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Review Article

Evaluation and Comparison of Different Methods for Improving Fault Ride-Through Capability in Grid-Tied Permanent Magnet Synchronous Wind Generators

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Several advantages make wind-driven permanent magnet synchronous generators (PMSGs) very promising in the wind energy market, especially their fault ride-through capabilities. With the high penetration levels of today, both the grid and wind power (WP) systems are being affected by each other. Due to grid faults, the DC-bus in PMSG systems typically experiences overvoltage, which can negatively affect the generator parameters and trip the system. However, advancements in power electronics, control systems, fault limiters, FACTS, and energy storage technology make it possible to find and design satisfactory solutions and approaches. The most recent FRTC-improving techniques are mainly modified or external techniques based on controllers in PMSG-based WP. This paper evaluates the in-depth schemes of FRTC, introducing the underlying theory and traits of the different approaches to highlight the advantages and drawbacks of each. Five scenarios of DC-link voltage under zero-grid voltage are carried out by using the MATLAB SIMULINK program to assess the FRTC methods. This study shows that external device-based approaches can be efficient, but some of them are expensive, thus updated controller methods are recommended to cut costs. Research findings of this study are expected to support the deployment of FRTC technologies, as well as provide valuable input into WP research on grid integration.

1. Introduction

Recent years have seen a rapid growth in the integration of renewable energy systems (RESs), and by the middle of this century, about $12 trillion are supposed to be saved by the decarbonized global energy system [1, 2]. The RESs specially wind farm will assist increasing a global access to green energy by lowering the production and distribution prices and losses as well as enabling capturing higher levels of the renewable energy output [3–6]. As a result, the researchers have focused their efforts on utilizing the wind energy. In particular, the number of wind farms rated at MW or more has grown significantly in recent years. Few of these are now under development across the world, with mega-plants proposed in Australia, France, Germany, the Netherlands, Paraguay, Portugal, the United Kingdom, and the United States [3, 5].

With a projected installed capacity of 20 GW, the Jiuquan Wind Power Base is the world's biggest wind farm [7]. In Gansu, China, 7,000 wind turbines will be built throughout the provinces of Jiuquan, Inner Mongolia, Hebei, Xinjiang, Jiangsu, and Shandong. The Renewable Energy Law was established in February 2005, with the objective of installing 200 GW of wind power throughout the country [7, 8]. Another is a 1,600 MW wind park in Jaisalmer, Rajasthan, which is India's largest wind farm [9]. Suzlon built wind farms for independent power producers and power utilities, in addition to private and public sector clients. The Alta Wind Energy Centre (AWEC) has a capacity of 1,548 MW and is located near Tehachapi, Kern County, California [10]. The first five stages of AWEC were completed. Two more stages were added the following year. The first stage will use 100 Ge 1.5 MW SLE turbines. Vestas V 90–3.0 MW turbines power the last six operating phases. The identical Vestas turbines power the seventh, eighth, and ninth stages. The latter two stages have GE 1.7 MW and GE 2.85 MW turbines installed [10]. However, to force the impact of renewable energy generation on the energy sector and the environment, pioneer countries have set strict goals to be achieved in this sector as indicated in Table 1 [5, 11, 12]. Given the rising levels of wind and solar systems' penetration in the electrical power grid and the results of loss of inertia and inconsistency of the energy supply and taking the requirements of the grid codes (GCs) into consideration, the necessity to keep those wind systems (WS) connected to the power grid during a disruption is now urgent and the failure to do so will have reprehensible influences on the security and reliability of the power system (PS) [13, 14]. Figure 1 shows the top ten global WS markets, encompassing on- and offshore industries [6, 15, 16].

Table 1: RE targets 36 countries interested in the installation of green sources.

Country	RE target (%)	To be reached by
China	40	2030
Iceland	72	2020
Norway	67.5	2020
Sweden	49	2020
Germany	18	2020
Finland	38	2020
Austria	34	2020
France	32	2030
French islands	32	2030
Denmark	30	2030
Turkey	30	2030
Romania	24	2030
Switzerland	24	2030
Japan	(22–24)	2030
Spain	32	2030
Australia	69	2030
Egypt	42	2035
Portugal	31; 40	2020; 2030
Chile	20	2025
Greece	18	2020
Italy	17	2020
Ireland	16	2020
Hungary	15	2020
UK	15	2020
Poland	15	2020
Netherlands	14.5	2020
Czech Republic	13.5	2020
Belgium	13	2020
Cyprus	13	2020
South Korea	11	2030
South Africa	10	2030
India	(35–40)	2022
USA	30	2020
Canada	63	2025
New Zealand	50; 90	2017; 2025
Honduras	50; 60; 80	2017; 2022; 2034

Recently, the two mainstream wind generators (WGs) are the doubly-fed induction generator (DFIG) [17, 18] and the permanent magnet synchronous wind generator (PMSWG) [19, 20]. Currently, PMSWG has received a lot of interest due to its advantages over other dominant ones such as higher efficiency, maximum power extraction, reliability, and operation at low speeds with high torque and no need for gearbox, these merits are enough to shift the wind market to push the industry of PMSWG [21–24]. PMSWG needs to adopt full-scale back-to-back converters (BTBCs) whereas DFIG uses partial BTBCs and requires a gearbox for accomplishing its operation. The full-scale BTBCs offer better efficiency and high cost compared with its partial counterpart so, protecting them is an essential and important thing to do [25–28]. Nonetheless, the fault ride-through capability (FRTC) of PMSWG is higher than DFIG, it is still revolutionary to augment its FRTC since the accrued excess power in the DC linkage under the voltage sag and swell will result in overvoltage which might subsequently lead to the tripping of the overall WS [29–31]. Many methods are examined with their control systems during symmetrical and asymmetrical faults to achieve FRTC, even at zero system voltage. They are presented and studied to solve this problem; however, these systems have benefits and of course limitations and this paper is here trying to address and conclude some of these limitations [32–37].

Faults may occur due to different reasons namely as a result of a short circuit, starting of induction machines, disconnection of capacitive loads, etc. The fault types which occur in the electrical power system are usually categorized as unsymmetrical (like: 1 LG, 2 LL, 2 LLG) and symmetrical (like: 3 LG) as listed in Table 2. From Table 2, 1 LG represents the highest happening percentage but it has a much lesser impact on the system. On the contrary, 3 LG is scarcely happening but its impact on the system is much more severe [38, 39]. To achieve a safe and reliable operation, FRTC has become the most prevalent grid connection specification for PMSWG around the world. The inherent instability and intermittency of WS, as well as the increasingly poor grid link, pose a major challenge and importance for FRTC topic [40, 41].

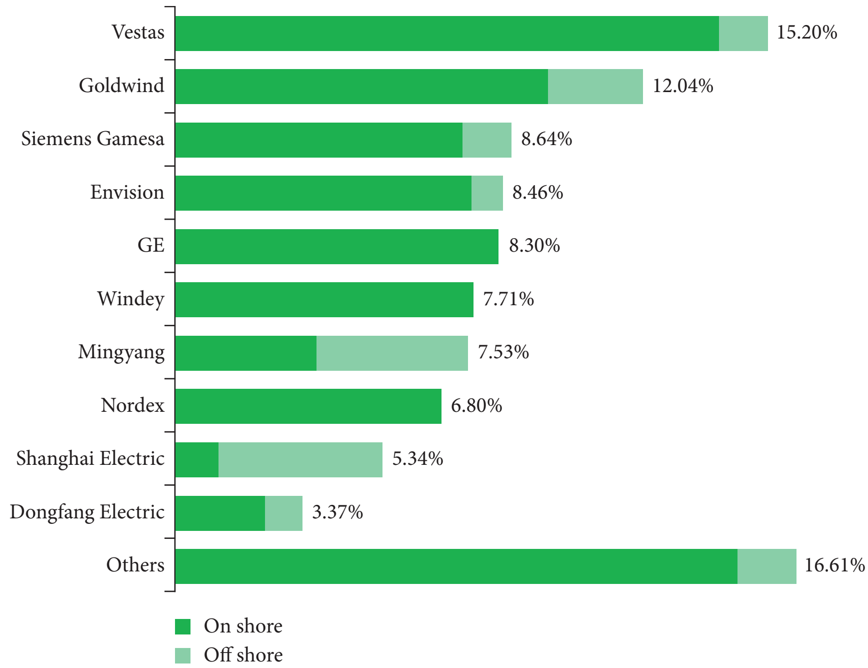

Figure 1: Top ten global WS markets, including on- and offshore sorts.

