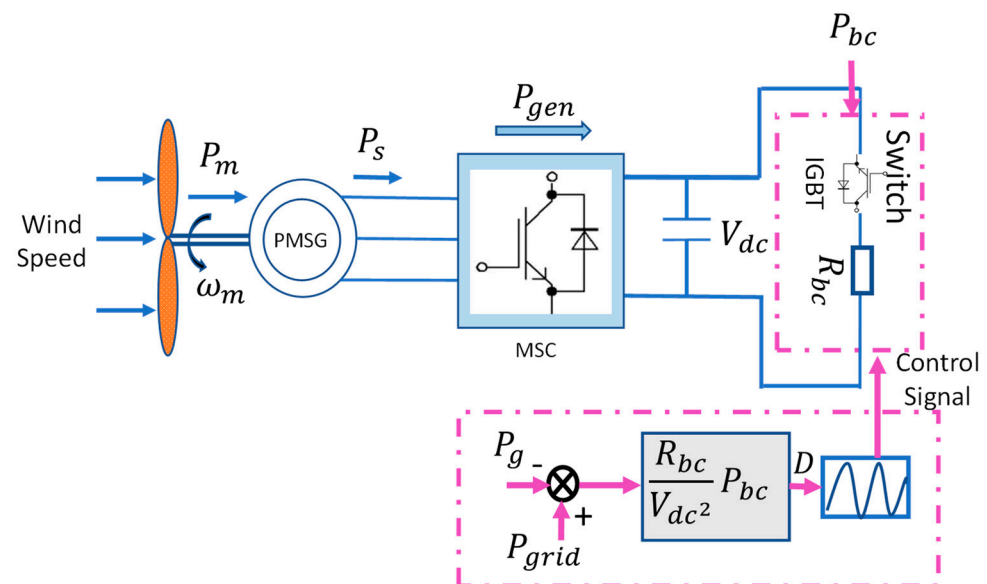
Figure 16. System control block diagram.

Reference [110] proposed a strategy for a normal operation mode, in which the chopper circuit stands by, and the PMSG operates normally. The GSC changes to the FRT mode when the system is in either LVRT or HVRT, and the chopper circuit activates when the DC-link voltage exceeds the threshold. However, this complex method's performance was unsatisfactory since the DC-link chopper had a lower LVRT than a normal crowbar.

5.3.3. Flexible AC Transmission System Methods

A flexible AC transmission system (FACTS) is a cutting-edge technological innovation that uses power electronic components to the functions. FACTS have effectively protected sensitive loads from voltage sag, transients, and damping oscillation [111]. FACTS devices have recently emerged as viable options for keeping WT systems linked to the utility grid network during outages. These devices are classified as series, shunt, or hybrid, depending on how they are connected; static synchronous compensators (STATCOM) are often connected in the shunt, as shown in Figure 17. STATCOM's primary purpose is to provide reactive power to the system to control the voltage at the PCC. Reference [112] used a converter and capacitor, which worked as a STATCOM for the LVRT enhancement of PMSG-WT. Likewise, reference [111] used STATCOM to compensate for the reactive

current capacity loss of the WECS due to its active power compensation during grid faults in PMSG WECS.

Figure 17. Wind turbine LVRT based on PMSG utilizing STATCOM.

Similarly, a static VAR compensator (SVC) is a shunt-connected device that aids in improving the system's steady-state and transient performance. Mahmoud et al. in [104] compared an active crowbar and a thyristor-switched capacitor (TSC) as an SVC-FACT device. Results indicate that both active crowbar and TSC could enhance the fault ride-through capability for grid-connected PMSG. A power electronic converter-based DVR protects critical loads from voltage variations on the supply 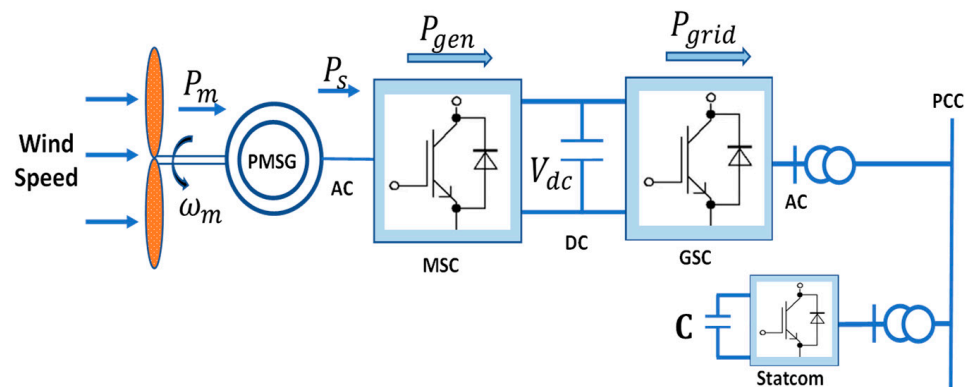side. This system is a linked series device that can provide and absorb both real and reactive power [113]. Its construction consists of a transformer connecting a three-phase voltage source converter between PCC and WT [114].

In PMSG-LVRT systems, GSC is often incapable of sensing the voltage through a dynamic voltage restorer (DVR). The injection transformer used with the DVR for LVRT applications of PMSG has a different design than a traditional transformer. The unified power flow controller (UPFC) is a hybrid connection topology. The UPFC-linked series component injects voltage and adjusts for voltage sags, while the shunt component injects reactive power into the utility grid [115]. The UPFC is the best FACTS device for PMSG-LVRT applications. However, it is expensive.

5.3.4. Energy Storage Methods

This system is an LVRT enhancement method based on external devices. For LVRT improvement in PMSGs, a buck–boost converter connects an energy storage system (ESS) to the DC-link capacitor, as shown in Figure 18 [116]. ESS absorbs the extra energy of the DC-link during a faulty event, preventing the DC-link from exceeding its voltage. After a fault is resolved, the stored energy is transferred to the grid, boosting the PMSG-WTPPs LVRT capabilities. Energy storage technologies that enhance LVRT capabilities include a battery, flow battery, flywheel, electrical double-layer capacitor, and superconducting magnetic energy storage (SMES) [117]. A magnetic coil stores energy in a superconducting magnetic storage device; the coils are charged by running DC via a huge cryogenic superconducting coil. It offers good energy storage, rapid reactivity, and power controllability [118]. The superconducting coil is classed as either a high-temperature coil (HTC) or a low-temperature coil (LTC), depending on the operating temperature. HTC runs at 70 Kelvin, whereas LTC runs at 5 K. The power ramp rate of SMES is quick, reaching 200 kW in 20 ms [119]. Reference [120] described an application of SMES with PMSG-based WECS for reducing power fluctuations, improving grid fault stability, and improving LVRT capabilities.
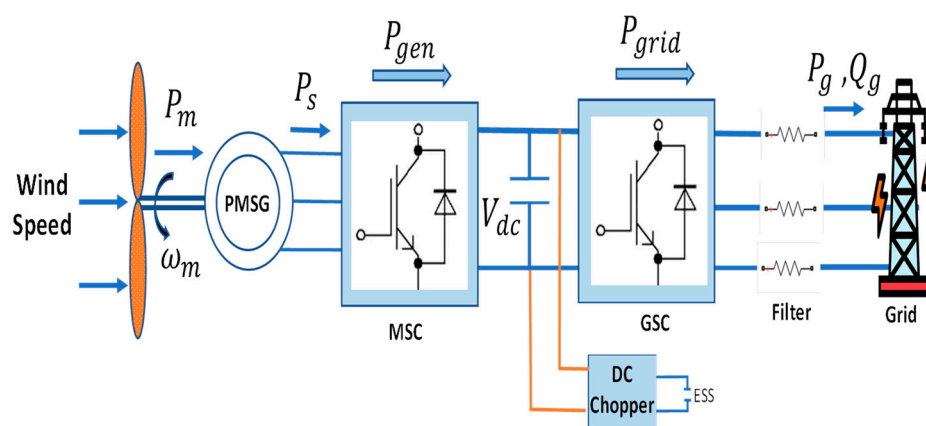
Figure 18. EES linked to a DC link to boost PMSG-based WECS LVRT.

In comparison, reference [118] presented a hybrid control method for superconducting fault current limiters (SFCL) and SMES to improve the LVRT capacity and transient stability of PMSG. Kim et al. in [121] offered a de-loaded approach, using lower rotor speed operation for greater reserve energy from rotor inertia stored in an ESS to effectively manage the LVRT successfully without any energy capacity problems while minimizing the loss in power production.

