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Offshore Wind Farm-Grid Integration: A Review on Infrastructure, Challenges, and Grid Solutions

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ABSTRACT Recently, the penetration of renewable energy sources (RESs) into electrical power systems is witnessing a large attention due to their inexhaustibility, environmental benefits, storage capabilities, lower maintenance and stronger economy, etc. Among these RESs, offshore wind power plants (OWPP) are ones of the most widespread power plants that have emerged with regard to being competitive with other energy technologies. However, the application of power electronic converters (PECs), offshore transmission lines and large substation transformers result in considerable power quality (PQ) issues in grid connected OWPP. Moreover, due to the installation of filters for each OWPP, some other challenges such as voltage and frequency stability arise. In this regard, various customs power devices along with integration control methodologies have been implemented to deal with stated issues. Furthermore, for a smooth and reliable operation of the system, each country established various grid codes. Although various mitigation schemes and related standards for OWPP are documented separately, a comprehensive review covering these aspects has not yet addressed in the literature. The objective of this study is to compare and relate prior as well as latest developments on PQ and stability challenges and their solutions. Low voltage ride through (LVRT) schemes and associated grid codes prevalent for the interconnection of OWPP based power grid have been deliberated. In addition, various PQ issues and mitigation options such as FACTS based filters, DFIG based adaptive and conventional control algorithms, ESS based methods and LVRT requirements have been summarized and compared. Finally, recommendations and future trends for PQ improvement are highlighted at the end.

INDEX TERMS Frequency control, Grid codes, harmonics, LVRT, offshore wind energy, power quality, stability, voltage control.

I. INTRODUCTION

Wind energy generation is increasingly becoming one of the key sources of electric energy for industrial as well as domestic use, due to its several advantages over fossil fuel counterparts [1]. This growth in wind energy can be seen from its installed capacity figures, where China is leading with a 237 GW of wind power available followed by US at around 105 GW [2]. Wind energy growth across Europe shows a remarkable improvement with installed capacity of 1.48 GW in 2008 to 25 GW in 2020. The UK and Germany having the largest installed capacity with a total of thirteen countries contributed in wind energy to achieve these numbers [3]-[5].

When it comes to offshore wind energy, the main advantage over its onshore counterpart is the consistency in generating power at a steady rate due to stronger and more consistent wind gusts. Offshore wind farms are distributed in various countries around the world, mostly in Europe, followed by Asia and America. Amongst these regions, Europe has largest installed capacity of 20.22 GW while Asia and America have 4.93 GW and 0.03 GW respectively as summarized in Table I [6]. It is noteworthy that offshore wind industry in the world has succeeded to add 6.1 GW of new capacity in 2019, which is considered the best year in history so far. An average annual increase of 18.6% until 2024 and 8.2% till the decade ends, whereas new annual offshore installations are expected to cruise up to achieve a milestone of around 20 GW in 2025 and 30 GW by 2030 [7]. Furthermore, the US government had announced a shared goal to deploy 30 GW of offshore wind energy in the America by 2030. The total installed offshore wind capacity in the most ambitious scenario by the European countries, including UK and Norway, will reach 450 GW and supply about 1/3 of the electricity demand.

TABLE I
OFFSHORE WIND ENERGY GROWTH (MW) IN RECENT YEARS [6]

Continent	Country	2015	2016	2017	2018	2019	2020
Europe	United-Kingdom	5,094	5,340	5,772	7,892	8,480	8,480
	Germany	3,310	3,305	5,395	5,843	7,372	7,770
	Belgium	713	713	878	1,556	1,556	2262
	Netherlands	376	518	1,118	1,118	1,118	1,118
	Denmark	1,269	1,269	1,264	1,294	1,701	1,701
Asia	China	937	2,038	2,238	3,330	4,685	10000
	Taiwan	0	0	8	8	128	128
	South Korea	11	11	44	44	44	124
	Japan	78	80	80	80	81	92
America	USA	0	0	30	30	30	30

Wind energy being a zero CO_2 emitting source, has a remarkable energy balance. According to a report delivered by The Global Wind Energy Council [8], with over 140,000 wind turbines operating in nearly 70 countries, an annual CO_2 saving of 1.5 billion tons has been achieved in 2020. This figure would ramp up to 3.2 billion tons/annum of emission reduction by 2030. Although deployment of offshore wind farms managed to solve the issues of climate change by bringing about a significant reduction, the penetration of such large scale OWPP in power system results in increased PQ and system stability issues. These system challenges originate due to operational mode (standalone or grid connected) as well as structural and performance constraints by OWPP. Some of these PQ issues include flickers, harmonics, voltage fluctuations, voltage sag and swells [9]-[11]. In several works, it is reported to address the issues of PQ in OWPP using simulation studies [12], [13] as well as through hardware approaches [14], [15]. With regards to stability of OWPP connected to the grid, different aspects that are reported in studies include; steady state frequency control [16], damping control [17], voltage control [18] as well as transient stability control [19].