Table 2: Fault types and their % happening [38].

Fault type	% occurrence
1 LG	70–85
2 L	15–8
2 LG	10–4
3 LG	5–3

For achieving FRTC, WS must endure faults and continue to be connected to the power grid to maintain voltage and frequency both before and after the fault. The control-based system (CBS) [42–44], the unit-based system (UBS) [29, 45, 46], and the coordinated control system (CCS) [47] are three major categories for the current FRTC techniques. Due to its lower cost and simplicity, UBS is renowned and consistently demonstrates its success in satisfying the FRTC for WGs, particularly the braking chopper (BC) system. The research on superconducting application technology has increased due to the ongoing efforts to lower the system's cost of these materials. Superconducting innovations, including SMES, supercapacitors, and superconducting fault current limiters (SFCL), have recently demonstrated potential benefits in improving the FRTC of WGs.

This study thoroughly evaluates several FRTC methods for PMSWG and introduces the fundamental ideas and features of the different methods to encourage the adoption of CBS, UBS, and CCS for achieving the FRTC and consequently boosting the grid integration of WS. The purpose of this essay is to assess the most recent developments in this field of study and summaries its current state. MATLAB software is used to illustrate and simulate the effect of the most well-known of these strategies on the DC-link (DCL) voltage. Based on the topics of research studies, the overall trends in the technological advancement are shown in percentage values. As a result, the article discusses potential future trends as well as the FRTC methods' existing advancements and difficulties.

2. PMSWG Description and Modeling for FRTC Studies

The operating system of WS is composed of two parts. First, the wind's kinetic energy is captured by the turbine's aerodynamic rotor, which converts it into mechanical energy. Second, the power conversion process is finished by using a WG to convert ME into electrical energy, which is then sent to an electrical power grid [48, 49]. As can be seen in Figure 2, the examined WS's basic structure is made up of a wind turbine (WT), PMSWG, machine side converter (MSC), DCL, grid side converter (GSC), filters, and associated complete control systems.

2.1. WT Characteristics. WS characteristics such as C_p, λ, P_M and T_m are expressed as in surveys [6, 50] and are given by equations (1)–(12).

$$P_M = 0.5C_p(\lambda.\beta)\rho A v_W^3, \quad (1)$$

$$C_p(\lambda.\beta) = 0.5176\left(\frac{116}{\lambda i} - 0.4\beta - 5\right)\exp^{(-21/\lambda i)} + 0.0068\lambda, \quad (2)$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda + .08\beta} - \frac{.035}{\beta^3 + 1}, \quad (3)$$

$$\lambda = \frac{\omega_r R}{V_W}. \tag{4}$$

From equation (4), we can obtain the value of ω_r at optimal λ and operated V_W

$$T_m = \frac{P_M}{\omega_r}, \tag{5}$$

$$T_m = J_{\text{eq}}\frac{d\omega_r}{dt} + B_{\text{eq}}\omega_r + T_e. \tag{6}$$

2.2. Modeling of PMSWG, DC-Link, and Grid. The PMSWG model is represented by the equations from (7) to (12). DCL can be characterized by equation (13) and serves as a middle bridge for transmitting power from MSC to GSC. The voltage at DCL $V_{\text{dc}} \geq 1.633V_{\text{grid}}$ according to [51] and [52]. Equations from (14) to (17) can be used to represent the grid model. In addition, the definitions and descriptions of the utilized symbols are given in [53–56].

$$V_{ds} = R_d I_d + \dot{\lambda_d} - \omega_e \psi_q, \tag{7}$$

$$V_{\text{qs}} = R_s I_q + \dot{\lambda_q} - \omega_{\text{e}} \psi_{\text{d}}, \tag{8}$$

$$\psi_d = L_d I_d + \psi_{pm}, \tag{9}$$

$$\psi_q = L_q I_q, \tag{10}$$

$$\lambda_d = L_d I_d + \psi_{pm}, \tag{11}$$

$$T_e = \frac{3}{2} n_p \left(\psi_{pm} I_q\right), \tag{12}$$

$$C\frac{dV_{\text{dc}}}{dt} = \frac{P_{\text{MSC}}}{V_{\text{dc}}} - \frac{P_{\text{GSC}}}{V_{\text{dc}}}, \tag{13}$$

$$V_{gd}^{*} = V_{id} - R_g I_{gd} - L_g \frac{d}{dt} I_{gd} - L_g \omega_e I_{gq}, \tag{14}$$

$$V_{gq}^{*} = V_{iq} - R_g I_{gq} - L_g \frac{d}{dt} I_{gq} - L_g \omega_e I_{gq}, \tag{15}$$

$$P_s = \frac{3}{2} V_{gd} I_{gd}, \tag{16}$$

$$Q_s = \frac{3}{2} V_{gd} I_{gq}. \tag{17}$$

3. FRTC Realization for a Grid-Connected PMSWG

This part explains the concepts of FRTC and discusses why modern GCs necessitate the realization of FRTC.

3.1. Operation of PMSWG during FRTC. As the penetration of WS increases, the need to address FRTC issues becomes more critical. Earlier, WS was allowed to trip when a fault occurs but now this cannot even be thought about. Normally, the P_{MSC} is often equal to the P_{GSC}, and thus, the DCL voltage is maintained at its regular value. When grid fault takes place, the voltage dip causes the P_{GSC} to rapidly decrease but the P_{MSC} does not change. Due to this accumulation of visible excess power, DCL experiences an overvoltage [57]. The DCL capacitor could be harmed as a result of this overvoltage, which could also stress MSC, GSC, and cause PMSWG saturation. To maintain continuous injected P to the electric grid, the GSC current increases. Therefore, eliminating excess power and avoiding DCL overvoltage constitute the fundamental principles for improving FRTC. As seen in Figure 2, there are three different types of strategies that can be employed to accomplish the goal: (1) decreasing P_{MSC}, which includes modified pitch angle control (PAC) and converter control; (2) raising P_{GSC}, symbolized by SFCL; and (3) immediately dissipating excess power ΔP, which is commonly carried out by BC [58]. In this study, the authors' passion is to analyze and evaluate the different methods as well as the PMSWG control systems studied in the literature.

Only when they are technically necessary for the reliable and secure functioning of a PS are WS designs obliged to include FRTC in accordance with GC specifications. The WS must maximize its reactive power (Q) injections into the system while staying within the WT restrictions, this is actually the fundamental need for FRTC. After the fault had already been cleared, the reactive current must be maximized for at least 150 milliseconds, or until the grid voltage is returned to its normal operating range [59]. For more clarification, Figure 3 is presented.

3.2. Modern GCs. The practical necessities obligatory on WSs are identified as GCs, which are demarcated by transmission systems operators to specify the mission of grid components such as generators or loads in all situations and rough draft the constitutional rights [52]. One of the significant topics in GCs instructions is the FRTC. Figure 3(a) displays the FRTC curves related to the GCs of different countries.

As depicted in Figure 3(a), the WS keeps on tied to the power grid (PG) above the curves during fault situations, and the WS may be separated from the PG under these curves. GCs require the WS to care about the voltage stability of the PG as well. Figure 3(b), as a portion of the Danish GC, displays how the Q behavior should be when voltage dips occur at the point of common coupling (PCC) [52, 60].

4. FRTC Enhancement Methods

UBS and CBS are the two most common forms of FRTC improvement approaches. To improve FRTCs, UBS solutions such energy storage, BC, FACTS, SFCL, and series dynamic braking resistor (SDBR) are frequently utilized