Sang et al. [122] improved their work in Sang et al. [123], where they explored the addition of energy storage batteries on the DC side to realize the functions of LVRT in PMSG-based WTs under the voltage source control strategy. Supercapacitors (SC) are series combinations of capacitors (C) arced with equivalent series resistance (ESR). Supercapacitors are grouped into electric double-layer capacitors (EDLC) and pseudo-capacitors [124]. EDLC is extensively utilized in PMSG-based WECS-LVRT applications. Since the charging and discharging processes have no physical effects on the electrode, EDLC may endure millions of cycles. Reference [125] proposed a control scheme for PMSG-LVRT improvement capabilities in which the rotor speed is raised within permissible limits to decrease the input power of the MSC during minor faults. Under severe faults, the rotor speed is set to the upper limit to reduce the input power of the MSC. The supercapacitor energy storage (SCES) is inactive with minor faults to prevent the SCES from switching often. Still, the SCES may absorb extra energy to prevent the DC-link capacitor from overvoltage under severe faults. Moreover, reference [54] proposed a control method for PMSGs during grid fault. The MSC supports DC-link voltage management by storing a portion of the surplus power in the drive shaft inertia of the PMSG, while the GSC injects a part of the active and reactive power needed to assist grid voltage recovery. In this condition, the LVRT capability is enhanced by regulating the DC-link voltage via batteries by a DC-DC converter and a brake chopper circuit. However, these techniques come with many costs.

5.3.5. Fault Current Limiter-Based LVRT Methods

Traditional fault current limiters (FCLs) have been employed in large power system networks to reduce fault currents [126]. In PMSGs, two kinds of FCLs are used: non-superconducting [127] and superconducting [128]. These are now widely used to reduce overcurrent in PMSG converters. Reference [127] employs multi-step bridge-type fault current limiters (MSBFCLs), a non-superconducting FCL type, to improve LVRT capabilities. MSBFCLs surpass superconducting FCLs regarding terminal voltage regulation, LVRT augmentation, DC-link excess voltage elimination, and GSC concentration. SFCLs can restrict fault currents due to their quenching state of operation, which transitions from superconducting to quenching. This gadget offers unique characteristics that cannot be accomplished with existing conventional limits. The primary benefit is that they contribute no impedance to the system during regular operations. As a result of the advances, resistor superconducting FCL (RSFCL) is now used, as illustrated in [129]. RSFCLs are parallel

superconducting resistances typically connected between the transformer and the GSC in series [126].

References [129,130] proposed using RSFCL during a short-circuit fault in the PCC. RSFCL will be converted from superconducting to high resistance to efficiently reduce the fault current and increase voltage, guaranteeing PMSG functioning and improving LVRT capabilities. A modified flux coupling-type SFCL was proposed in [131], which shows a practical fault current limit in PMSGs. The DC-link capacitor will be charged during a failure if the power excess cannot be dissipated promptly, resulting in an overvoltage. Modified SFCL is used to reduce the fault current and rectify voltage loss.

The SFCL is also anticipated to reduce DC-link overvoltage and maintain power balance, thus improving LVRT capabilities. In addressing FRT issues, reference [127] investigated the multi-step bridge-type fault current limiter (MSBFCL) applications, as shown in Figure 19. The MSBFCL performance is categorized into normal and fault modes. In the normal mode, all switches are ON. When the PCC voltage drops during a grid failure, the DC reactors prevent an abrupt voltage decrease and fault current growth at fault onset. As the PCC voltage drops below 0.9 pu, the MSBFCL control system activates the total resistor's discrete steps by closing the circuit's switches. Reference [132] also looks at the trigger-type SFCL in PMSGs to improve FRT capabilities. They are very rapid in quenching, have high limiting capacities, are resistive, regulate errors, and improve system stability. They are, however, somewhat costly, and for high-voltage applications, SFCLs need a considerable superconductor length. Table 2 summarizes WoS-indexed hardware-based FRT solutions.
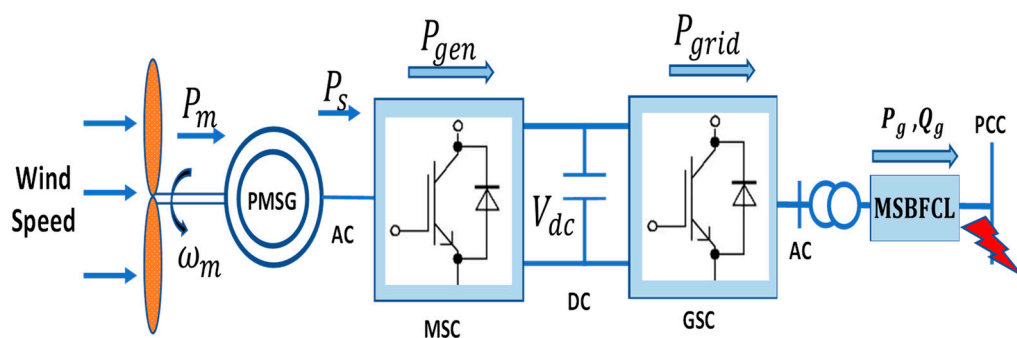
Figure 19. PMSG-based WECS LVRT capabilities using MSBFCL.

Table 2. Hardware-based PMSG LVRT solution schemes.

Reference	Solution
[106,133,134]	Crowbar method
[109,110,120,135–141]	Chopper resistor technique
[142]	Electromagnetic coupler method
[111,143–147]	FACTS devices
[104]	Crowbar and FACTS
[118,147,148]	Energy storage systems and fault current prohibitors
[47,116,120,149]	Energy storage systems
[127,129,130,150–157]	Fault current prohibitors
[158–160]	Supercapacitor energy storage
[46]	Current source inverter technique
[161]	Sic-based inverter technique
[162]	Quasi-Z source inverter technique
[163,164]	Multi-point clamped technique
[165,166]	Super magnetic energy storage systems
[167]	PV support technique
[168]	DFIG support
[169]	Parallel capacitor technique

5.4. Hybrid LVRT Techniques

While control methods may enhance PMSG-LVRT, they may not meet stringent grid code criteria. Thus, hardware and software solutions should be utilized during extreme voltage drops, which helps reduce the hardware rating and enhance LVRT. Some publications offer hybrid solutions, as presented in Table 3.

Table 3. PMSG hybrid LVRT solutions.

Reference	Methodology
[170]	Superconducting fault current limiter (SFCL) cum modified control strategy
[123]	Energy Storage cum virtual resistor method
[107]	Rotor Inertia cum crowbar technique
[171,172]	Optimization techniques and braking chopper
[125]	Supercapacitor cum coordinated control technique
[173]	Energy storage source and fuzzy logic
[174]	Crowbar and role interchange of converters

5.5. Financial Suitability

WT generators are linked to the grid, and grid failures disrupt the system, causing a power outage. Economically, LVRT capability techniques are classified as high, medium, and low costs. The numerous switches and coupling transformers in FACTS devices make them expensive. Moreover, the FACTS device controller circuit complicates LVRT capabilities. Due to its low number of switches, the braking chopper is a low-cost energy storage device. The RSC and GSC controllers are less expensive and do not need additional devices. Table 4 shows the economic estimates of the FRT systems.

Table 4. Economic estimation.

FRT Scheme	Cost
Energy storage devices/batteries	High
DC chopper	cheap
FACTS	Very high
Crowbar	cheap
Machine and grid-side converters	Moderate

6. Conclusions

Present research studies are focused on expanding the supply of renewable energy sources into grid power networks, which will help meet future energy needs using green energy.

The growing use of wind energy in the utility grid network emphasizes the need for wind power plants to be connected to the grid to provide maximum system steady-state and transient stability. This review's bibliometric analysis demonstrates a rising tide of works addressing FRT for PMSG WTPP. The bibliometric study provides a data-driven visualization of author keywords and countries of origin, which can facilitate better international cooperation among scientists. In addition, this study reveals the co-citation behaviors of the top journals in the PMSG WT FRT domain, which can guide writers in selecting the best venues for publishing their results.

Further, the most current and highly referenced works addressing the PMSG WP are presented via a systematic review. The papers are summarized in Tables 1–3 and sorted into software, hardware, and hybrid categories. Most researchers only considered distribution grids when discussing PMSG FRT, neglecting the effects on transmission lines. As seen in the literature, intelligent system-based control strategies are superior to their traditional counterparts. However, the effectiveness of intelligent strategies compared to traditional ones in the context of PMSG FRT methodologies is not well explored.