Stability of HVDC based OWPPs is compromised due to oscillatory interactions of power electronic converters with AC grid compensation equipment and dynamic power controllers [20], [21]. Over charging of large subsea cables and inrush currents from the connecting transformers are some of the sources of harmonic resonance oscillations in OWPP. This issue of resonance instability in OWPP is addressed in several studies, where its impact is analyzed by locating peaks (parallel resonance) and valleys (series resonance) obtained from a frequency domain scans, using different methodologies such as impedance-based approach [22] and modal analysis [23].

The grid codes usually state connection requisites of the offshore wind farms with the grid during and after a fault occurs. Several works in the literature discuss grid codes for wind power integration to the gird. For instance, authors in [24]-[25] have thoroughly listed these codes for European countries, the grid code requirements of LVRT as well as active and reactive power for a wind farm connected to the grid. Mehrdad et al presented a comprehensive review on fault ride through (FRT) guidelines and corresponding grid codes in various countries [26]. Similarly, a comparative study of US and China standards on integration of wind energy with power grid is discussed in [27], while [28] investigates the technical requirements for Turkish grid.

The advances in flexible AC transmission systems (FACTS) devices used in the electric power network to overcome the PQ issues has also excelled the reliable use of OWPP in the electric grid [29], [30]. These are power electronics based high frequency switching devices combined with passive elements to mitigate PQ issues by controlling the network parameters [31]. Among those devices, static synchronous compensator (STATCOM), static VAR compensators (SVC), dynamic voltage restorer (DVR), and unified power flow controller (UPFC) are effective in resolving PQ issues like harmonics, load unbalancing and to retain voltage regulation [32]-[34]. The DVR, when employed with a proper control scheme, is an efficient device for rectifying power fluctuations occur due to intermittent wind energy. It also improves LVRT ability of a wind turbine generator in case of symmetrical and asymmetrical faults occur on grid [35], [36]. STATCOM is known for its reactive power injection and absorption ability to achieve voltage control and improved stability with fast response time [37]. It enhances the dynamic stability in line commutated HVDC offshore wind systems where conventional passive filtering fails to provide adequate reactive power compensation [29], [38].

Although preceding literature discusses methods on PQ issues and their mitigation in wind energy systems, a comprehensive review encompassing the new challenges of integration, transmission, PQ and stability with regards to offshore wind energy is not presented in an inclusive manner yet. Several studies have reported methods of PQ issue mitigation in conventional wind farms [39],[40]. Furthermore, authors reviewed aspects of stability [41], LVRT standards [42], grid codes [43] in relation to wind energy systems. The aim of this paper is to thoroughly discuss and summarize the contemporary PQ challenges faced due to the penetration of OWPPs in the power grid. Advances in stability aspects of OWPP connected grid systems have been meticulously

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analyzed. Updated grid code regulations and standards concerning OWPP are reviewed along with in depth breakdown of reported LVRT schemes applied to achieve a robust power output.

This paper is organized as follows: Section I introduces some latest globally installed capacity figures in wind based energy systems along with literature being published on PQ problems. The OWPP overview and different wind turbine type's attributes with regard to PQ are addressed in section II. Section III presents various PQ as well as stability challenges occurring in OWPP. Grid code requirements for interconnection of wind energy systems and LVRT requirements are summarized in section IV. Section V presents various mitigation techniques for PQ and stability issues along with LVRT methodologies in OWPP. Section VI concludes the article by pondering upon some recommendations and future trends with regards to offshore wind farm development.

II. OVERVIEW OF OFFSHORE WIND POWER PLANT (OWPP)

In the course of the past few years, various schemes for OWPP-grid interconnection have experienced enormous progress. This is further enhanced by different PECs topologies used in wind turbines for better flexibility of operation. This section reports the OWPPs integration methodologies as well as available wind turbine topologies that are prerequisite to maintain the stability and quality of the energy being supplied.

A. OWPP-GRID TRANSMISSION INTEGRATION

A generic schematic of grid connected wind power system is depicted in Fig. 1. The mechanical system includes tower, drive train, rotor blades, wind sensors and brakes [44]. Components of electrical system include the generator, electronic converters, harmonic filters on grid side, transformers, cables and common coupling point [45]. The control system components usually consist of intelligent devices responsible to maintain efficient and robust operation between electrical as well as mechanical systems [18], [46]-[49].

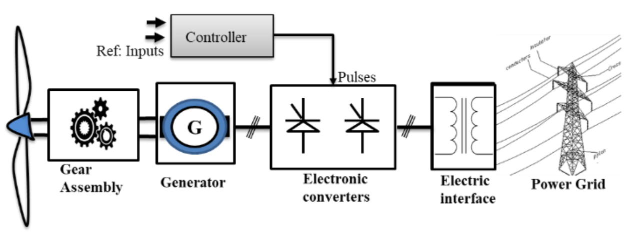

FIGURE 1. Grid connected wind energy system

Nowadays, the existing transmission system technologies for long distance OWPP include, a) AC collection-AC transmission and b) AC collection-DC transmission as shown in Fig. 2. The former high voltage alternating current (HVAC) transmission (Fig. 2(a)) is used extensively in offshore-based farms due to its simple design and mature technology. The generated voltage is usually around 700V, which is then stepped-up to 33 kV (66KV in some cases [50]) medium voltage level [51]. The transmitted power is compensated with suitable shunt reactor to counter over-voltage level and charging current issues of the subsea cable, increasing the overall transmission capacity. To further increase the transmission distance as well as capacity, low frequency AC transmission methodology is reported in literature [52], [53]. In this scheme, power is transmitted at one third of the system frequency to achieve reduced charging power, skin effect and improved real power capacity.