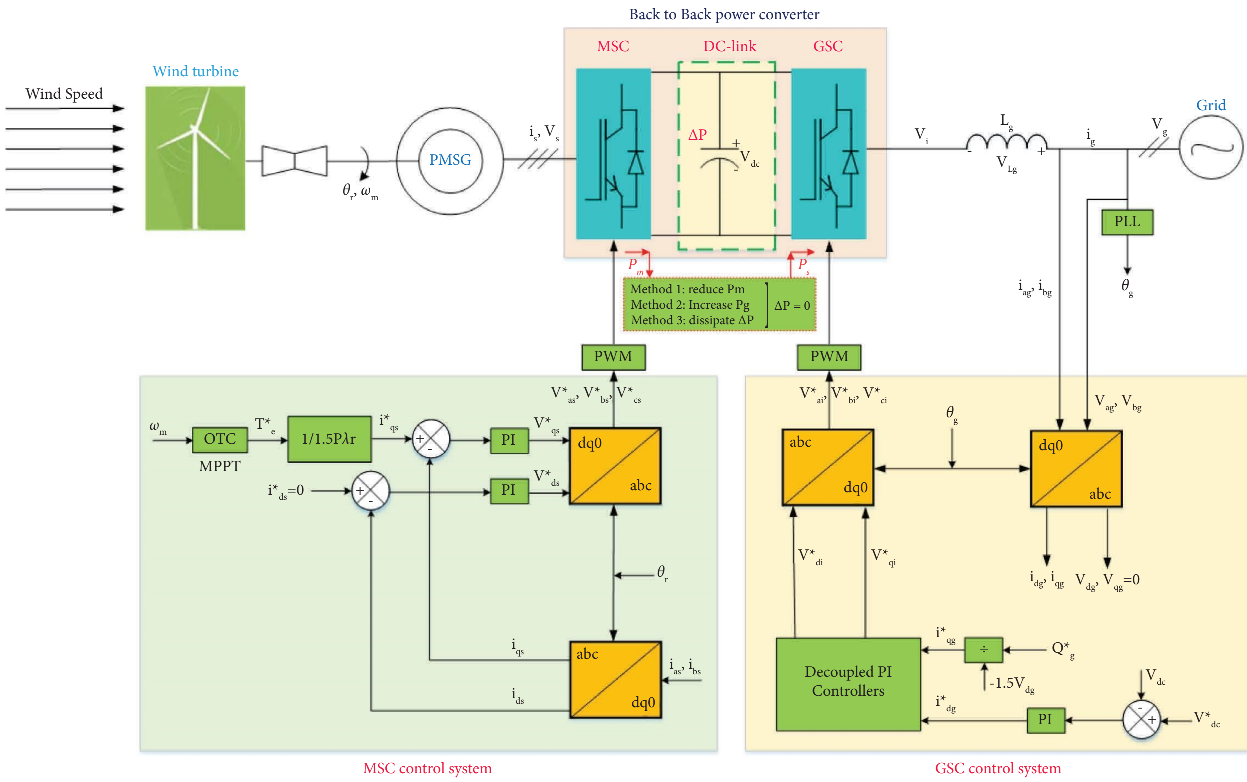

FIGURE 2: PMSWG connected to the grid via BTBCs with their control system.

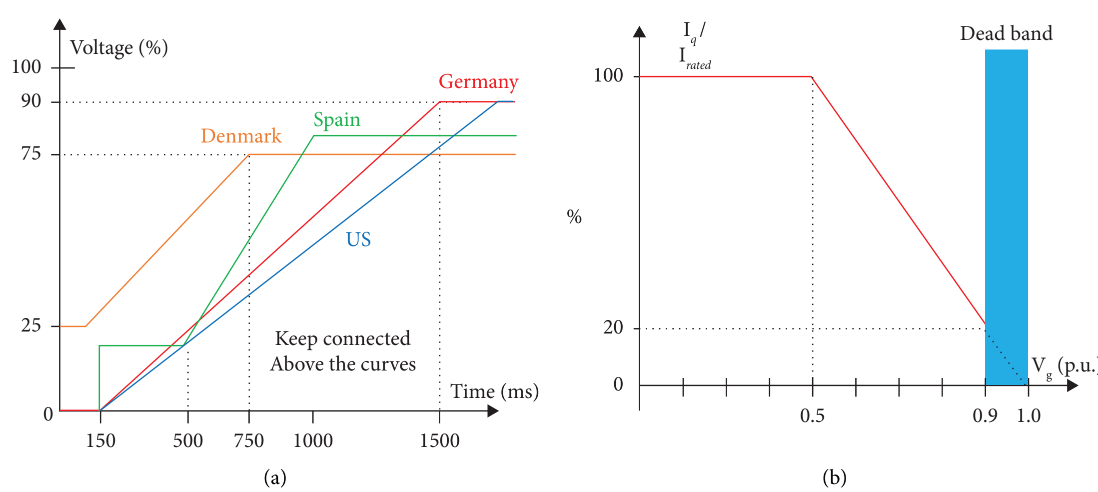

FIGURE 3: GC requirements that consist of (a) ride-through curve of different codes and (b) support curve of reactive current [60].

[29]. The CBS options can be like PAC and modified converter control loops as reported in [52, 57, 61]. The possible FRTC methods are summed up in Figure 4.

4.1. UBS Methods. UBSs are presented here to clarify their benefits, drawbacks, and principles of operation.

4.1.1. Energy Storage Units (ESUs). ESUs can be linked to the DCL through a (DC\DC) power converter or at the PCC bus in the investigated system as depicted in Figures 5 and 6, respectively. The ESS can absorb or feed P&Q from or to the system in need of compensation by managing and controlling the DC/DC and voltage source converters (VSCs). The two converters give system-side a very high degree of controllability but at a considerable cost and power loss. Compared to the AC side, DC side ESU mitigates the application of a VSC which results in reducing losses and prices. The DC side integration can stabilize the DCL voltage and achieve FRTC [62, 63]. The majority of current research focuses on the ESU control approach, involving enhanced control strategy and optimizing PI controller gains, as illustrated in Table 3.

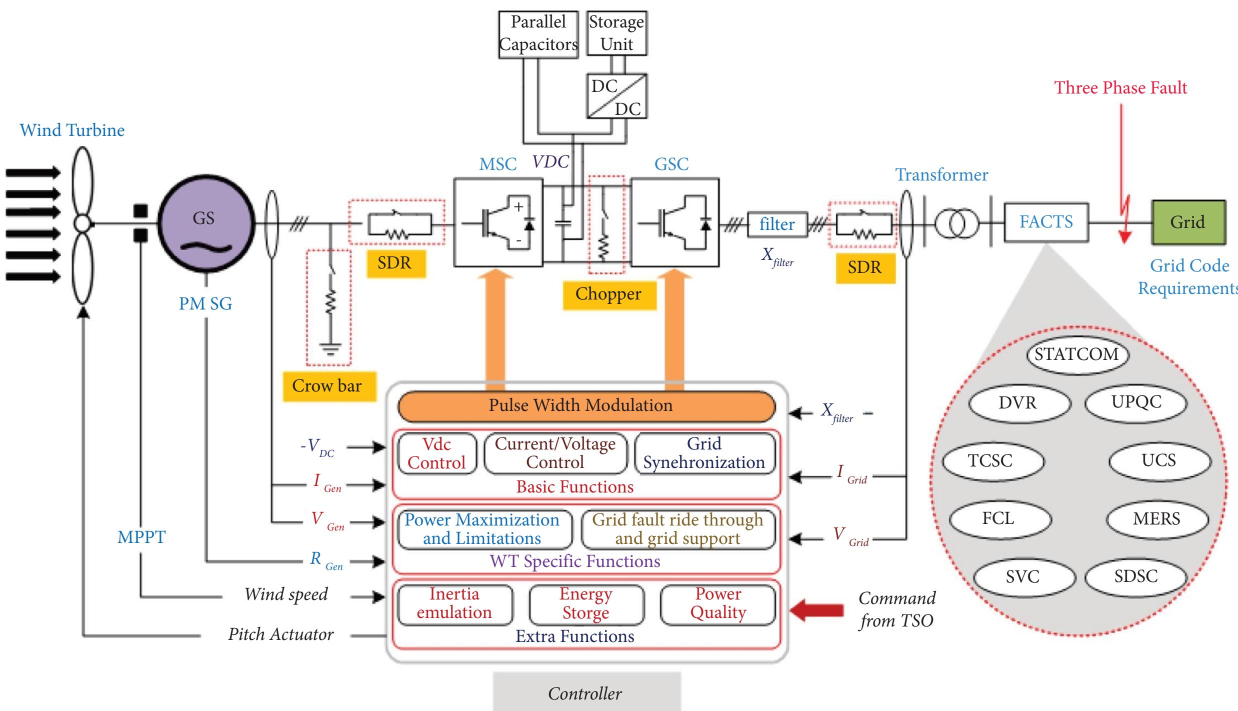

FIGURE 4: The designed and implemented FRTC methods for PMSWG.

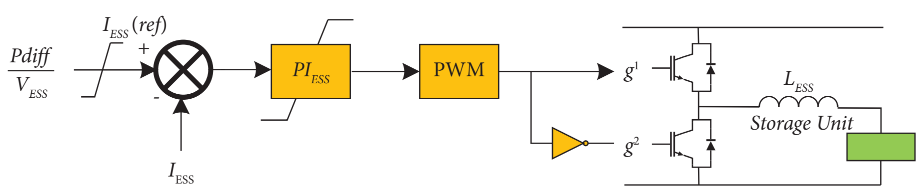

FIGURE 5: The connection of the storage unit to the DCL via a DC\DC converter with the control system.