ESS, connected to the WTG DC-link, can simultaneously enhance LVRT capabilities and help smoothen wind power fluctuations. However, a few researchers who coupled ESS to the DC-link discussed power smoothing. Determining an effective PMSG converter control, hardware technique, and hybrid augmentation solutions that work even when the grid is severely disrupted is, thus, critical since each suggested solution works best under a specific condition.

Future Research Scope

An overview of the FRT analysis, modeling, and improvements for permanent magnet synchronous generator wind turbines is given. Protective hardware, control systems, and hybrid techniques are three types of LVRT solutions that are thoroughly discussed. Based on the literature analysis, it is concluded that:

- It is adequate to utilize properly tuned controllers during mild voltage drops. Protective hardware is required for extreme voltage drops. A hybrid technique is advised to reduce the hardware rating and improve system dependability.
- Software solution implementation is cheaper than most hardware methods suggest in the literature. Meanwhile, combining a crowbar and a DC-link chopper seems to be the most cost-effective hardware option. They successfully safeguard the converter and DC-link capacitor but cannot provide the grid's reactive power needs.
- Previous research only targeted voltage dips at the PCC, neglecting propagation from the transmission grid to the low voltage level.
- With more microgrids and smart grids at the distribution level, more research may study the IMPACT of voltage disturbance on the overall system and recommend solutions to improve the LVRT.
- To fully comprehend the system's efficacy in any given scenario, it is necessary to conduct more research using field data to examine the effects of grid disruptions on PMSG wind turbines.
- The rising popularity of machine learning and its many potential uses, as well as the wealth of available system information, suggest that future research should explore the possibility of using such methods to improve performance forecasting and LVRT.
- The application of nanomaterials has made superconducting materials less expensive. Hence, more research should focus on its application with other ancillary services to enhance PMSG LVRTs.

Author Contributions: All authors contributed equally to the paper; E.F.M. was responsible for writing the initial manuscript, data collection, and the idea. T.F.M., J.S., S.M.A. and O.A.-R. were mainly responsible for supervising, organizing, and revising the paper. All authors have read and agreed to the published version of the manuscript.

References

1. Heffron, R.J.; Körner, M.F.; Schöpf, M.; Wagner, J.; Weibelzahl, M. The role of flexibility in the light of the COVID-19 pandemic and beyond: Contributing to a sustainable and resilient energy future in Europe. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110743. [CrossRef]
2. Khanna, M. COVID-19: A Cloud with a Silver Lining for Renewable Energy? *Appl. Econ. Perspect. Policy* **2021**, *43*, 73–85. [CrossRef]
3. Alemzero, D.; Acheampong, T.; Huaping, S. Prospects of wind energy deployment in Africa: Technical and economic analysis. *Renew Energy* **2021**, *179*, 652–666. [CrossRef]
4. Renewable Electricity Generation Increase by Technology, 2019–2020 and 2020–2021—Charts—Data & Statistics—IEA. Available online: https://www.iea.org/data-and-statistics/charts/renewable-electricity-generation-increase-by-technology-2019-2020-and-2020-2021 (accessed on 16 August 2021).
5. Jiang, P.; van Fan, Y.; Klemeš, J.J. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Appl. Energy* **2021**, *285*, 116441. [CrossRef]

6.   Mahela, O.P.; Gupta, N.; Khosravy, M.; Patel, N. Comprehensive overview of low voltage ride through methods of grid integrated wind generator. *IEEE Access* **2019**, *7*, 99299–99326. [CrossRef]

7.   Dao, C.; Kazemtabrizi, B.; Crabtree, C. Wind turbine reliability data review and impacts on levelised cost of energy. *Wind Energy* **2019**, *22*, 1848–1871. [CrossRef]

8.   Huda, A.S.N.; Živanović, R. Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools. *Renew. Sustain. Energy Rev.* **2017**, *76*, 974–988. [CrossRef]

9.   Tina, G.M.; Licciardello, S.; Stefanelli, D. Strategic role of new power generation assets for the security of the future Italian power system. In Proceedings of the 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019, Genova, Italy, 11–14 June 2019. [CrossRef]

10. Sarkar, M.N.I.; Meegahapola, L.G.; Datta, M. Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization Algorithms. *IEEE Access* **2018**, *6*, 41458–41489. [CrossRef]

11. Abdel-Rahim, O.; Chub, A.; Vinnikov, D.; Blinov, A. DC integration of residential photovoltaic systems: A survey. *IEEE Access* **2022**, *10*, 66974–66991. [CrossRef]

12. Hu, Y.L.; Wu, Y.K.; Chen, C.K.; Wang, C.H.; Chen, W.T.; Cho, L.I. A Review of the Low-Voltage Ride-Through Capability of Wind Power Generators. *Energy Procedia* **2017**, *141*, 378–382. [CrossRef]

13. Barra, P.H.A.; de Carvalho, W.C.; Menezes, T.S.; Fernandes, R.A.S.; Coury, D.V. A review on wind power smoothing using high-power energy storage systems. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110455. [CrossRef]

14. Fault Ride through' or Low Voltage Ride through (All Fields) AND 'PMSG' (All Fields)—120—Web of Science Core Collection. Available online: https://0810o9l49-1105-y-https-www-webofscience-com.mplbci.ekb.eg/wos/woscc/summary/1c00b1fe-ade4-456c-b636-aea6c98492ad-49d4b9e2/date-descending/1 (accessed on 24 August 2022).

15. van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]

16. Ding, X.; Yang, Z. Knowledge mapping of platform research: A visual analysis using VOSviewer and CiteSpace. *Electron. Commer. Res.* **2020**, *22*, 787–809. [CrossRef]

17. Yu, Y.; Li, Y.; Zhang, Z.; Gu, Z.; Zhong, H.; Zha, Q.; Yang, L.; Zhu, C.; Chen, E. A bibliometric analysis using VOSviewer of publications on COVID-19. *Ann. Transl. Med.* **2020**, *8*, 816. [CrossRef]

18. Taherian-Fard, E.; Sahebi, R.; Niknam, T.; Izadian, A.; Shasadeghi, M. Wind turbine drivetrain technologies. *IEEE Trans. Ind. Appl.* **2020**, *56*, 1729–1741. [CrossRef]

19. Wanjoeh, S.; Radman, G. Detailed Dynamic Modeling, Control, and Analysis of a Grid-Connected Variable Speed SCIG Wind Energy Conversion System. *Am. J. Electr. Power Energy Syst.* **2021**, *10*, 15–24. [CrossRef]

20. Ahmed, S.D.; Al-Ismail, F.S.M.; Shafiullah, M.; Al-Sulaiman, F.A.; El-Amin, I.M. Grid Integration Challenges of Wind Energy: A Review. *IEEE Access* **2020**, *8*, 10857–10878. [CrossRef]

21. Bhukya, J.; Mahajan, V. The controlling of the DFIG based on variable speed wind turbine modeling and simulation. In Proceedings of the 2016 IEEE 6th International Conference on Power Systems, ICPS 2016, New Delhi, India, 4–6 March 2016. [CrossRef]

22. Beainy, A.; Maatouk, C.; Moubayed, N.; Kaddah, F. Comparison of different types of generator for wind energy conversion system topologies. In Proceedings of the 2016 3rd International Conference on Renewable Energies for Developing Countries, REDEC 2016, Zouk Mosbeh, Lebanon, 13–15 July 2016. [CrossRef]

23. Kumar, G.B.A.; Shivashankar; Keshavamurthy. Design and Control of Solar-Wind Integrated Conversion System with DFIG for Maximum Power Point Tracking. In Proceedings of the 5th IEEE International Conference on Recent Trends in Electronics, Information and Communication Technology, RTEICT 2020, Bangalore, India, 12–13 November 2020; pp. 292–298. [CrossRef]

24. Morgan, E.F.; Megahed, T.F.; Suehiro, J.; Abdelkader, S.M. A Fault Ride-Through Technique for PMSG wind turbines using Superconducting Magnetic Energy Storage (SMES) under Grid voltage sag conditions. *Renew. Energy Power Qual. J.* **2022**, *20*, 79–83. [CrossRef]

25. Yaramasu, V.N.R.; Wu, B. *Model Predictive Control of Wind Energy Conversion Systems*; John Wiley & Sons: Hoboken, NJ, USA, 2016.