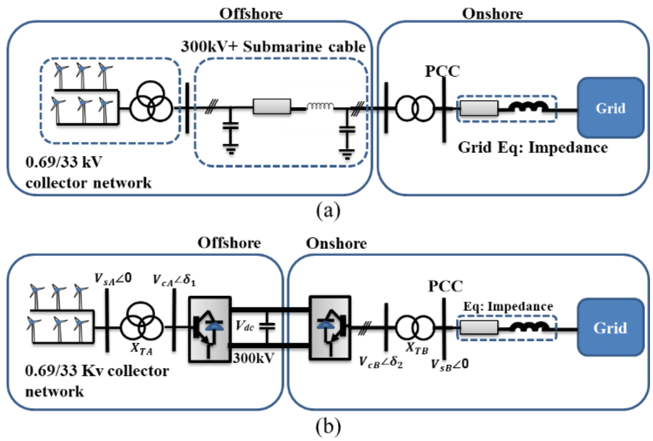

FIGURE 2. Conventional configuration of an (a): HVDC and (b): HVAC, links in offshore wind farm

The AC collection – DC transmission makes use of high voltage direct current (HVDC) where turbine is linked through a cable, to a DC converter facility. Transmission is either line commutated converter (LCC) based or voltage source converter (VSC) based [54]. The active and the reactive power flow in VSC-HVDC system depend on the voltages magnitude, the phase angle δ between these voltages and the reactance of the transformer (Fig. 2(b)). The sending end active power and the reactive power can be expressed as

$$P_{send} = \frac{V_{sA}V_{cA}}{X_{TA}} \sin \delta_1 \quad (1)$$

$$Q_{send} = \frac{V_{sA}^2}{X_{TA}} - \frac{V_{sA}V_{cA}}{X_{TA}} \cos \delta_1 \quad (2)$$

Similarly, for the receiving end active and reactive power are calculated by

$$P_{rec} = \frac{V_{sB}V_{cB}}{X_{TB}} \sin \delta_2 \quad (3)$$

$$Q_{rec} = -\frac{V_{sB}^2}{X_{TB}} + \frac{V_{sB}V_{cB}}{X_{TB}} \cos \delta_2 \quad (4)$$

where V_{sA} and V_{sB} are source voltages, V_{cA} and V_{cB} are converter output voltages, while X_{TA} and X_{TB} are transformer reactances at both ends. HVDC interconnection scheme is still in development stages as it involves placement of HV switches and filter bank. This results a high initial cost particularly for large-scale interconnection of offshore and onshore stations [55]. Its advantages include independent control of active and reactive power control without the need of external voltage

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source. Besides, it can achieve current control by altering the triggering angles of the converters [56], [57].

B. TURBINE TOPOLOGIES

Based on speed control, there are four types of wind turbines used in OWPP. Type I turbine is a conventional squirrel cage induction generator (SCIG) based structures with fixed-ratio gearbox connected to grid through a step up transformer. The soft starter here limits the inrush current, while reactive power compensation is provided by capacitor banks as depicted in Fig. 3(a).

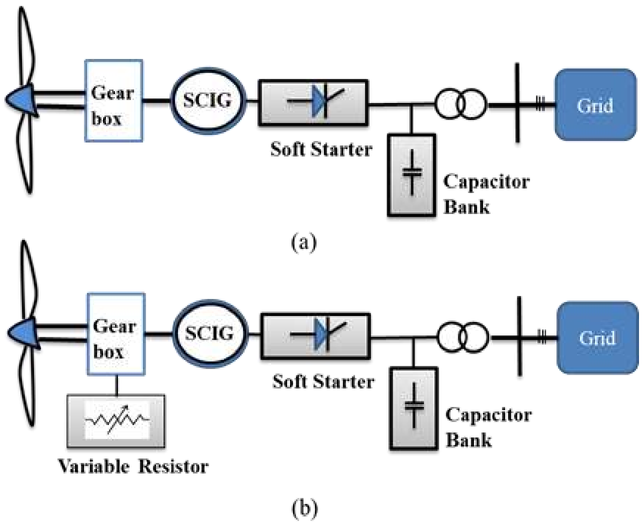

FIGURE 3. Wind turbine configurations (a) Type I (b) Type II

The type II, as presented in Fig. 3(b), is another structure of the wind turbine, where it generally comprises a wound rotor induction generator (WRIG), having variable resistors in rotor circuit. Through this variable resistance, rapid rotor current control can be achieved, which helps maintain constant power during adverse wind conditions [58]. Type III turbines make use of doubly fed induction generators (DFIGs) as presented in Fig. 4(a). The possibility of having a constant-frequency AC from a DFIG when operated by a variable-speed rotor enhances the energy efficacy of the system [59]. As this type of turbine applies the power electronics converters to control the active and reactive power, it results in generating the 3rd, 5th and 7th harmonic components [60]. Related pros and cons of DFIG based turbine system are listed in Fig. 4(b).