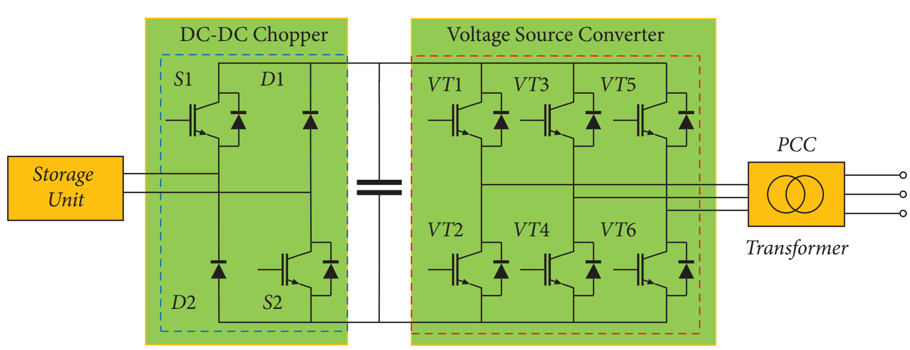

FIGURE 6: Connection of the storage unit to the PCC via a DC\DC and VS converters.

TABLE 3: ESS-related studies in many structures.

References	Position (kV)	Power converter controllers	
		DC/DC	VSC
[64]	25	FLC	Conventional PI
[65]	66	PSO-based PI	PSO-based PI
[66]	690	ANN-based PI	ANN-based PI
[67]	66	Adaptive ANN	Conventional PI
[68]	66	SMAPA-based adaptive PI	SMAPA-based adaptive PI

Battery, flywheel, SMES, and supercapacitor are four different types of ESUs utilized in FRTC realization [52].

Batteries come in a variety of forms, including lead-acid (LA), nickel-cadmium (NiCd), sodium-sulfur (NaS), and lithium-ion (LiI) and are one of the oldest and most widely used choices for ESUs. The LA performs extremely poorly at both low & high environmental temperatures while also having a brief lifespan. The NiCd has a high cyclic life and requires a little maintenance. Despite its positive technical qualities, the NiCd type has not been commercially successful owing to its high prices which are more than ten times that of LA. One of the most promising choices for high-power energy storage applications is the NaS. This sort has high energy density as well as high energy efficiency. The LiI type is commonly utilized in tiny applications such as mobile phones and portable electrical gadgets. Its major characteristic is its ability to charge and discharge quickly. Because of its short-time constants, it is suitable for applications where response time and weight are essential factors to care about (about 200 ms) [69].

A flywheel is an electromechanical tool used to store kinetic energy. Energy is transferred to the flywheel when the system is operating as a motor, and the flywheel charges as an ESU. The machine regenerates through the drive, which causes energy to be released. It offers advantageous qualities in terms of a longer cyclic life, a wide working temperature range, higher power, and energy density. Due to their self-discharge, they are poor long-term ESU candidates [70].

SMES is an electromagnetic storage unit that stores energy in the form of a magnetic field. It is composed of 3 parts: a superconducting coil, a refrigeration system, and a power conditioning system. The energy is stored across the coil during SMES charging mode, and the stored energy is fed into the power grid using power converters during SMES discharging mode. The SMES coil is kept cool below its superconducting critical temperature, and the amount of energy it can store depends on the current's strength and coil's inductance. These systems are an excellent choice for FRTC because of their intriguing properties such as high-power density, longer cyclical life, low energy density, almost minimal energy loss, and rapid time response. Despite their technological capabilities, few systems are developed, due to their exorbitant cost [71, 72]. The internal resistance of the power circuit and nontrivial quantities of self-discharge could be detrimental to SMES and its managing system might impact the overall WS efficiency. The SMES can be linked at the DC bus through the DC\DC converter or at the PCC bus, but it needs a VSC in addition to the DC\DC as depicted in Figures 5 and 6. These converters can be controlled with different controllers such as FLC, optimized PI, ANN, and others. The feasibility of this solution is low.

The electrochemical cell types that form the basis of supercapacitors (SCs) have two conducting poles, a solution, and a pore membrane that allows ions to pass between the two poles. Due to its extremely low relative resistance, and short-time constant, it is a candidate for short-time scale applications with high responses. Other important features are long cyclical life, no need for maintenance, independence of chemical reactions, very fast response, and a high degree of energy effectiveness. Last but not the least, it should be highlighted that the biggest disadvantage of SC is its high price, which is expected to be five times that of a LA [73].

Based on the characteristics of the various ESU types, tools for FRTC augmentation such as SCs and SMES are short-term, small power saving systems. SC is an appealing alternative for improving FRTC since, in comparison to other types of ESUs, it offers a very fast response [74]. SC's power capacity was decreased in [75] using mechanical momentum. In normal and abnormal conditions, SC improved power smoothing and store the excess power at the DCL. Nonetheless, to store some energy in the rotor, the speed target in the MSC is adjusted to greater than it would be under regular circumstances. As a result, the power generated from the PMSWG will be lower and consequently, the SC rating may be decreased. In [76], SC reference current was obtained by V_{dc} after going via the PI controller with an error. Additionally, the rating of SC was selected at 30% of the BTBC rating in order to lower its budget. The BC system dissipates the remaining gap in P.

SMES is now another alternative for usage in WS because of its great efficiency. Despite being expensive, it also responds quickly. SMES and SC were hence preferable choices among ESUs for realizing FRTC in PMSWG. The fundamental disadvantage of ESUs is that they need a large amount in deep continuous voltage drop in MW-class WTs [77].

4.1.2. BC System. A BC system was suggested to be installed in DCL to dissipate surplus power during grid disturbances. The BC is composed of a high-power resistor and a series of IGBT switches, with the advantages of low cost and a simple control structure. BC can only dissipate power and cannot enhance Q injection to the grid since it must dissipate all WG power in order to free the GSC capacity to inject Q into the grid. This methodology may be used with other methods to improve the system performance [45, 54, 71, 78]. Figure 7 depicts the BC system and its control.

4.1.3. SDBR System. As shown in Figure 8, the SDBR is a series-connected resistor that is normally short-circuited between the WG and PCC and is put into the circuit during a failure. It is most commonly utilized in fixed-speed WS types [72, 73]. The output GSC voltage is boosted during grid voltage drops by the flowing current through the resistance, as explained in [74]. Overvoltage in the DCL is prevented as a result of dissipated energy at the DCL. When the safety thresholds for DCL voltage or GS current are exceeded, the bypass switch opens.

As a result, both GS current and DCL voltage are constrained. A centralized control strategy utilizing an SDBR and a STATCOM was presented in [79] to address this issue. Similar to the BC technique, the fundamental shortcoming of SDBR is the loss of Q injection to the grid. Despite the fact that SDBR is recommended for fixed-speed WS, it can also be used for other WGs when integrated with an appropriate FACTS instrument.

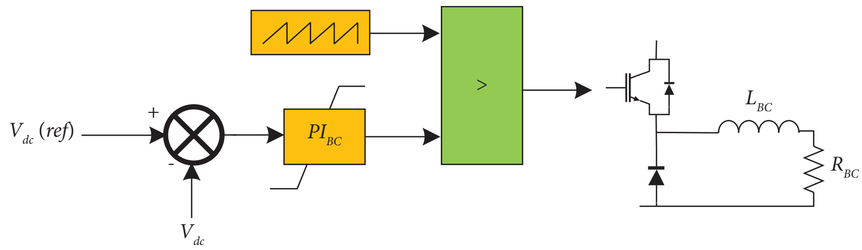

Figure 7: Connection of the BC unit to the DCL with its control system.

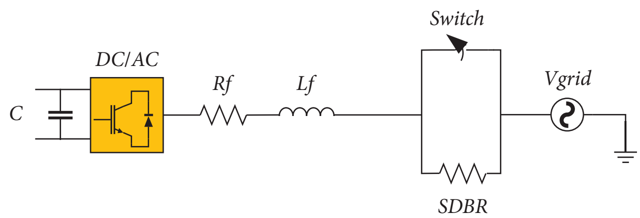

Figure 8: SDBR unit with its control system.