26. Nasiri, M.; Milimonfared, J.; Fathi, S.H. A review of low-voltage ride-through enhancement methods for permanent magnet synchronous generator based wind turbines. *Renew. Sustain. Energy Rev.* **2015**, *47*, 399–415. [CrossRef]

27. Yu, J.; Li, J.; Hu, W.; Zhang, G.; Wang, H.; Huang, Q.; Chen, Z. Small-signal modeling of wind farm with direct-drive PMSG using the component connection method. *Energy Rep.* **2021**, *7*, 334–342. [CrossRef]

28. AbdelRahim, O.; Abu-Rub, H.; Ahmed, S.M. Space vector PWM for a five to three matrix converter. In Proceedings of the Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 17–21 March 2013; pp. 3246–3250. [CrossRef]

29. Gaber, M.; Abdel-Rahim, O.; Orabi, M. Novel Overlap Method to Eliminate Vector Deviation Error in SVM of Current Source Inverters. *IEEE Trans. Power Electron.* **2021**, *36*, 2320–2333. [CrossRef]

30. Sobczak, K.; Obidowski, D.; Reorowicz, P.; Marchewka, E. Numerical Investigations of the Savonius Turbine with Deformable Blades. *Energies* **2020**, *13*, 3717. [CrossRef]

31. Shao, H.; Yan, H.; Cai, X.; Qin, Y.; Zhang, Z. Aggregation Modeling Algorithm of PMSM Wind Farm Considering Submarine Cable Power Loss. In Proceedings of the 2021 IEEE 12th Energy Conversion Congress & Exposition—Asia (ECCE-Asia), Singapore, 24–27 May 2021; pp. 1169–1174. [CrossRef]

32. Abdel-Rahim, O.; Funato, H.; Abu-Rub, H.; Ellabban, O. Multiphase Wind Energy generation with direct matrix converter. In Proceedings of the IEEE International Conference on Industrial Technology (ICIT), Busan, Republic of Korea, 26 February–1 March 2014; pp. 519–523. [CrossRef]

33. Aleem, S.H.E.A.; Abdelaziz, A.Y.; Zobaa, A.F. Egyptian Grid Code of Wind Farms and Power Quality. In *Handbook of Distributed Generation: Electric Power Technologies, Economics and Environmental Impacts*; Springer: Cham, Switzerland, 2017; pp. 227–245. [CrossRef]

34. Tsili, M.; Papathanassiou, S. A review of grid code technical requirements for wind farms. *IET Renew. Power Gener.* **2008**, *3*, 308–332. [CrossRef]

35. Salem, A.A.; Eldesouky, A.A.; Farahat, A.A.; Abdelsalam, A.A. New Analysis Framework of Lyapunov-Based Stability for Hybrid Wind Farm Equipped with FRT: A Case Study of Egyptian Grid Code. *IEEE Access* **2021**, *9*, 80320–80339. [CrossRef]

36. Gligor, A.; Grigoras, G.; Neagu, B.-C.; Ibrahim, R.A.; Zakzouk, N.E. A PMSG Wind Energy System Featuring Low-Voltage Ride-through via Mode-Shift Control. *Appl. Sci.* **2022**, *12*, 964. [CrossRef]

37. Abdelrahem, M.; el Hafni, A.; Kennel, R.; Hackl, C.M. Predictive phase locked loop for sensorless control of PMSG based variable-speed wind turbines. In Proceedings of the 2017 8th International Symposium on Sensorless Control for Electrical Drives, SLED 2017, Catania, Italy, 18–19 September 2017; pp. 151–156. [CrossRef]

38. Ahsanullah, K.; Dutta, R.; Rahman, M.F. Analysis of Low-Speed IPMMs with Distributed and Fractional Slot Concentrated Windings for Wind Energy Applications. In *IEEE Transactions on Magnetics*; IEEE: Piscataway, NJ, USA, 2017; Volume 53. [CrossRef]

39. Abdel-Rahim, O.; Abu-Rub, H.; Iqbal, A.; Kouzou, A. Five-to-three phase direct matrix converter with model predictive control. In Proceedings of the 4th International Conference on Power Engineering, Energy and Electrical Drives, Istanbul, Turkey, 13–17 May 2013; pp. 204–208. [CrossRef]

40. Nasiri, M.; Arzani, A.; Savaghebi, M. Current limitation for the machine side converter of permanent magnet synchronous generator wind turbines during grid faults. *IET Renew. Power Gener.* **2020**, *14*, 3448–3456. [CrossRef]

41. Mendes, V.F.; Matos, F.F.; Liu, S.Y.; Cupertino, A.F.; Pereira, H.A.; de Sousa, C.V. Low Voltage Ride-Through Capability Solutions for Permanent Magnet Synchronous Wind Generators. *Energies* **2016**, *9*, 59. [CrossRef]

42. Arani, M.F.M.; Mohamed, Y.A.R.I. Assessment and Enhancement of a Full-Scale PMSG-Based Wind Power Generator Performance under Faults. *IEEE Trans. Energy Convers.* **2016**, *31*, 728–739. [CrossRef]

43. Nasiri, M.; Mohammadi, R. Peak Current Limitation for Grid Side Inverter by Limited Active Power in PMSG-Based Wind Turbines During Different Grid Faults. *IEEE Trans. Sustain. Energy* **2017**, *8*, 3–12. [CrossRef]

44. Abdel-Rahim, O.; Ali, Z.M. Control of seven-to-three phase Direct Matrix Converter using Model Predictive control for multiphase wind generation. In Proceedings of the 16th International Conference on Harmonics and Quality of Power (ICHQP), Bucharest, Romania, 25–28 May 2014; pp. 199–203. [CrossRef]

45. Zoghlami, M.; Kadri, A.; Bacha, F. Analysis and application of the sliding mode control approach in the variable-wind speed conversion system for the utility of grid connection. *Energies* **2018**, *11*, 720. [CrossRef]

46. Abdelsalam, I.; Alajmi, B.N.; Marei, M.I.; Alhajri, M.F. Wind energy conversion system based on open-end winding three-phase PMSG coupled with ac−dc buck-boost converter. *J. Eng.* **2019**, *2019*, 4336–4340. [CrossRef]

47. Kim, C.; Kim, W. Enhanced Low-Voltage Ride-Through Coordinated Control for PMSG Wind Turbines and Energy Storage Systems Considering Pitch and Inertia Response. *IEEE Access* **2020**, *8*, 212557–212567. [CrossRef]

48. Ghadimi, M.; Nazarzadeh, J. Optimal tracking control for asymmetrical fault ride through in the back-to-back converters. *IET Renew. Power Gener.* **2020**, *14*, 1359–1367. [CrossRef]

49. Qais, M.H.; Hasanien, H.M.; Alghuwainem, S. A Grey Wolf Optimizer for Optimum Parameters of Multiple PI Controllers of a Grid-Connected PMSG Driven by Variable Speed Wind Turbine. *IEEE Access* **2018**, *6*, 44120–44128. [CrossRef]

50. Ghany, A.A.; Shehata, E.G.; Elsayed, A.-H.M.; Mohamed, Y.S.; Haes Alhelou, H.; Siano, P.; Diab, A.A.Z. Novel Switching Frequency FCS-MPC of PMSG for Grid-Connected Wind Energy Conversion System with Coordinated Low Voltage Ride Through. *Electronics* **2021**, *10*, 492. [CrossRef]

51. Varma, S.D.K.; Obulesh, Y.P.; Saibabu, C. A Co-ordinated Ride Through Capability and Power Quality Enhancement Scheme for Grid Tied PMSG Based Wind Energy. *Int. J. Renew. Energy Res.* **2021**, *11*, 535–545.