Type IV or permanent magnetic synchronous generator (PMSG) based turbine are directly driven systems with full-scale AC-DC-AC converters (Fig. 5(a)). The possibility to be directly connected to a wind turbine without using the gearbox is crucial in harsh weather conditions [61], [62]. PMSG based turbine are suitable for offshore installations due to advantages they offer such as high energy density, simple control schemes, no rotor winding, bidirectional power flow and self-excitation structure. Fig. 5(b) compares some aspects of the PMSG based wind turbine. The voltage and frequency from grid side can be controlled with small influence from the wind speed. Various control schemes like Pulse Width Modulation (PWM) for converter control and adaptive system learning for maximum power tracking are described in [63]-[65].

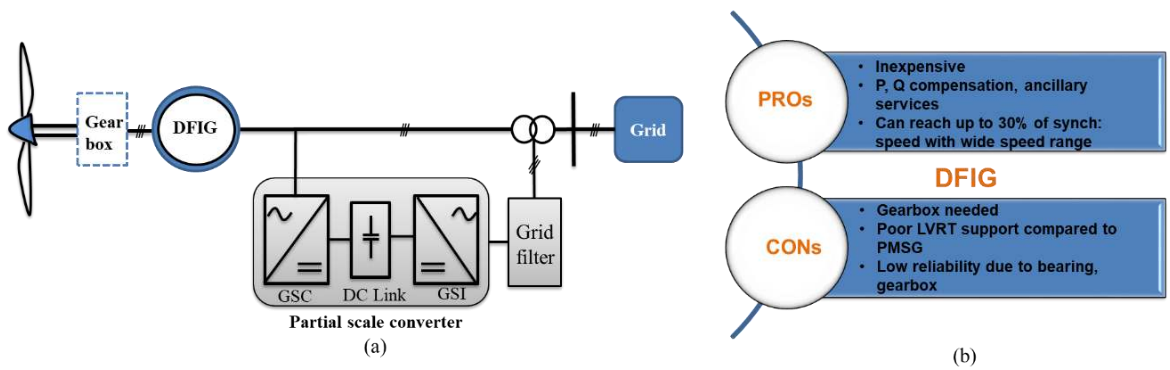

FIGURE 4. (a) Type III Wind turbine system, (b) Pros and cons in DFIG based turbine

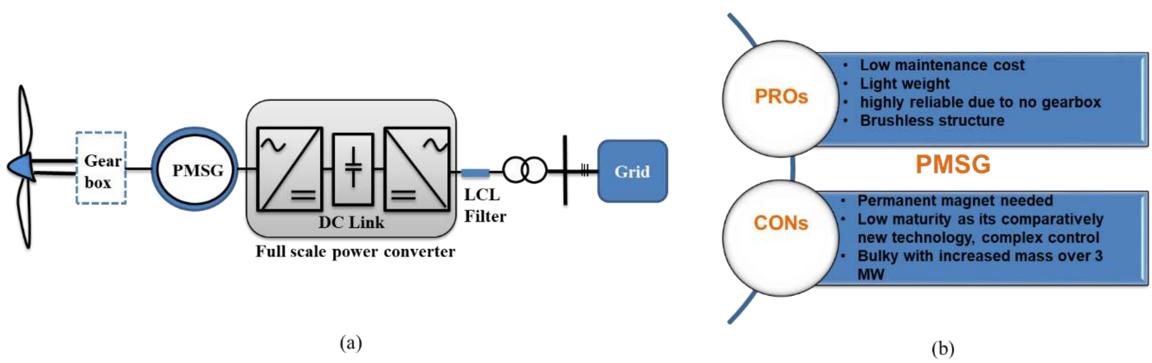

FIGURE 5. (a) Type IV Wind turbine, (b) Pros and cons in PMSG based turbine

III. CHALLENGES IN OWPP

The aspect of PQ in OWPP cannot be undermined, as a single wind turbine can contribute up to 10 MW of power into the grid and it is also used as standalone DG [66]. In OWPP, due to intermittent nature of wind as well as presence of nonlinear power circuitry, bring about various PQ issues fluctuations in voltage and frequency, and circulation of harmonics that ultimately effect the system stability [67]. This section addresses these challenges, which need to be taken into consideration for continuous supply of stable energy to the customer.

A. POWER QUALITY ISSUES

PQ disturbances at OWPP are regularly monitored to check whether, output complies with the permitted grid regulations. It is worth mentioning that PQ issues include flickers, voltage sags/swell, harmonics, transients as well as voltage and frequency fluctuations. Table II shows some PQ issues with respect to severity to the grid [68].