4.1.4. FACTS Units. FACTS units are other solutions to keep the WS connected to the PG under fault states, and they may be divided into 3 sets: shunt, series, and hybrid connections. Shunt connections such as STATCOM and SVC are linked to the PCC to improve the system's stability, and their configurations are depicted in Figure 9. In voltage sag circumstances, both STATCOM and SVC can inject Q into the grid, although STATCOM's output Q is greater than SVC's [80]. In [81], when both PMSWG and fixed-speed WS were utilized, the PMSWG's GSC was employed as a STATCOM to supply needed Q. Results show that this configuration allows for reducing the STATCOM size and cost.

The series type dynamic voltage restorer (DVR) injects series voltage to compensate voltage sags [82]. The DVR, as shown in Figure 10, consists of a 3-phase VSC linked in series between the WS and PG by an injecting transformer [79, 83]. The structure of the injecting transformers is different from that of regular transformers in order to avoid saturation and high inrush current [84]. Although DVR can address voltage sag, it is incapable to handle the deep voltage sag. Therefore, it needs additional units [85, 86].

UPQC is a hybrid connection type and consists of a series part and shunt part as seen in Figure 11. The series portion give a jab voltage to pay off for voltage dip and the shunt portion give a shot Q to the PG. This type can effectively enhance FRTC; however, it needs higher costs in comparison with the shunt or series methods [87].

A SMES-based interline AC-DC UPFC security system was proposed in [88] and is depicted in Figure 12. The connection between the DFIG and the bus is linked in series with the AC side of the UPQC to adjust for the PCC voltage. Regarding the UPQC's DCL, it is attached in parallel with the PMSWG's DCL. The UPQC performs admirably in improving the hybrid WS's overall performance in a variety of conditions, but the price remains prohibitively expensive. The cost of the UPQC investigation was computed in [84].

4.1.5. SFCL Technique. The GS application of SFCL raises the terminal voltage and generates resistance heat by converting extra electricity during faults [89, 90]. The SFCL can be categorized in to three types, resistive SFCL (R-SFCL), flux-coupling-type SFCL (FC-SFCL), and voltage compensation type active SFCL (VCTA-SFCL) [91]. Even though there are some additional SFCLs, they have not been used in the field of PMSWG [91–93].

Simple structure, quick responsiveness, and self-healing are traits of the R type. Additionally because it automatically detects high currents and automatically transitions from quench states to superconducting states, it does not require any kind of control mechanism. It can be inserted at any position between the GSC and the failure point.

In [94, 95], a 34.5 kV transmission system with the improved GSC control method was used to maintain the P and give Q support. It was sometimes placed into the PMSWG's DCL as seen in Figure 13 [96]. The resistance is fixed and created for a specific voltage dip, which is its main drawback. Therefore, when the voltage droop deviates from the post-situation, an extreme or inadequate voltage augmentation may take place, which could further degrade the FRTC performance. Furthermore, it is unable to support Q on its own.

Figure 14(a) depicts the FC-structural SFCL's layout. It is made up of a superconducting coil, a MOV, a controlled switch S, and a coupling transformer [97, 98]. S is closed in a regular condition, and SC has no resistance; and when S is open, considerable resistance is found. Although its structure is more complex and its price is higher, its purpose is comparable to that of the first type.

The VCTA-SFCL configuration is shown in Figure 14(b). Its main components are an air-core superconducting transformer, an air-core ES unit, a VSC, and a filter [95]. The secondary winding of the transformer's current could be adjusted by adjusting VSC, which enables the appropriate resistance of VCTA-SFCL to be attained. It has a lot more flexibility than the other two categories listed. Its cost is also considerable, and its control system is sophisticated. A comparative study among the three presented types is in Table 4. In Table 4, L refers to low, M refers to medium, and H refers to high, and those are used to indicate the level of complexity and financial expenditure needed.

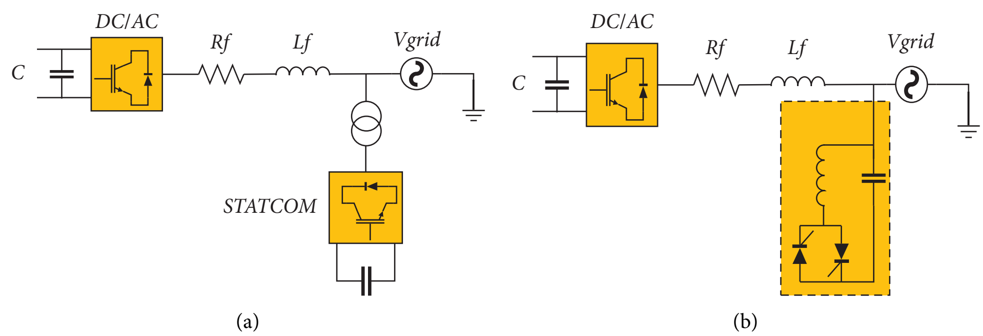

Figure 9: The connection of STATCOM (a) and SVC (b) to the PCC.

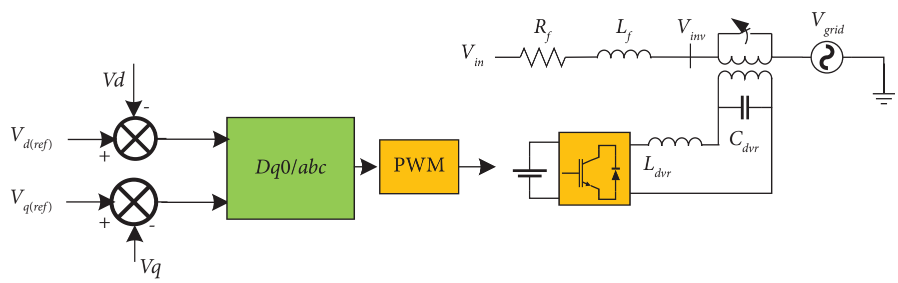

Figure 10: The connection of DVR to the PCC with its control system.

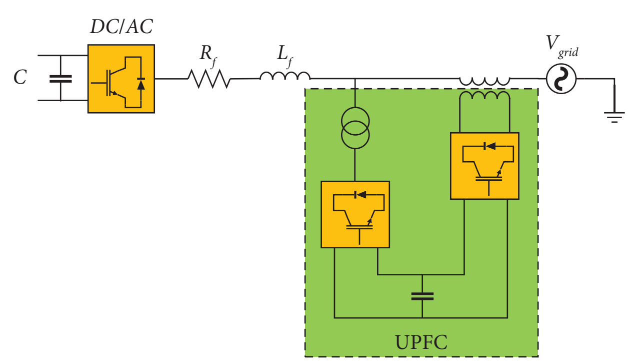

Figure 11: The connection of UPQC to the PCC.

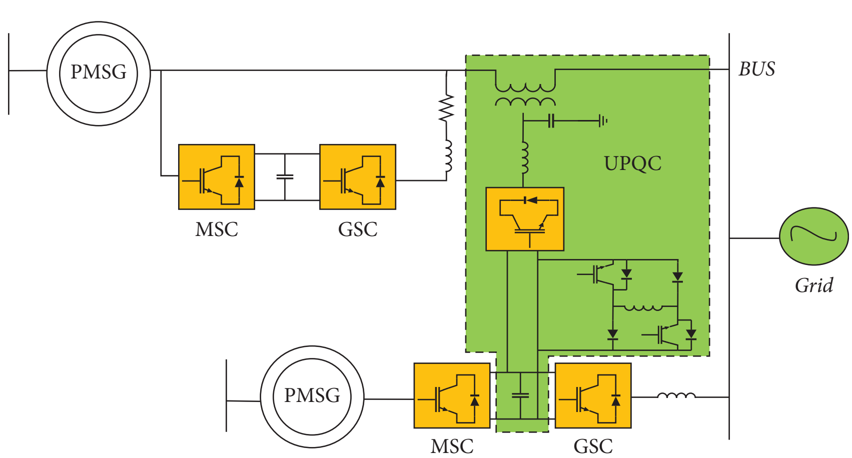

Figure 12: A configuration gathers PMSWG, DFIWG, SMES, and UPQC.

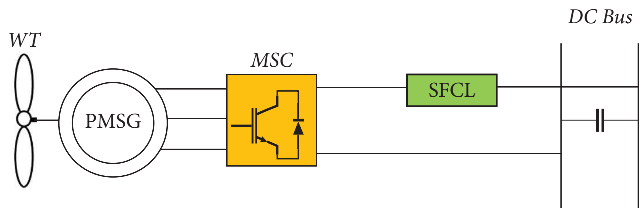

Figure 13: Connection of SFCL at the DCL.