52. Wang, J.; Ben, Y.; Zhang, J.; Feng, H. Low voltage ride-through control strategy for a wind turbine with permanent magnet synchronous generator based on operating simultaneously of rotor energy storage and a discharging resistance. *Energy Rep.* **2022**, *8*, 5861–5870. [CrossRef]

53. Ali, M.A.S. Enhanced Transient Performance of Wind-Driven PMSG: A Revised Control Structure of Wind-Power Converters. *Adv. Electr. Comput. Eng.* **2022**, *22*, 61–70. [CrossRef]

54. Marmouh, S.; Boutoubat, M.; Mokrani, L.; Machmoum, M. A coordinated control and management strategy of a wind energy conversion system for a universal low-voltage ride-through capability. *Int. Trans. Electr. Energy Syst.* **2019**, *29*, e12035. [CrossRef]

55. Xing, P.; Fu, L.; Wang, G.; Wang, Y.; Zhang, Y. A compositive control method of low-voltage ride through for PMSG-based wind turbine generator system. *IET Gener. Transm. Distrib.* **2018**, *12*, 117–125. [CrossRef]

56. Mahmoud, M.M.; Ratib, M.K.; Aly, M.M.; Abdel–Rahim, A.-M.M. Application of Whale Optimization Technique for Evaluating the Performance of Wind-Driven PMSG Under Harsh Operating Events. *Process Integr. Optim. Sustain.* **2022**, *6*, 447–470. [CrossRef]
57. Qais, M.H.; Hasanien, H.M.; Alghuwainem, S. A novel LMSRE-based adaptive PI control scheme for grid-integrated PMSG-based variable-speed wind turbine. *Int. J. Electr. Power Energy Syst.* **2021**, *125*, 106505. [CrossRef]
58. Nasiri, M.; Mobayen, S.; Zhu, Q.M. Super-Twisting Sliding Mode Control for Gearless PMSG-Based Wind Turbine. *Complexity* **2019**, *2019*, 6141607. [CrossRef]
59. Nasiri, M.; Mobayen, S.; Faridpak, B.; Fekih, A.; Chang, A. Small-Signal Modeling of PMSG-Based Wind Turbine for Low Voltage Ride-Through and Artificial Intelligent Studies. *Energies* **2020**, *13*, 6685. [CrossRef]
60. Okedu, K.E.; Al Tobi, M.; Al Araimi, S. Comparative Study of the Effects of Machine Parameters on DFIG and PMSG Variable Speed Wind Turbines During Grid Fault. *Front. Energy Res.* **2021**, *9*, 681443. [CrossRef]
61. Ribeiro, R.; Boeira, R.; Leborgne, R.C.; de Oliveira, R.A.; Bollen, M.H.J. Assessment of LVRT Requirements and Dynamic Behavior of a Mixed PMSG/DFIG Wind Power Plant. In Proceedings of the 2020 IEEE pes Transmission & Distribution Conference and Exhibition—Latin America (T&D LA), Montevideo, Uruguay, 28 September–2 October 2020. [CrossRef]
62. Ma, Y.; Tao, L.; Zhou, X.; Shi, X. Analysis and Control of Fault Ride-Through Capability Improvement for Wind Energy Conversion System Using Linear Active Disturbance Rejection Control With Correction Link. *IEEE ACCESS* **2020**, *8*, 73816–73827. [CrossRef]
63. Qais, M.H.; Hasanien, H.M.; Alghuwainem, S. Optimal Transient Search Algorithm-Based PI Controllers for Enhancing Low Voltage Ride-Through Ability of Grid-Linked PMSG-Based Wind Turbine. *Electronics* **2020**, *9*, 1807. [CrossRef]
64. Alhejji, A.; Bouzid, Y. Robust Adaptive PI Controller Of Low Voltage Ride-Through For PMSG-Based Wind Turbine. In Proceedings of the 2019 6th International Conference on Control, Decision and Information Technologies (CODIT 2019), Paris, France, 23–26 April 2019; pp. 1233–1237.
65. Mahmud, M.A.; Roy, T.K.; Littras, K.; Islam, S.N.; Oo, A.M.T. Nonlinear Partial Feedback Linearizing Controller Design for PMSG-Based Wind Farms to Enhance LVRT Capabilities. In Proceedings of the 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Madras, India, 18–21 December 2018.
66. Yang, B.; Yu, T.; Shu, H.; Qiu, D.; Zhang, Y.; Cao, P.; Jiang, L. Passivity-based linear feedback control of permanent magnetic synchronous generator-based wind energy conversion system: Design and analysis. *IET Renew. Power Gener.* **2018**, *12*, 981–991. [CrossRef]
67. Dey, P.; Datta, M.; Fernando, N.; Senjyu, T. Fuzzy-based Coordinated Control to Reduce DC-link Overvoltage of a PMSG based Wind Energy Systems during Grid Faults. In Proceedings of the 2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS), Kitakyushu, Japan, 23–25 April 2018.
68. Qais, M.H.; Hasanien, H.M.; Alghuwainem, S. Whale optimization algorithm-based Sugeno fuzzy logic controller for fault ride-through improvement of grid-connected variable speed wind generators. *Eng. Appl. Artif. Intell.* **2020**, *87*, 103328. [CrossRef]
69. Qais, M.H.; Hasanien, H.M.; Alghuwainem, S. Enhanced salp swarm algorithm: Application to variable speed wind generators. *Eng. Appl. Artif. Intell.* **2019**, *80*, 82–96. [CrossRef]
70. Parmar, J. Design Fuzzy based PI Controller for PMSG and IG based Combined WECS. In Proceedings of the 2019 Innovations in Power and Advanced Computing Technologies (I-PACT), Vellore, India, 22–23 March 2019.
71. Gencer, A. Analysis and Control of Low-Voltage Ride-Through Capability Improvement for PMSG Based on an NPC Converter Using an Interval Type-2 Fuzzy Logic System. *Elektron. Elektrotech.* **2019**, *25*, 63–70. [CrossRef]
72. Muftau, B.; Fazeli, M.; Egwebe, A. Stability analysis of a PMSG based Virtual Synchronous Machine. *Electr. Power Syst. Res.* **2020**, *180*, 106170. [CrossRef]
73. Saad, N.H.; El-Sattar, A.A.; Marei, M.E. Improved bacterial foraging optimization for grid connected wind energy conversion system based PMSG with matrix converter. *Ain Shams Eng. J.* **2018**, *9*, 2183–2193. [CrossRef]
74. Dey, P.; Datta, M.; Fernando, N.; Senjyu, T. Coordinated Control Technique of PMSG based Wind Energy Conversion System during Repetitive Grid Fault. In Proceedings of the 2018 IEEE International Conference on Industrial Technology (ICIT), Lyon, France, 20–22 February 2018; pp. 915–920. [CrossRef]
75. Chen, J.; Duan, W.; Yang, X.; Zhang, L.; Shan, Y.; Yang, B.; Shu, H.; An, N.; Yu, T. Overall Adaptive Controller Design of PMSG Under Whole Wind Speed Range: A Perturbation Compensation Based Approach. *Processes* **2019**, *7*, 732. [CrossRef]
76. Nguyen, P.T.H.; Studli, S.; Braslavsky, J.H.; Middleton, R.H. Coordinated Control for Low Voltage Ride Through in PMSG Wind Turbines. *IFAC Pap.* **2018**, *51*, 672–677. [CrossRef]
77. Babaghorbani, B.; Beheshti, M.T.H.; Talebi, H.A. An improved model predictive control of low voltage ride through in a permanent magnet synchronous generator in wind turbine systems. *Asian J. Control* **2019**, *21*, 1991–2003. [CrossRef]
78. Zhang, Z.; Zhang, Z.; Liu, X.; Hao, Q.; Zhang, Z. LVRT Control of Back-to-Back Power Converter PMSG Wind Turbine Systems: An FPGA Based Hardware-in-the-Loop Solution. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 7–12.
79. Nguyen, P.T.H.; Middleton, R.H.; Studli, S. Model Predictive Control for Wind Turbines to Enhance Low Voltage Ride Through Capability. In Proceedings of the 2021 IEEE pes Innovative Smart Grid Technologies—ASIA (ISGT ASIA), Singapore, 1–5 November 2021. [CrossRef]
80. Jahanpour-Dehkordi, M.; Vaez-Zadeh, S.; Mohammadi, J. Development of a Combined Control System to Improve the Performance of a PMSG-Based Wind Energy Conversion System Under Normal and Grid Fault Conditions. *IEEE Trans. Energy Convers.* **2019**, *34*, 1287–1295. [CrossRef]

81. Zhang, J.; Sun, H.; Li, W.; Jia, Y.; Han, Z.; Tao, X. A FRCC method based on rapid voltage response for LVRT recovery of D-PMSG. *Energy Sources Part A Recovery Util. Environ. Eff.* **2019**, 1–17. [CrossRef]

82. Tripathi, S.M.; Tiwari, A.N.; Singh, D. Low-voltage ride-through enhancement with the ω and T controls of PMSG in a grid-integrated wind generation system. *IET Gener. Transm. Distrib.* **2019**, *13*, 1979–1988. [CrossRef]

83. Haridy, A.L.; Abdelbasset, A.-A.A.M.; Hemeida, A.M.; Elhalwany, Z.M.A. Optimum Controller Design Using the Ant Lion Optimizer for PMSG Driven by Wind Energy. *J. Electr. Eng. Technol.* **2021**, *16*, 367–380. [CrossRef]