TABLE II
POWER QUALITY ISSUES IN POWER SYSTEM

PQ Issue	Causes	Outcome	Affect
Flicker	Supply Voltage variation	Equipment damage or malfunction	Moderate
Harmonic	Nonlinear loads, cable, Transformer	Power loss, overheating of load	Moderate
Voltage Sag	Sudden switching, inrush current, poor wiring	Overloading issue, Grabbled signal	Moderate
Voltage Swell	Heavy loads on/off, fault at supply side	Equipment damage, data loss, overheating	Mild
Transient	Lightning, snubber circuits	Efficiency loss, disturbance in equipment	Severe
Frequency Instability	High Loading	Motors and sensitive load malfunction	Mild

1) FLICKERS

Flickers can be defined as fast variation in supplied voltage that may last for a certain period so that the variation in electric light can be recognized visually [69]–[71]. Voltage fluctuation value k can be estimated by

$$k = \frac{dU}{U_n} \times 100\% = \frac{U_{max} - U_{min}}{U_n} \times 100\% \qquad (5)$$

where Un is the nominal voltage while U_{max} and U_{min} show voltage peak value of the half period RMS value.

IEC standard 61400-21 establishes codes for defining PQ requirements of wind generation [72]. A portion of the mentioned standard makes use of the time domain readings of current and voltage taken at terminals of the wind turbine to measure flickers due to the switching action. A wind turbine produces more flickers in weak grids because of inverse relationship of flickers emission and short-circuit capacity [73]. Another important factor to affect flickers level is grid impedance angle. Flickers emission reduction can be achieved by maintaining 90° angle difference between grid impedance angle and turbine power factor. As variable speed turbines have the ability to manage reactive power, flickers can be alleviated by regulating this reactive power [74].

2) HARMONICS

In an OWPP penetrated grid system, the voltage source inverter stimulates some harmonics while the others harmonics are from grid background, which are reflected back to the turbine farm terminals, and therefore at the point of common coupling (PCC). In addition, the large capacitance in the form of subsea cables and compensating capacitor banks resonant frequencies influences the resonant frequencies of the system. These resonances result in the amplification of the harmonic emission in two ways. Firstly from individual turbines into the power grid i.e. primary emission. Secondly, flow of harmonic currents from the grid into the wind park termed as secondary emission [82]. The harmonic analysis of OWPP connected to the electric-grid can be conducted by an equivalent circuit depicted in Fig. 6 [83].

$$V_{PCC} = I_{h,p}\left(\frac{Z_p}{Z_p+Z_s}\right) - V_{h,s}\left(\frac{1}{Z_p+Z_s}\right) \qquad (6)$$

$$I_{PCC} = I_{h,p}\left(\frac{Z_p Z_s}{Z_p+Z_s}\right) + V_{h,s}\left(\frac{Z_p}{Z_p+Z_s}\right) \qquad (7)$$

where I_{PCC} and V_{PCC} represent the current and voltage at the PCC, Z_p and Z_s respectively show the harmonic impedance of the wind farm side and utility grid, $I_{h,p}$ and $V_{h,s}$ are the wind farm harmonic current source and grid harmonic voltage source, respectively. Using these parameters, harmonic contribution from either side can be assessed by means of various methods like active power direction method, IEC voltage phasor method and voltage-current ratio approach [75].

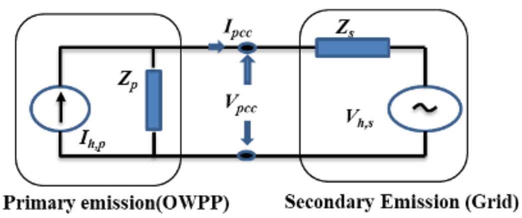

FIGURE 6. Equivalent circuit of harmonic model in OWPP

In addition to harmonics, OWPP could also cause supraharmonics (SP), i.e. distortion in the frequency range above 2 kHz. SP discharges in OWF are closely associated with PWM strategy used for conversion in power inverter of wind turbine. The magnitude of SP at the PCC is usually lower than regular harmonics (3rd, 5th, 7th) [76]. However, lack of standard limits to quantify the effects of these high frequency emissions in OWPPs is the area that needs to be investigated. Ammar et al in [77] propose that in order to measure SP up to 9 kHz, the chosen signal-sampling rate should be in accordance with the rules of signal analysis. Nonetheless, FFT samples need to be fetched by power of two, such that the total sampling becomes 20.48 kHz, according to IEC 61000-4-7. Lastly, raw components of 5 Hz FFT resolution are distributed into 200 Hz bands, as shown in Fig. 7.

