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

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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.

Keywords: permanent magnet synchronous generators; grid codes; fault ride-through; wind energy; fault condition

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.
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].

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.

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.

\[ P_w = \frac{1}{2} \rho AV_w^3 C_p(\lambda, \beta) \]  \hspace{1cm} (1)

where \( P_w \) is the captured wind power (W); \( C_p \) is the power coefficient; \( \rho \) 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 (\( \lambda \)) and pitch angle (\( \beta \)), respectively, as expressed in the following equation [29,30].

\[ C_p(\lambda, \beta) = c_1 \left( \frac{C_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda}} + c_6 \lambda \]  \hspace{1cm} (2)

where

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda - 0.08 \beta - 0.035} - \frac{1}{\beta^3 + 1} \]  \hspace{1cm} (3)

\[ \text{Turbine Power Characteristics} \]

\[ \text{Max. power at base wind speed (12 m/s) and beta ~ 0 deg} \]

\[ \text{12 m/s} \]

\[ \text{10.8 m/s} \]

\[ \text{9.6 m/s} \]

\[ \text{8.4 m/s} \]

\[ \text{7.2 m/s} \]

\[ \text{6 m/s} \]

\[ \text{-0.2} \]

\[ \text{0} \]

\[ \text{0.2} \]

\[ \text{0.4} \]

\[ \text{0.6} \]

\[ \text{0.8} \]

\[ \text{1} \]

\[ \text{Turbine speed (m/s)} \]

\[ \text{Turbine output power (pu)} \]

Figure 5. Schematic of a PMSG-WT.

3.2. Aerodynamic Modeling

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

\[ P_m = P_g + P_s \]

\[ Q_m = Q_s \]

\[ P_m = \frac{1}{2} \rho AV_w^3 C_p(\lambda, \beta) \]  \hspace{1cm} (4)

where \( \lambda \) is the optimal value of \( \lambda \) and \( \beta \) is the rotor speed of the wind generator.

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].

\[
P_{\text{MPPT}} = \frac{1}{2} \rho A \left( \frac{\omega_r R}{\lambda_{\text{opt}}} \right)^3 c_{\text{opt}}
\]

where \( \lambda_{\text{opt}} \) is the optimal value of \( \lambda \) and \( \omega_r \) 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]:

\[
\frac{d\psi_{sd}}{dt} = -V_{sd} - R_s I_{sd} - \omega_e \psi_{sq}
\]

\[
\frac{d\psi_{sq}}{dt} = -V_{sq} - R_s I_{sq} - \omega_e \psi_{sd}
\]

From Equations (5) and (6)

\[
\psi_{sd} = (L_{sd} + L_{md}) I_{sd} + \psi_m
\]

\[
\psi_{sq} = (L_{sq} + L_{mq}) I_{sq}
\]

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; \( \omega_e \) is the angular velocity; \( \psi_{sd} \) and \( \psi_{sq} \) 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 \( \psi_m \) 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:

\[
L_d \frac{dI_{sd}}{dt} = -V_{sd} - R_s I_{sd} - \omega_e L_q I_{sq}
\]

\[
L_q \frac{dI_{sq}}{dt} = -V_{sq} - R_s I_{sq} - \omega_e L_d I_{sd} + \omega_e \psi_m
\]

\[
I_{sd} = L_{sd} + L_{md}
\]

\[
I_{sq} = L_{sq} + L_{mq}
\]

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

\[
P_s = V_{sd} I_{sd} + V_{sq} I_{sq}
\]

\[
Q_s = V_{sq} I_{sd} - V_{sd} I_{sq}
\]

The electrical torque of the generator is given as:

\[
T_e = 0.5p(\psi_m I_{sq} + (L_d - L_q) I_{sd} I_{sq})
\]

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

\[
T_e = \left( \frac{3}{2} \right) p(\psi_m I_{sq})
\]

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].](image)

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.

\[
\frac{\Delta I_o}{I_n} = k \frac{\Delta V}{V_n} \quad (17)
\]

\[
\Delta V = V - V_0 \quad (18)
\]

where \(\Delta I_o\) is the required reactive current change during the fault; \(I_n\) is the rated current; \(\Delta V\) 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].](image)
**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.](image-url)
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.

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 10. Keyword map of the PMSG FRT technique over time.
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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.
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**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.
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.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Solution</th>
</tr>
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<tbody>
<tr>
<td>[52–55]</td>
<td>Stored rotor kinetic energy technique</td>
</tr>
<tr>
<td>[56]</td>
<td>Whale optimization technique</td>
</tr>
<tr>
<td>[57]</td>
<td>Least mean and square root of exponential (LMSRE) algorithm</td>
</tr>
<tr>
<td>[45,58]</td>
<td>Sliding mode control</td>
</tr>
<tr>
<td>[59]</td>
<td>Artificial intelligence</td>
</tr>
<tr>
<td>[60,61]</td>
<td>Machine parameters varying technique</td>
</tr>
<tr>
<td>[62]</td>
<td>Linear active disturbance rejection control</td>
</tr>
<tr>
<td>[49,63]</td>
<td>A grey wolf optimization of conventional PI controllers</td>
</tr>
<tr>
<td>[64–66]</td>
<td>Feedback linearization-based controller</td>
</tr>
<tr>
<td>[67–71]</td>
<td>A fuzzy controller</td>
</tr>
<tr>
<td>[72–76]</td>
<td>Pitch angle control</td>
</tr>
<tr>
<td>[80,81]</td>
<td>A fast reactive current controller</td>
</tr>
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Table 1. Cont.

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

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].](image-url)
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).

$$D = \frac{\text{braking resistance (R}_{bc}\text{)}}{\text{DC-link voltage (V}_{dc}\text{)}} \times \left( \frac{P_g - P_{grid}}{2} \right)$$  \hspace{1cm} (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.

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-FACTS 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.
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. 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.](image)

Table 2. Hardware-based PMSG LVRT solution schemes.

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

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

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.

<table>
<thead>
<tr>
<th>FRT Scheme</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy storage devices/batteries</td>
<td>High</td>
</tr>
<tr>
<td>DC chopper</td>
<td>cheap</td>
</tr>
<tr>
<td>FACTS</td>
<td>Very high</td>
</tr>
<tr>
<td>Crowbar</td>
<td>cheap</td>
</tr>
<tr>
<td>Machine and grid-side converters</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

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.

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