84. Ramachandran, V.; Pitchaimuthu, R.; Selvan, M.P. Systematized Active Power Control of PMSG-Based Wind-Driven Generators. *IEEE Syst. J.* **2020**, *14*, 708–717. [CrossRef]

85. He, Y.; Wang, M.; Xu, Z. Coordinative Low-Voltage-Ride-Through Control for the Wind-Photovoltaic Hybrid Generation System. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 1503–1514. [CrossRef]

86. Yao, J.; Li, J.; Guo, L.; Liu, R.; Xu, D. Coordinated control of a hybrid wind farm with PMSG and FSIG during asymmetrical grid fault. *Int. J. Electr. Power Energy Syst.* **2018**, *95*, 287–300. [CrossRef]

87. Fernandez, R.D.; Valenciaga, F.; Pena, R.R. Wind energy conversion system under asymmetrical voltage failures: Analysis and nonlinear control. *Asian J. Control* **2022**, *24*, 58–73. [CrossRef]

88. Gajewski, P. Improved control strategy of wind energy conversion system with PMSG during low voltage sags. *Prz. Elektrotechniczny* **2020**, *96*, 123–128. [CrossRef]

89. Shahriari, S.A.A.; Mohammadi, M.; Raoofat, M. Enhancement of low-voltage ride-through capability of permanent magnet synchronous generator wind turbine by applying state-estimation technique. *Compel Int. J. Comput. Math. Electr. Electron. Eng.* **2020**, *39*, 363–377. [CrossRef]

90. de Armas, M.; Gomez, S.A.; Amenedo, J.L.R.; Alonso-Martinez, J. Virtual Synchronous Machine fault ride through capability with Reactive Power Synchronization. In Proceedings of the 2020 20th IEEE International Conference on Environment and Electrical Engineering and 2020 4th IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS EUROPE), Madrid, Spain, 9–12 June 2020.

91. Zhang, Y.; Dong, C.; Liu, Q. Low Voltage Ride Through Control Strategy Considering Transient Overvoltage in Wind Power HVDC Transmission System. In Proceedings of the 2021 3rd Asia Energy and Electrical Engineering Symposium (AEEES 2021), Chengdu, China, 26–29 March 2021; pp. 396–401. [CrossRef]

92. Sagiraju, D.K.V.; Yeddulapeda, O.; Choppavarapu, S.B. A new control approach to improve the dynamic performance and ride through capability of PMSG wind energy system. *J. Renew. Sustain. Energy* **2018**, *10*, 043310. [CrossRef]

93. Roy, A.K.; Biswal, G.R.; Basak, P. An integrated rule-based power management and dynamic feed-forward low voltage ride through scheme for a grid-connected hybrid energy system. *J. Renew. Sustain. Energy* **2020**, *12*, 056303. [CrossRef]

94. Khan, A.; Ahmad, H.; Ahsan, S.M.; Gulzar, M.M.; Murawwat, S. Coordinated LVRT Support for a PMSG-Based Wind Energy Conversion System Integrated into a Weak AC-Grid. *Energies* **2021**, *14*, 6588. [CrossRef]

95. Saidi, Y.; Mezouar, A.; Amine, B.B.M.; Brahmi; Meddah, A.; Khalfallah, B.; Kerrouche, K.D.E. A Comprehensive Review of LVRT Capability and Advanced Nonlinear Backstepping Control of Grid-Connected Wind-Turbine-Driven Permanent Magnet Synchronous Generator During Voltage Dips. *J. Control. Autom. Electr. Syst.* **2022**, *33*, 1773–1791. [CrossRef]

96. Nasiri, M.; Faridpak, B.; Farrokhifar, M. Low Voltage Ride Through Enhancement in PMSG-based Wind Turbines using De-loading Droop. In Proceedings of the 2020 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), Tehran, Iran, 4–6 February 2020.

97. Baruwa, M.O.; Fazeli, M.; Egwebe, A.M. New control paradigm for both islanded and grid-connected operation of PMSG-based wind turbine. *J. Eng.* **2019**, *2019*, 5142–5146. [CrossRef]

98. Jiang, S.; Fan, C.; Huang, N.; Sun, S.; Li, G. LVRT Test Bench for Wind Turbines Based on Virtual Voltage Divider. In Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 5–10 August 2018.

99. Chen, G.; Cai, X. Reconfigurable Control for Fault-Tolerant of Parallel Converters in PMSG Wind Energy Conversion System. *IEEE Trans. Sustain. Energy* **2019**, *10*, 604–614. [CrossRef]

100. Abdelkhalek, N.M.; Abdelsalam, I.; Marei, M.I. A Reduced Cost Wind Energy Conversion System based on Permanent Magnet Synchronous Generator with a Parallel Connected AC-DC Buck-boost Converter. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS EUROPE), Palermo, Italy, 12–15 June 2018.

101. Vijayapriya, R.; Raja, P.; Selvan, M.P. A Modified Active Power Control Scheme for Enhanced Operation of PMSG-Based WGs. *IEEE Trans. Sustain. Energy* **2018**, *9*, 630–638. [CrossRef]

102. Gencer, A. Analysis and Control of Fault Ride-Through Capability Improvement for Wind Turbine Based on a Permanent Magnet Synchronous Generator Using an Interval Type-2 Fuzzy Logic System. *Energies* **2019**, *12*, 2289. [CrossRef]

103. Telukunta, V.; Pradhan, J.; Agrawal, A.; Singh, M.; Srivani, S.G. Protection challenges under bulk penetration of renewable energy resources in power systems: A review. *CSEE J. Power Energy Syst.* **2017**, *3*, 365–379. [CrossRef]

104. Mahmoud, M.M.; Hemeida, A.M.; Senjy, T.; Ewais, A.M. Fault Ride-Through Capability Enhancement For Grid-Connected Permanent Magnet Synchronous Generator Driven by Wind Turbines. In Proceedings of the 2019 IEEE Conference on Power Electronics and Renewable Energy (IEEE CPERE), Aswan, Egypt, 23–25 October 2019; pp. 567–572.

105. Nguyen, T.T.; Kim, H.M.; Yang, H.S. Impacts of a LVRT control strategy of offshore wind farms on the HTS power cable. *Energies* **2020**, *13*, 1194. [CrossRef]