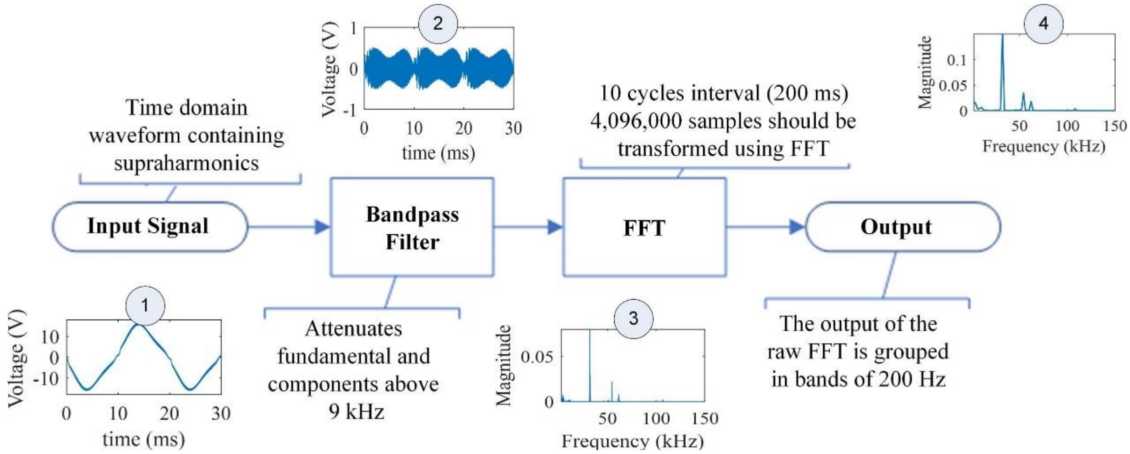

FIGURE 7. **Measurement scheme for supraharmonics** [77]

3) VOLTAGE SAG AND SWELL

Temporary reduction of the RMS voltage between 0.9 and 0.1 pu of nominal value from half-cycle to few seconds is termed as a voltage sag, while the voltage swell or over voltage is an increase in the RMS (effective) voltage to between 1.1 and 1.8 pu of normal value from half-cycle to one minute. It is in accordance with European Standard EN 50160 - IEEE 1159 [78]-[80]. A voltage sag due to wind generator penetration may result in disconnection, if voltage drops under a certain value. This voltage dip can also result in a high current through IGBT inverter which connects a PMSG to the grid [81]. Fast removal of sag and swell in such cases events is crucial. Hence, voltage and time duration limits allowed in various countries grid code and regulations are shown in Table III [82].

TABLE III
VOLTAGE SAG/SWELL AND TIME REQUIREMENTS

Country	Voltage Sag		Voltage Swell	
	Rise	Time(sec)	Drop	Time (sec)
Germany	120	0.1	0%	0.15
Denmark	120%	0.1	20%	0.5
UK	-	-	15%	0.14
Spain	130%	0.25	0%	1.5
Italy	125%	0.1	0%	0.2
China	-	-	20%	0.625
USA	140%	1	15%	1

B. STABILITY ISSUES

As wind power penetration level increases in electric grid, researchers focus more towards the problem of power system stability. Stability issue in OWPP is mostly caused, either by any uncertainty occurring at wind turbine side, or a fault/ disturbance at the grid side. With an increasing number of wind farms connected, controlling dynamic characteristics of overall power systems is becoming more challenging [83]. A related phenomenon of sub synchronous resonance (SSR) has gained attention in recent years. It has been reported to cause oscillations below system's rates frequency in grid connected wind farm system in vicinity of series compensated transmission line [84], [85]. To investigate this issue, an impedance-based stability analysis (SA) is usually adopted, which makes use of ratios of analytically derived impedances of OWPP and line converters looking from the PCC side. Nyquist plots of above-mentioned impedances are mostly used to identify potential low frequencies causing SSR [86].

1) SMALL SIGNAL STABILITY

The small signal stability refers as to how a system behaves whenever a minor change occurs in its state variables [87]. This stability issue generally happens due to lack of damping torque, which leads to increase the amplitude of rotor oscillations. Any variation in the operating conditions of the power system can be analyzed through eigenvalues of the system state matrix [88], [89]. The small signal stability studies of the power system variability due to the OWPP have been reported in literature by using different schemes like singular value decomposition based least squares analysis and Prony analysis [90], [91]. Such schemes help in understanding the effects of load change on grid side as well as wind speed inconsistency on small-signal angular stability. Authors in [92] discuss the extension of small-signal stability region to a more robust small-signal stability region via hyperplane approximation, within which the power system retains stability even with perturbations due to uncertain nodal variations from OWPP. Similarly, a DFIG based direct drive control scheme is given in [93] to study small signal stability and dynamic response of the system. Comparative results proved the superiority of the proposed controller under system disturbances while linked with a single as well as four-machine infinite bus system. Small signal stability analysis of a large variable speed wind turbines is presented in [94]. This method used bifurcation analysis to compute the boundaries of small signal stability, when system is subjected to line trip and load variations.