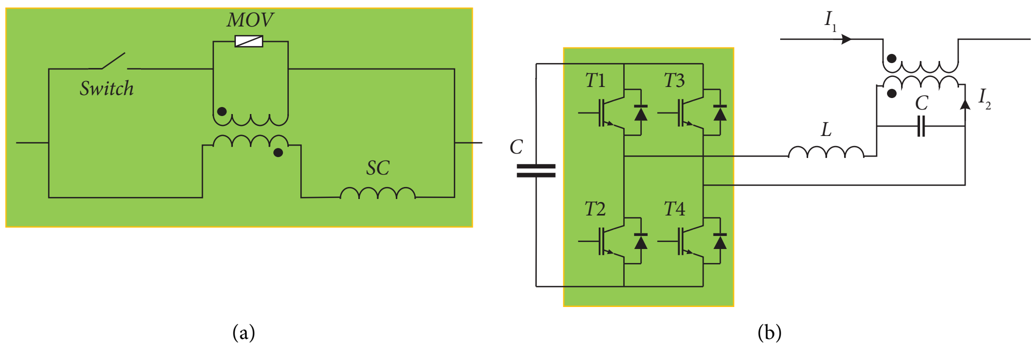

Figure 14: Configurations of SFCL, (a) FC-SFCL, and (b) VCTA-SFCL.

Table 4: The performance comparison of presented SFCL types.

References	Technique	Cost	Complexity	Q support	Power smooth capability
[95, 96, 99]	R-SFCL	L	L	Require additional method	✗
[97, 98]	FC-SFCL	M	M	Require additional method	✗
[100]	VCTA-SFCL	H	H	Require additional method	✗

4.1.6. Hybrid Methods: (SMES + SFCL). Dynamic performance enhancement of PMSWG based on hybrid methods may be obtained by two strategies (1) a combination use Figure 15 of SFCL Figure 16 and SMES device, (2) integrating the functions of (SFCL + SMES) into one device [101].

(1) Both SFCL and SMES were aggregated with a coordinated control method in [101] to compensate for voltage and current during short circuit faults as depicted. In [101], the SFCL was linked directly to PCC and SMES linked through power converters to maintain the energy balance. In [102, 103], the SMES was used to reduce the power imbalance between the MSC and the GSC, and the SFCL was applied to reduce the fault current and increase the GSC output voltage. The SFCL's resistance is intended to raise Pg to half of the desired value during a fault, and the SMES absorbs the remaining extra power. Decreasing the critical current and the SFCL resistance results in the system's reduced cost.

(2) A SFCL + SMES strategy was designed to be a one tool to realize FRTC as well as smoothing the real power P [104]. The new proposed strategy has series and parallel connection parts to limit the fault current and to deliver power compensation, respectively. The hybrid SFCL + SMES strategy suggested in [105] was linked to the grid through a power transformer as depicted. The device generally functions in the SMES mode to allow for the rapid power transfer; however, when a fault occurs, fault current restriction is directly put in action and once the fault has been addressed, the device returns back to the SMES mode.

4.2. CBS Methods. All of the methods listed in the previous section involve additional equipment that adds to the system's overall cost. It is wanted to augment FRTC with minutest added fee. Therefore, several research papers concentrate on CBS techniques. As follows, two types of these techniques are listed:

4.2.1. PAC Method. PAC was utilized in WS in [102] to limit incoming power during wind gusts. It may be used to supplement FRTC and other capabilities such as power levelling in PMSWG. It reduces the taken WT energy by regulating the PA of the blades, even if it has a sluggish response due to the mechanical dynamic forces of the sluggish system.

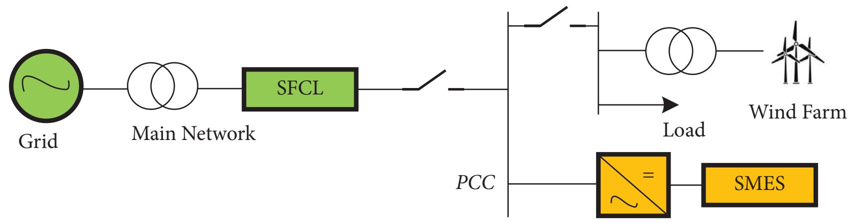

Figure 15: The integration of WS to grid with the support of SFCL + SMES.

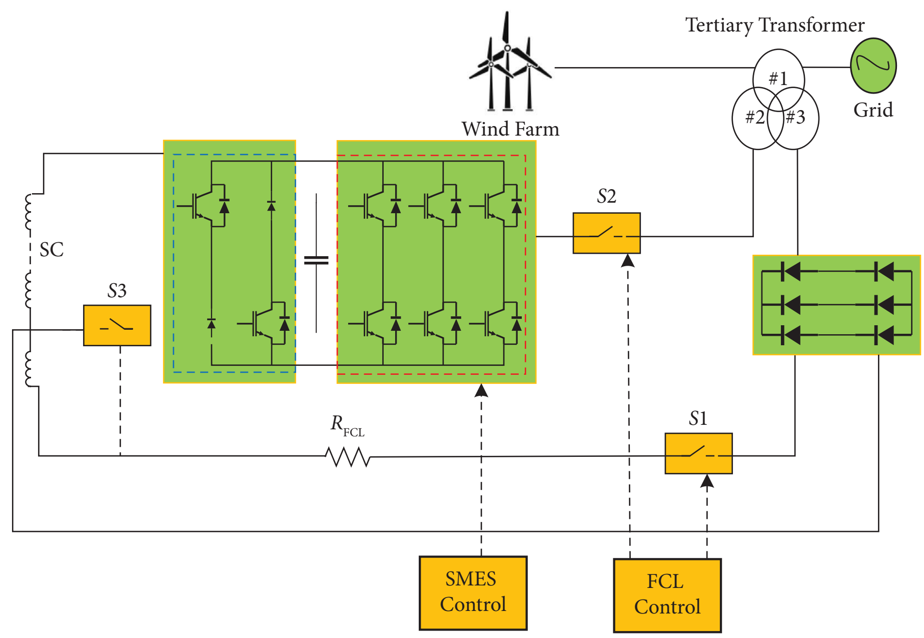

Figure 16: The aggregation of (SFCL and SMES) in one unit.

In [106], an upgraded FRTC control by mutual modified BTB converter controller (MBTBCC) and PAC were presented as seen in Figure 17. The standard control option is initiated once the wind speed exceeds the prescribed range. However, once the PG voltage decreases, the employed controller (PI/FLC), after flowing through it, regulates the set point of the PA. The solution's delayed start to a drop in PG voltage is among its key drawbacks. However, this strategy substantially reduces the input power to the DCL, and the requisite Q cannot be fed into the PG, per the GCs. Due to the lack of extra needs, PAC is a comparatively inexpensive solution.

4.2.2. MBTBCC Method. The BTBC interface between PMSWG and the PG can be used for FRTC augmentation. The PMSWG deloading (DL) approach for FRTC was proposed in [104], as shown in Figure 18. The result is that the excess energy was transformed into and stored as kinetic energy. The PMSWG is calculated by dividing the desired target torque by a DL decline. As a result, the DCL voltage remains within the allowable range. However, in the event of PG issues, the GSC might go out of control.

In [107], a new control structure was performed, in which MSC regulated the DCL voltage and the GSC improved MPPT as seen in Figure 19. In this method, the power generation in the PMSWG was lowered when the grid voltage dropped and the DCL voltage deviates from the nominal value, resulting in the lower input power to the DCL and keeping its voltage constant [108]. The P controlled and the Q is fed to the PG based on GCs since the WG-P is regulated via GSC. The mechanical portion of the WT functions as energy storage in this strategy, which is comparable to the deloading concept. In [107], FRTC was investigated under which case the GSC functioned as a STATCOM in a fault scenario, and the studied methodology was determined to be successful and effective when compared to the BC method. Reference [108] employed a feedback linearization approach to improve FRTC due to the nonlinear relationship flanked by V_{dc} and desired P, and the method used resulted in a reduction in V_{dc} overshoot.

The BTBCs and their controllers are becoming more vital in PMSWG with the role of filling the GC necessities. The PMSWG controllers are classified into MSC and GSC controllers. A comprehensive summary of controller structures used during FRTC of PMSWG is presented in Table 5.

4.3. Comparison Assessment of Complexities and Economics FRTC Methods. It is significant to compare the complexities

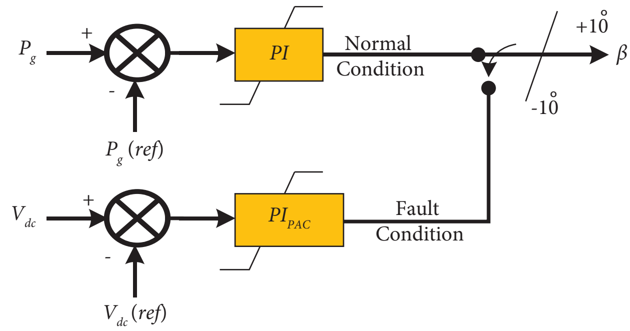

FIGURE 17: Operation of the PAC system.