106. Zhou, A.; Li, Y.W.; Mohamed, Y. Mechanical Stress Comparison of PMSG Wind Turbine LVRT Methods. *IEEE Trans. Energy Convers.* **2021**, *36*, 682–692. [CrossRef]
107. Gencer, A. Analysis and Control of Fault Ride Through Capability Improvement PMSG Based on WECS Using Active Crowbar System During Different Fault Conditions. *Elektron. Elektrotech.* **2018**, *24*, 63–69. [CrossRef]
108. Barros, L.S.; Barros, C.M.V. An internal model control for enhanced grid-connection of direct-driven PMSG-based wind generators. *Electr. Power Syst. Res.* **2017**, *151*, 440–450. [CrossRef]
109. Van, T.L.; Truong, T.H.; Cao, M.T.; Nguyen, P.C.; Nguyen, H. Improved Control Scheme for Low Voltage Ride-Through of PMSG-based Wind Energy Conversion Systems. In Proceedings of the 2018 4th International Conference on Green Technology and Sustainable Development (GTSD), Ho Chi Minh City, Vietnam, 23–24 November 2018; pp. 169–174.
110. Yuan, L.; Meng, K.; Huang, J.; Dong, Z.Y.; Zhang, W. Coordinated LVRT and HVRT control scheme for PMSG-based wind farm. In Proceedings of the 2019 29th Australasian Universities Power Engineering Conference, AUPEC 2019, Nadi, Fij, 26–29 November 2019. [CrossRef]
111. Geng, H.; Liu, L.; Li, R. Synchronization and Reactive Current Support of PMSG-Based Wind Farm during Severe Grid Fault. *IEEE Trans. Sustain. Energy* **2018**, *9*, 1596–1604. [CrossRef]
112. Aref, M.; Oboskalov, V.; Mahnitko, A.; Varfolomejeva, R. Protection design scheme of Grid connected PMSG wind turbine. In Proceedings of the 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 12–13 October 2017.
113. Farhadi-Kangarlu, M.; Babaei, E.; Blaabjerg, F. A comprehensive review of dynamic voltage restorers. *Int. J. Electr. Power Energy Syst.* **2017**, *92*, 136–155. [CrossRef]
114. Upadhvay, P.; Singh, N.; Yadav, S.; Gupta, S. Voltage quality compensation of DFIG with series DVR (SDVR) under three phase fault. In Proceedings of the 2018 2nd International Conference on Electronics, Materials Engineering and Nano-Technology, IEMENTech 2018, Kolkata, India, 4–5 May 2018. [CrossRef]
115. Srivastava, P.K.; Tiwari, A.N.; Singh, S.N. Performance Analysis of PMSG based Wind Energy Conversion System with Different LVRT Enhancement Methods. *Recent Adv. Electr. Electron. Eng. Former. Recent Pat. Electr. Electron. Eng.* **2019**, *13*, 470–485. [CrossRef]
116. Bahar, F.A.; Ajami, A.; Mokhtari, H.; Hojabri, H. A general analytical approach to reach maximum grid support by PMSG-based wind turbines under various grid faults. *J. Cent. South Univ.* **2019**, *26*, 2833–2844. [CrossRef]
117. Nadeem, F.; Hussain, S.M.S.; Tiwari, P.K.; Goswami, A.K.; Ustun, T.S. Comparative review of energy storage systems, their roles, and impacts on future power systems. *IEEE Access* **2019**, *7*, 4555–4585. [CrossRef]
118. Huang, C.; Xiao, X.Y.; Zheng, Z.; Wang, Y. Cooperative Control of SFCL and SMES for Protecting PMSG-Based WTGs under Grid Faults. *IEEE Trans. Appl. Supercond.* **2019**, *29*, 8–13. [CrossRef]
119. Argyrou, M.C.; Christodoulides, P.; Kalogirou, S.A. Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications. *Renew. Sustain. Energy Rev.* **2018**, *94*, 804–821. [CrossRef]
120. Kim, C.; Gui, Y.; Zhao, H.; Kim, W. Coordinated LVRT control for a permanent magnet synchronous generator wind turbine with energy storage system. *Appl. Sci.* **2020**, *10*, 3085. [CrossRef]
121. Kim, C.; Kim, W. Low-Voltage Ride-Through Coordinated Control for PMSG Wind Turbines Using De-Loaded Operation. *IEEE Access* **2021**, *9*, 66599–66606. [CrossRef]
122. Sang, S.; Zhang, C.; Cai, X.; Molinas, M.; Zhang, J.; Rao, F. Control of a Type-IV Wind Turbine with the Capability of Robust Grid-Synchronization and Inertial Response for Weak Grid Stable Operation. *IEEE Access* **2019**, *7*, 58553–58569. [CrossRef]
123. Sang, S.; Pei, B.; Huang, J.; Zhang, L.; Xue, X. Low-voltage ride-through of the novel voltage source-controlled pmsg-based wind turbine based on switching the virtual resistor. *Appl. Sci.* **2021**, *11*, 6204. [CrossRef]
124. Molina, M.G. Energy Storage and Power Electronics Technologies: A Strong Combination to Empower the Transformation to the Smart Grid. *Proc. IEEE* **2017**, *105*, 2191–2219. [CrossRef]
125. Yan, X.; Yang, L.; Li, T. The LVRT Control Scheme for PMSG-Based Wind Turbine. *Energies* **2021**, *14*, 518. [CrossRef]
126. Alam, M.S.; Abido, M.A.Y.; El-Amin, I. Fault Current Limiters in Power Systems: A Comprehensive Review. *Energies* **2018**, *11*, 1025. [CrossRef]
127. Firouzi, M.; Nasiri, M.; Benbouzid, M.; Gharehpetian, G.B. Application of multi-step bridge-type fault current limiter for fault ride-through capability enhancement of permanent magnet synchronous generator-based wind turbines. *Int. Trans. Electr. Energy Syst.* **2020**, *30*, e12611. [CrossRef]
128. Chen, L.; Chen, H.; Yang, J.; He, H. Development of a Voltage Compensation Type Active SFCL and Its Application for Transient Performance Enhancement of a PMSG-Based Wind Turbine System. *Adv. Condens. Matter Phys.* **2017**, *2017*, 9635219. [CrossRef]
129. Xu, L.; Lin, R.; Ding, L.; Huang, C. Enhancing the LVRT Capability of PMSG-Based Wind Turbines Based on R-SFCL. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *322*, 072044. [CrossRef]
130. Huang, C.; Zheng, Z.; Xiao, X.; Chen, X. Enhancing low-voltage ride-through capability of PMSG based on cost-effective fault current limiter and modified WTG control. *Electr. Power Syst. Res.* **2020**, *185*, 106358. [CrossRef]
131. Chen, L.; He, H.; Chen, H.; Wang, L.; Zhu, L.; Shu, Z. Study of a Modified Flux-Coupling-Type SFCL for Efficient Fault Ride-Through in a PMSG Wind Turbine Under Different Types of Faults. *Can. J. Electr. Comput. Eng.* **2017**, *40*, 189–200. [CrossRef]
132. Lee, H.J.; Lim, S.H.; Kim, J.C. Application of a superconducting fault current limiter to enhance the low-voltage ride-through capability of wind turbine generators. *Energies* **2019**, *12*, 1478. [CrossRef]

133. Mahmoud, M.M.; Hemeida, A.M.; Abdel-Rahim, A.-M.M. Behavior of PMSG Wind Turbines with Active Crowbar Protection Under Faults. In Proceedings of the 2019 Innovations in Power and Advanced Computing Technologies (I-PACT), Vellore, India, 22–23 March 2019.

134. Chen, C.; Liu, H.; Wu, L.; Shen, C.; Ju, Y. LVRT Test data analysis of converter-interfaced wind turbines. *J. Eng.* **2019**, *2019*, 1550–1553. [CrossRef]

135. Soliman, M.M.; El-Saady, G. A Fault Ride Through Strategy for Wind Energy Conversion System based on Permanent Magnet Synchronous Generator. In Proceedings of the 2018 International Conference on Innovative Trends in Computer Engineering (ITCE' 2018), Aswan, Egypt, 19–21 February 2018; pp. 453–460.

136. Chen, W.; Zheng, T.; Han, J. Fault Characteristic Analysis of a Permanent Magnet Synchronous Generator-based Wind Farm. In Proceedings of the 2019 22nd International Conference on Electrical Machines and Systems (ICEMS 2019), Harbin, China, 11–14 August 2019; pp. 1791–1797.

137. Chen, W.; Zheng, T.; Han, J. Fault Characteristic and Low Voltage Ride-Through Requirements Applicability Analysis for a Permanent Magnet Synchronous Generator-Based Wind Farm. *Energies* **2019**, *12*, 3400. [CrossRef]

138. Yuan, L.; Meng, K.; Huang, J.; Dong, Z.Y.; Zhang, W.; Xie, X. Development of HVRT and LVRT Control Strategy for PMSG-Based Wind Turbine Generators. *Energies* **2020**, *13*, 5442. [CrossRef]

139. Calik, H.; Dabakoglu, A.; Oguz, Y. Investigation of Dynamic Behaviour of Double Feed Induction Generator and Permanent Magnet Synchronous Generator Wind Turbines in Failure Conditions. *Int. J. Renew. Energy Res.* **2021**, *11*, 721–729.

140. Nasiri, M.; Arzani, A. Robust control scheme for the braking chopper of PMSG-based wind turbines-A comparative assessment. *Int. J. Electr. Power Energy Syst.* **2022**, *134*, 107322. [CrossRef]

141. Khezrabad, A.N.; Rahimi, M. Performance and dynamic response enhancement of PMSG-based wind turbines employing boost converter-diode rectifier as the machine-side converter. *Sci. Iran.* **2022**, *29*, 1523–1536. [CrossRef]

142. You, R.; Chai, J. A Novel Synchronous Type Variable Speed Wind Turbine and Its Control Strategy Study. *IEEJ Trans. Electr. Electron. Eng.* **2022**, *17*, 807–815. [CrossRef]

143. Aluko, A.O.; Akindeji, K.T. Mitigation of low voltage contingency of doubly fed induction generator wind farm using static synchronous compensator in south Africa. In Proceedings of the 2018 IEEE PES/IAS Powerafrica Conference, Cape Town, South Africa, 26–29 June 2018; pp. 13–18.