2) TRANSIENT STABILITY

Transient stability is the capability of the power grid to sustain synchronism when experiencing large disturbances [95]. Severe disturbances may contain component outages, reduced inertia, load variations or faults that cause large excursions of generator's rotor angle. The response of the system is affected by the nonlinear power-angle relationship. The interval of

TABLE IV
SUMMARY OF VARIOUS SA TECHNIQUES IN OWPP

Stability	Technique	Description	Reference
Small signal stability	State space stability analysis	SA performed on PMSG based systems has shown improved dynamic response and when compared to a DFIG based system with similar parameters	[93]
	Least square extended Prony analysis	Wind power variability as result of disturbance introduced in a 1000MW OWPPs considered	[90]
	Modal state analysis	Analyzed the effects of load change and dynamic interactions, on adding DFIG based WT in to the grid	[91]
	State space stability analysis	Perturbations due to intermittent wind have been modeled using state-matrix and a robust stability scheme proposed	[92]
Transient stability	H∞	Linear parameter varying control is presented for increased transient stability of interconnected system having four AC-DC lines	[96]
	Equal area criterion	A real time corrected kinetic energy method is proposed, which quickly finds CCT with less comp: burden.	[97]
	Approx. dynamic programming	Supplementary power controller applied to DFIG based WF system to mitigate PQ issues at PCC and to retain stability during varying operating conditions	[98]
	Approx. dynamic programming	Using reinforced learning of neural network in a DFIG integrated WF, inter-area oscillations damping and improved stability margins of tie-lines achieved	[99]

interest while observing transient stability is generally 3 to 5 sec following the disturbance. This time period can extend up to 10–20 sec in case of large system with prevailing inter-area fluctuations [100]. A study presented in [96] applies efficient feedback control scheme by utilizing mechanical power as well as DC channel power of the system as control objective to enhance the transient stability of the interconnected wind farm system. Another scheme in [97], uses an advanced real-time technique relating to corrected kinetic energy to calculate critical clearing time (CCT), to assess the transient stability of an interconnected grid with wind turbines. Schemes related to adaptive control have proved to be effective for augmenting transient stability in DFIG based grids. These methods make use of neural networks based on dynamic programming to control reactive power and improves the closed-loop performance of the wind connected power grids [98], [99]. Table IV summarizes different SA and their solution methodologies in OWPP.

C. VOLTAGE AND FREQUENCY ISSUES

In an electrical power system, the reactive power flow is related to the voltage variation, while the frequency change corresponds to a change in the active power in the system. In an OWPP, electromechanical devices that are usually used to generate the electricity are the induction generators, which require reactive power for excitation. Therefore, DFIG based wind farm are of lesser help for supporting the grid with reactive power when compared to synchronous machines [42].

1) VOLTAGE CONTROL

With increasing level of offshore wind energy penetrations into the grid, voltage stability is becoming a challenge. PMSG based wind turbines are able to manage reactive power in case of voltage deviation at the PCC. Nevertheless, for induction based wind generators it is not the case as they accelerate during disturbances/faults, which require reactive power consumption [101]. Voltage control of a wind farm need to be designed in such a way that demand of reactive power output to be met is in accordance with the dispatch instructions form grid side to support the voltage of PCC. In this regard, voltage and reactive power control must meet the requirements below [102]:

- Voltage at PCC should be maintained ranging from 97% to 105% of the nominal voltage at grid side
- Its speed of regulation and control accuracy should meet the demand of voltage control of grid operation.

The reactive power issue in OWPP is addressed by ZH Rather et al [103], in which voltage stability performance of the system is examined using mixed integer dynamic optimization approach. It is concluded that better system efficiency and reliability can be achieved by optimal allocation of dynamic reactive power sources. Wang et al. [104] show through simulations, the influence of the voltage variation at the PCC by various capacities and underwater cable lengths for large-scale offshore wind farm connected to power grid in Taiwan. In large OWPP systems, the use of hierarchal control to regulate PCC voltage is a viable option. This strategy have two levels viz. centralized control (CC) and local control (LC), as shown in the Fig. 8. The CC manages the voltage at PCC, whereas the LC supervises the power injection from GSI to trail the expected set point from the CC [105].

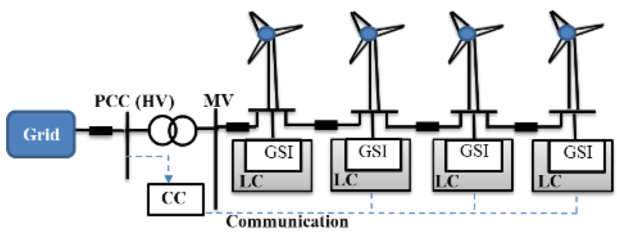

FIGURE 8. Hierarchal voltage control scheme in OWPPs

2) IMPACTS OF FREQUENCY VARIATION

OWPP penetration in the grid proportionally increases the unpredictability and frequency variation of the power output. The operating conditions change due to these deviations in frequency, because it alters the frequency related parameters like reactance and the slip of the wind turbines. Furthermore, modern variable speed wind turbines such as type III and IV are connected to the grid with end-to-end power converters. The intermediate DC voltage in this AC-DC-AC interface creates electrical decoupling between OWPP and the grid. Consequently, the system inertia reduces, as the generator rotor does not see the changes in frequency [106]. Additionally the interconnected conventional power units are overburdened to regulate the frequency variations. This phenomenon deteriorates frequency and inertia regulation, especially in islanded systems with no grid support [107].