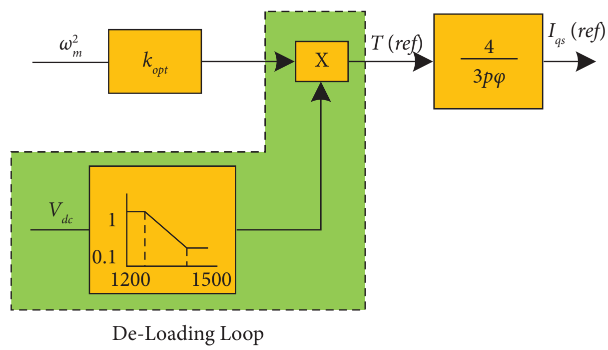

FIGURE 18: The deloading scheme.

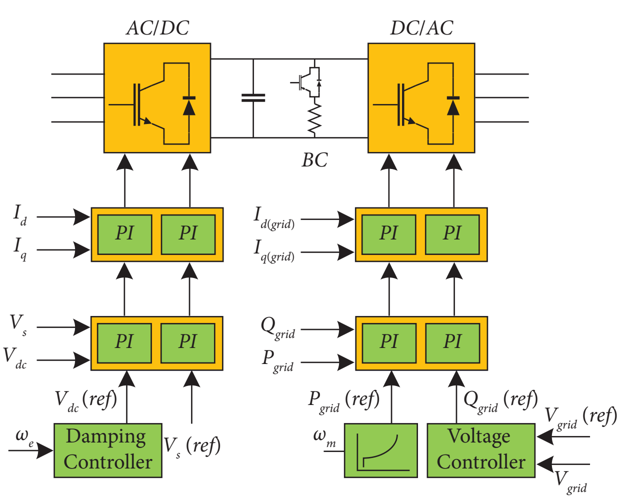

FIGURE 19: The modified control schemes of MSC and GSC.

and economic systems of the investigated FRTC approaches. In place of previously discussed, some FRTC systems, particularly those relying on superconducting science, are more costly than others. Approaches can be divided into three cost categories: high (H), medium (M), and low (L) depending on the quantity of electronic switches and further components are utilized, such as coupling transformers, magnetic inductance, resistance, and superconducting elements. The priciest types of equipment are FACTS because they have a lot of switches and typically require coupling transformers. However, the knowledge and technical abilities of their switches may make this FRTC approach more difficult. The ESSs are also an expensive strategy because the majority of them are pricey hardware. The BC and SDBR technologies are less expensive than UBS because they use high-power resistors and fewer switches. Finally, because they do not incorporate extra components into their design, CBS technologies are more economical FRTC techniques. Table 6 sums up a comparative assessment among the aforementioned solutions in terms of cost, simplicity, DCL overvoltage suppression, favorable Q support capability, and additional device requirements.

5. Trends in Technology and Research Status (Statistical Analysis)

In this section, investigations on the most current advancements in the state of the art of FRTC enhancement methods for PMSWG have been carried out and presented as follows:

5.1. Grid Integration (GI) Issues. Achieving FRTC, production smoothness P, and Q compliance are required in contemporary [145, 147–149]. In numerous research studies, FRTC has been noted as a significant issue [150–154]. Numerous academic publications have examined the two aforementioned needs. Figure 20 shows the desirability of the GI issues in the percentage form to demonstrate the FRTC issue's 63% market domination.

5.2. FRTC Methods. In conclusion, researchers have shown interest in investigating PMSWG that will benefit much

Table 5: Different controllers in FRT mechanism of (MSC-GSC) PMSG-based WTG.

Refs	Controllers Type	MSC	GSC	Merits	Disadvantages	Observations
[106]	PAC	✓	✗	(i) Smoothing of P was realized	(i) Slow response	(i) Smooths the WG-P
[109, 110]	Feedback linearization	✗	✓	(ii) V_{dc} was kept at allowable limits without overshooting	(ii) Nonlinear relationship	(ii) Adjusts the V_{dc}
[111, 112]	MBTBC	✗	✓	(iii) It decreases the generated P	(iii) Occasionally GSC may party of control	(iii) Deloads WG
[113, 114]	FOC	✓	✗	(iv) Speed control	(iv) Current was limited	(iv) Controls the current
[113, 115]	VOC	✗	✓	(v) It controls V_{dc}, P, and Q	(v) P is not fed	(v) Controls the V_{dc}
[116]	Compositive control	✓	✗	(vi) Transferring excess power into kinetic energy	(vi) Delay of fault finding	(vi) Converts the extra power into kinetic energy
[117, 118]	Direct predictive torque (T) control	✓	✓	(vii) Control of T with no ripples	(vii) Switching table was needed	(vii) Meets the peak T\A necessities
[119]	Modified control of P	✓	✓	(viii) Supply P during fault period (vi) Mitigate the oscillation in V_{dc}	(viii) BTBC losses were not considered	(viii) Controls the fed P to the grid
[120, 121]	BTBCCs	✗	✓	(x) Keep the peak current of the GSC	(vi) Prospect of levitation overcurrent	(vi) Controls V_{dc} under peak P
[44, 122]	Type-2 fuzzy control	✓	✗	(xi) Regulate V_{dc}	(x) Fuzzy sets were 3-D	(x) Controls the feeding P & Q to the grid

Table 6: Comparative of implemented different FRTC methods.

References	Methods	Cost	Simplicity	GC compliance: V_{dc} within limits	GC compliance: Q support	Additional units	Power smooth
[106, 123–125]	PAC	L	✓	✗	L	✓	✗
[126–128]	PC	M	✓	✗	L	✓	✗
[129–132]	Storage units	H	✗	✓	M and H	✗	✓
[20, 61, 133, 134]	BC	M	✓	✓	L	✓	✗
[86, 135–137]	FACTS	H	✗	✓	H	✗	✓
[138–141]	SDBR	M	✓	✓	L	✓	✗
[107, 108, 142, 143]	MBTBC	L	✗	✓	L	✓	✗
[91, 144–146]	FCL	Based on its type	Based on its type	✓ but based on its connection place	L	✓	✗

from the example of the current development in FRTC approaches [31, 51, 59, 96, 150–153, 155, 156]. According to the priorities of research investigations, Figure 21 depicts the general tendencies of the technological advancement in percent figures.

6. Simulation Results and Comparisons of Different Methods

During voltage dips, the main issue in the system is the overvoltage in the DCL capacitor of the BTBC. Keeping the DCL voltage at allowable limits during zero voltage dip proves the effectiveness of the applied methods. Five simulation scenarios are carried out for clarifying some of the FRTC enhancement methods' impact on the DCL voltage using the MATLAB\Simulink program. The investigated zero voltage dip persists for 0.2 seconds and that leads to overvoltage at this link as depicted in Figure 22. In Figure 22, the symbols C, C_1, C_2, C_3, and C_4 represent system without the FRTC method, with storage unit, with FACTS unit, with improved control system-addition unit, and with BC unit, respectively. Figure 22 demonstrates that all approaches except C_1 limit the DCL's overvoltage but still exceed the permitted value (1.1 pu) [157], which is shown in Table 7. Finally, it can be concluded that Figure 22 and Table 7 clarify the clear benefit of C_1. Tables 8–10, respectively, contain the parameters for the simulated PMSWG, FRTC improvement techniques, and controllers' parameters.

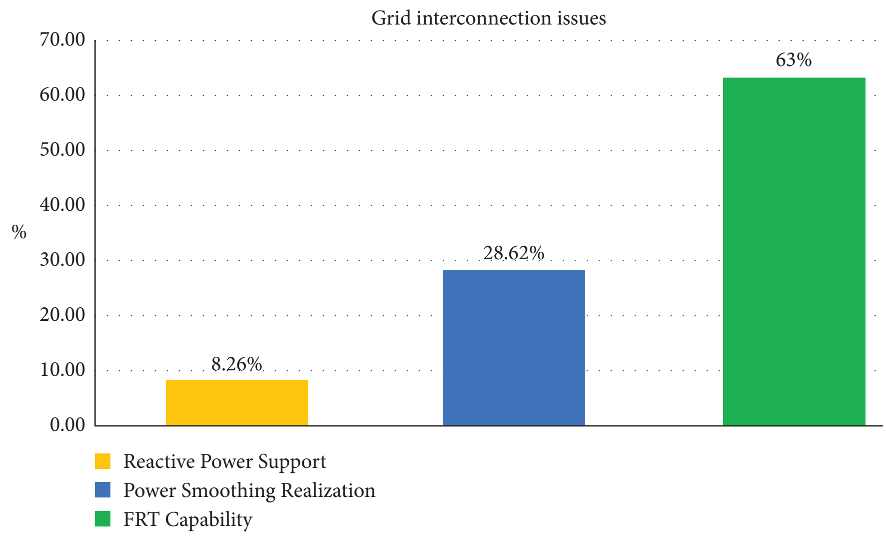

FIGURE 20: Percentage figures for grid integration issue.