144. Dey, P.; Datta, M.; Fernando, N.; Senjyu, T. Fault-ride-through Performance Improvement of a PMSG based Wind Energy Systems via Coordinated Control of STATCOM. In Proceedings of the 2018 IEEE International Conference on Industrial Technology (ICIT), Lyon, France, 20–22 February 2018; pp. 1236–1241. [CrossRef]

145. Hiremath, R.; Moger, T. Comprehensive review on low voltage ride through capability of wind turbine generators. *Int. Trans. Electr. Energy Syst.* **2020**, *30*, e12524. [CrossRef]

146. Dayo, S.A.; Memon, S.H.; Uqaili, M.A.; Memon, Z.A. LVRT Enhancement of a Grid-tied PMSG-based Wind Farm using Static VAR Compensator. *Eng. Technol. Appl. Sci. Res.* **2021**, *11*, 7146–7151. [CrossRef]

147. Zheng, Z.; Xie, Q.; Huang, C.; Xiao, X.; Li, C. Superconducting Technology Based Fault Ride Through Strategy for PMSG-Based Wind Turbine Generator: A Comprehensive Review. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 5403106. [CrossRef]

148. Chen, L.; Li, G.; Chen, H.; Koh, L.H. Combined Use of SFCL and SMES for Augmenting FRT Performance and Smoothing Output Power of PMSG Based Wind Turbine. In Proceedings of the 2018 Asian Conference on Energy, Power and Transportation Electrification (ACEPT), Singapore, 30 October–2 November 2018.

149. Bahar, F.A.; Ajami, A.; Mokhtari, H.; Hojabri, H. A novel FRT strategy based on an analytical approach for PMSG-based wind turbines with ESS power rating reduction. *Turk. J. Electr. Eng. Comput. Sci.* **2018**, *26*, 2737–2752. [CrossRef]

150. Okedu, K.E. Augmentation of DFIG and PMSG Wind Turbines Transient Performance Using Different Fault Current Limiters. *Energies* **2022**, *15*, 4817. [CrossRef]

151. Okedu, K.E. Improving the Performance of PMSG Wind Turbines During Grid Fault Considering Different Strategies of Fault Current Limiters. *Front. Energy Res.* **2022**, *10*, 909044. [CrossRef]

152. Sheng, Y.; Li, C.; Jia, H.; Liu, B.; Li, B.; Coombs, T.A. Investigation on FRT Capability of PMSG-Based Offshore Wind Farm Using the SFCL. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 3091054. [CrossRef]

153. Mahmoud, M.M.; Salama, H.S.; Aly, M.M.; Abdel-Rahim, A.-M.M. Design and implementation of FLC system for fault ride-through capability enhancement in PMSG-wind systems. *Wind. Eng.* **2021**, *45*, 1361–1373. [CrossRef]

154. Taher, S.M.; Arani, Z.D.; Rahimi, M. A New Approach for Low Voltage Ride Through Enhancement in Grid-Connected Wind Farms. In Proceedings of the 2020 10th Smart Grid Conference (SGC), Kashan, Iran, 16–17 December 2020. [CrossRef]

155. Kheibargir, D.; Zeinali, R.; Aliabadi, S.M. Augmentation of fault ride-through capability of PMSG in a wind power plant using resistive SFCL and a new reactive current injection controller. In Proceedings of the 34th International Power System Conference (PSC2019), Tehran, Iran, 9–11 December 2019; pp. 623–631.

156. Yehia, D.M.; Mansour, D.-E.A.; Yuan, W. Fault Ride-Through Enhancement of PMSG Wind Turbines With DC Microgrids Using Resistive-Type SFCL. *IEEE Trans. Appl. Supercond.* **2018**, *28*, 2821362. [CrossRef]

157. Alam, M.S.; Abido, M.A.Y. Fault Ride Through Capability Enhancement of a Large-Scale PMSG Wind System with Bridge Type Fault Current Limiters. *Adv. Electr. Comput. Eng.* **2018**, *18*, 43–50. [CrossRef]

158. Fang, H.; Zhang, X. Improvement of Low-Voltage Ride-Through Capability for Wave Energy Conversion System. *IEEE Trans. Ind. Electron.* **2022**, *69*, 8123–8133. [CrossRef]

159. Worku, M.Y.; Abido, M.A. Fault Ride-Through and Power Smoothing Control of PMSG-Based Wind Generation Using Supercapacitor Energy Storage System. *Arab. J. Sci. Eng.* **2019**, *44*, 2067–2078. [CrossRef]
160. Sathya, E.; Maruthupandi, P. Enhancement of Low Voltage Ride Through Capability for PMSG Based Wind Energy Conversion System With Super Capacitor. In Proceedings of the 2018 4th International Conference on Electrical Energy Systems (ICEES), Chennai, India, 7–9 February 2018; pp. 57–60.
161. Ma, C.-T.; Shi, Z.-H. A Distributed Control Scheme Using SiC-Based Low Voltage Ride-Through Compensator for Wind Turbine Generators. *Micromachines* **2022**, *13*, 39. [CrossRef]
162. Moghadasi, N.; Esmaeli, A.; Soleymani, S.; Mozafari, B. Quasi-Z-source matrix converters to be used in PMSG-based WECS: Modeling, control, and comparison. *Int. Trans. Electr. Energy Syst.* **2018**, *28*, e2544. [CrossRef]
163. Yalla, N.; Agarwal, P. Active input current shaping with new MPC structured TP-TL-5L converter with reduced PSD count for renewable energy conversion. *Int. J. Electr. Power Energy Syst.* **2019**, *110*, 386–399. [CrossRef]
164. Yalla, N.; Agarwal, P. New MPC-5LUC with reduced PSD count for MVHP direct-drive WECS with PMSG: A cost-effective solution. *IET Electr. Power Appl.* **2019**, *13*, 1474–1487. [CrossRef]
165. Jin, J.X.; Yang, R.H.; Zhang, R.T.; Fan, Y.J.; Xie, Q.; Chen, X.Y. Combined low voltage ride through and power smoothing control for DFIG/PMSG hybrid wind energy conversion system employing a SMES-based AC-DC unified power quality conditioner. *Int. J. Electr. Power Energy Syst.* **2021**, *128*, 106733. [CrossRef]
166. Elshiekh, M.E.; Mansour, D.-E.A.; Zhang, M.; Yuan, W.; Wang, H.; Xie, M. New Technique for Using SMES to Limit Fault Currents in Wind Farm Power Systems. *IEEE Trans. Appl. Superconduct.* **2018**, *28*, 1–5. [CrossRef]
167. Fard, M.T.; Hagh, M.T. Current Source Inverter Based Grid Connected Hybrid PV-Wind Power Generation Unit. *Int. J. Electron.* **2020**, *107*, 839–857. [CrossRef]
168. Mthiyane, B.; Buraimoh, E.; Davidson, I.E. Investigation of Fault Ride Through Capabilities of DFIG and PMSG Wind System. In Proceedings of the 2021 IEEE PES/IAS Powerafrica Conference, Virtual, 23–27 August 2021; pp. 447–451. [CrossRef]
169. Mahmoud, M.M.; Aly, M.M.; Salama, H.S.; Abdel-Rahim, A.-M.M. An internal parallel capacitor control strategy for DC-link voltage stabilization of PMSG-based wind turbine under various fault conditions. *Wind. Eng.* **2022**, *46*, 983–992. [CrossRef]
170. Xie, Q.; Zheng, Z.; Huang, C.; Dai, T. Coordinated Fault Ride Through Method for PMSG-Based Wind Turbine Using SFCL and Modified Control Strategy. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 5402805. [CrossRef]
171. Mahmoud, M.M.; Aly, M.M.; Abdel-Rahim, A.-M.M. Enhancing the dynamic performance of a wind-driven PMSG implementing different optimization techniques. *Appl. Sci.* **2020**, *2*, 684. [CrossRef]
172. Mahmoud, M.M.; Aly, M.M.; Salama, H.S.; Abdel-Rahim, A.-M.M. Dynamic evaluation of optimization techniques-based proportional-integral controller for wind-driven permanent magnet synchronous generator. *Wind. Eng.* **2021**, *45*, 696–709. [CrossRef]
173. Kim, C.; Kim, W. Coordinated Fuzzy-Based Low-Voltage Ride-Through Control for PMSG Wind Turbines and Energy Storage Systems. *IEEE Access* **2020**, *8*, 105874–105885. [CrossRef]
174. Basak, R.; Bhuvaneswari, G.; Pillai, R.R. Low-Voltage Ride-Through of a Synchronous Generator-Based Variable Speed Grid-Interfaced Wind Energy Conversion System. *IEEE Trans. Ind. Appl.* **2020**, *56*, 752–762. [CrossRef]