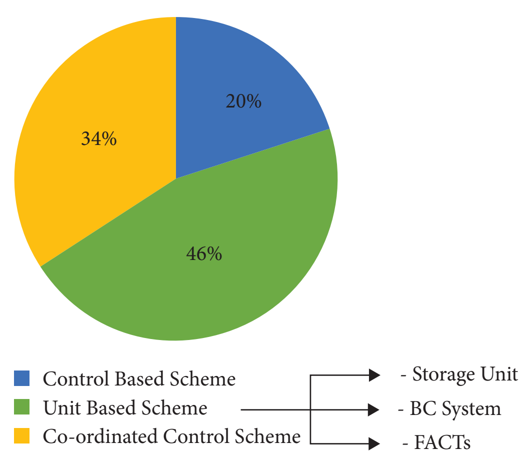

FIGURE 21: Percentages representing current global technology development tendencies.

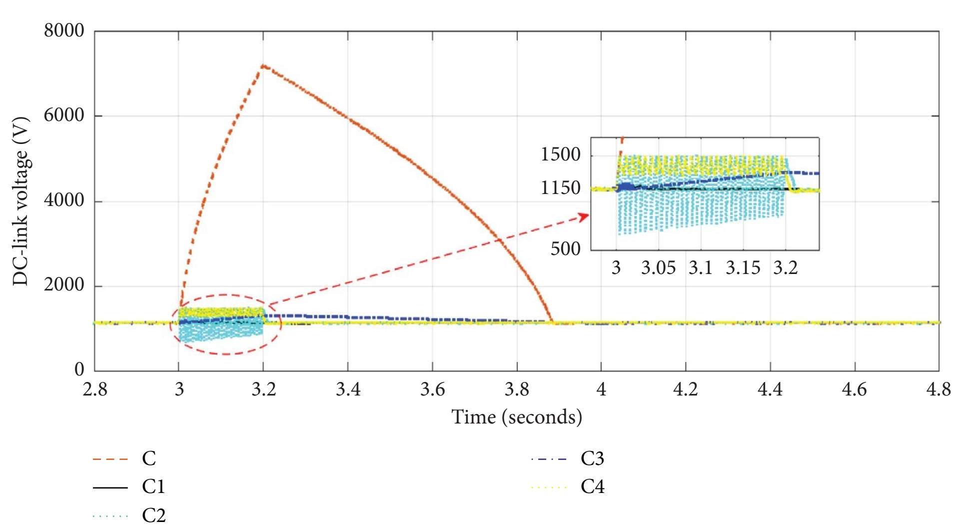

FIGURE 22: V_{dc} during 100% voltage dip (worst condition).

Table 7: Performance comparison of simulated FRTC methods for DCL voltage.

FRTC methods	DCL voltage value (pu)	Overvoltage period (seconds)	Percentage increase (%)
C	6.2608	0.9	526.08
C_1	1.026	0.03	2.6
C_2	1.304	0.21	30.4
C_3	1.1547	0.7	15.47
C_4	1.304	0.21	30.4

Table 8: Simulated PMSWG parameters [6, 20].

Components	Parameter	Symbol	Value
WT	Blade radius	R	33.05 m
	Rated wind speed	v_W	12 m/s
	Optimal power coefficient	C_P	0.44
	Optimal tip speed ratio	λ_{opt}	10.5
	Wind density	ρ	1.225 kg/m^3
PMSWG	Rated power	P	1.5 MW
	Rated stator voltage	V	575 V
	Pole pairs	p	40
	Generator stator resistance	R_s	0.01 pu
	Generator inductance in the d frame	L_d	0.7 pu
	Generator inductance in the q frame	L_q	0.7 pu
	A flux of the permanent magnets	ψ_{pm}	0.9 pu
BTBC	MSC frequency switching	$F_{\text{sw-MSC}}$	1650 Hz
	GSC frequency switching	$F_{\text{sw-GSC}}$	1650 Hz
	DCL voltage	V_{DC}	1150 V
	DCL capacitor	C_{DC}	10000 μF
	Grid frequency	F	60 Hz
Filter	Inverter side inductance	L_i	0.3 pu
	Inverter side resistance	R_i	0.003 pu
	Filter capacitor	C_f	0.0267 pu
	Damping resistance	R	0.003 pu

Table 9: Simulated FRTC methods parameters [52].

Device	Parameter	Value
Storage unit	Power	1 MW
	Voltage	500 V
	Capacitance	7 F
	Inductance	13 μH
	F_{sw}	1000 Hz
SDBR	Resistance	0.4 Ω
	F_{sw}	500 Hz
DVR	P	1 MW
	Transformer voltage	575\575 V
	F_{sw}	5000 Hz
	L	40 μH
	C	8 μF
	V_{DC}	500 V
BC	P	1 MW
	F_{sw}	500 Hz
	Voltage of BC	1200 V
	R	1 Ω
	L	mH

Table 10: Controller gains of the studied system [20, 158].

MSC gains				GSC gains		BC	PAC	ESS
K_{p1} & K_{p2}	K_{i1} & k_{i2}	K_{p3}	K_{p4}	K_{p5} & K_{i4}	K_{i5} & K_{i3}	K_p & K_i	K_p & K_i	K_p & K_i
1.4	136.11	8	400	0.83	5	0.08	10 & 300	0.1 & 4

7. Future Research Directions

(i) WSs are expected to be one of the pillars for achieving net zero emissions and driving the worldwide energy evolution, it might become one of the main sources of energy as the use of green energy increases. WSs support the global energy subsidy reform policies and implications. Because of this, we must shift our attention from how effectively WSs function to how to increase their potential for their active support.

(ii) In light of UBS′ large prices, CBS for FRT is an alluring substitute. Together, CBS and UBS can reduce the costs associated with the schemes and increase PMSWG's capacity to offer active support.

(iii) Hybrid approaches can increase the performance of the PMSWG as a whole, rather than only the FRTC, at a reduced cost.

(iv) The bulk of WSs are located in remote areas and are transferred by LCC-based HVDC, making it crucial to investigate FRTC techniques under complex voltage variations caused by LCC-based HVDC faults. In this case, a disturbance that is not only a brief low voltage is bothering the WT.

(v) Even though PMSWGs have more control flexibility than DFIG, there is not much research on this topic. Extensive research should be carried out on the PMSWG since it can efficiently handle these disruptions by fully using controllability.

(vi) Application of recent controllers such as neuro-fuzzy, hybrid ANN controllers in FRTC methods and PMSWG to assess their effectiveness.

(vii) Optimal sizing of the units using recent metaheuristic techniques for FRTC enhancement methods.

(viii) The designed FRTC methods only consider the DCL voltage, however additional research and analysis are required to determine how these methods would affect the WG system.

8. Conclusion

This review paper assesses several FRTC augmentation systems for PMSWG, which may be classed as CBS, UBS, and CCS. Several techniques' topology and fundamental operation are presented throughout the study. In this work, several approaches from both categories were presented, assessed, and simulated for PMSWG to improve FRTC by maintaining DCL voltage within permissible ranges. The merits and downsides of the FRTC enhancement techniques classes have been contrasted and appraised. A comparison of simulated and discussed approaches revealed that UBS and CBS are efficient procedures, although UBS raises system costs and CBS raises system complexity. In addition, the cost, simplicity, GCs compliance, power smoothing, and additional unit needs of the FRTC approaches were compared. According to the comparative study, the cost-effective solutions are adequate for the FRTC difficulties and reflect the future trend for increasing PMSWG's FRTC as well as its dynamic performance. By advocating the use of FRTC technology, this study is intended to help utility operators, researchers, manufacturers, and engineers working in the field of grid integration of WSs.

Data Availability

The data used to support the findings of this study are available on reasonable request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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