In European power grids, frequency regulation is maintained within limits using three-way control strategy as depicted in Fig. 9. In case of any deviation**,** primary control keeps the balance between power generation and consumption. Secondary control triggers automatically when there is active power deficit on the line. This stage lasts for about 15 minutes, and if the frequency deviation of frequency persists, tertiary control comes inline. The tertiary control mitigates the persistent frequency deviations after the production outages or long-lasting load variations. Time control makes sure that discrepancy between synchronous time and universal coordinated time of the system must be avoided, which happens due to frequency deviation [108].

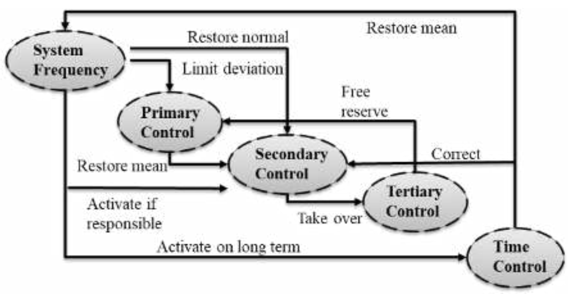

FIGURE 9. Multi-level Frequency Control in wind farm generation

3) RAMP RATE REQUIREMENTS

Wind power changes continuously and as a result, an important issue related to grid integration is upholding the economic cost of wind energy and the system resiliency. This intermittency of wind energy is countered by calling fast ramping or peak-load units, so that balance of supply and demand must be kept. Such events threaten the benefits of wind energy-low fuel cost and reduced CO_2 footprint [109]. An OWPP need to have the ability to limit increased and decreased power rates. By and large, the ramp-rate limit (RRL) for a short duration of 1-minute addresses system regulation capability. A longer duration of 10-minute typically is applied on grid load-following capability [43].

In this regard, active RRL by Denmark specifies the commencement of constraint to be accomplished with in 2 to 10 seconds, whenever an order to change the parameter is received. The maximum RRL constraint is 100 kW/sec [110]. The grid code standards of China stipulates the power dispatch facility to deliver the power RRL within 1 to 10 minutes [111].

According to ISO-NE department in US, response rate to a peak or valley in power output OWPP should not overdo $\Delta 10\ \%/sec$.

IV. GRID CODE REQUIREMENTS

Grid codes mainly contain standards and guidelines for active and reactive power control of the system. The interruption of OWPP under PQ issues is undesirable when a substantial share of the total network generation comes from wind power. Hence, grid codes need OWPP to continue their uninterrupted operation under several fault situations. This ability of wind turbine to stay in connection with the power grid in case of any fault or voltage imbalance for specified amount of time is termed as LVRT. LVRT capability is instantly needed as it takes into the account fault percentage and interval during which wind farms need to be able to withstand the fault [112]. Electrical network operators have grid code requirements that vary from one country to another depending on the organization and characteristic features of the system. Although that needs to comply with international standards like IEC and IEEE. In Table V, a comparative description of different IEEE and IEC standards is provided related to LVRT techniques as well as harmonic limits for wind generation systems.

TABLE V
IEEE AND IEC GRID CODE REQUIREMENTS FOR PQ IN OWPP

Standard	Provisions of the standard
IEEE 1668 - 2014	This standard methods for examining equipment's LVRT ability when connected to the grids with voltage networks with voltage dips persisting for a minute [113]
IEEE 1547.4 -2013	This standard talks about the aspects of integrating distribution generation sources with main grid [114]
IEEE 519	This standard defines the harmonic current and voltage limits at PCC [115]
IEC 61000 3-2	It defines limits of equipment's harmonic current with input current > 16A [116]
IEC 61400-27	This code states dynamic models of different wind turbines to enhance power system stability [117]
IEC 61508	This standard defines the operational safety for electronic converters [118]
IEC 60050-415	This standard focuses on safety regulations and protection of wind generation systems under various operating conditions [119]
IEC 61400-21	This standard states assessments and measurements for power quality of wind turbines and LVRT ability of OWPP [120]

In the context of OWPP, IEC has formulated standards for measurement and assessment of PQ characteristics of grid connected wind turbines i.e. IEC 61400-21 [121]. As a result of connecting wind farms to a transmission system instead of a distribution system [72], modern wind turbines acquire the ability to control both active and reactive power in steady as well as in transient conditions. A detailed study of grid code requirements to enhance the participation of OWPP in frequency stability and virtual inertia is presented in [122]. Frequency bounds adopted by the different countries as per international grid codes requirements is provided in Table VI

[123]. Frequency variation between the OWPP and power grid can cause synchronization imbalance as well as disturbance in active power output. Unlike conventional generators, wind turbine generators usually do not have the ability of giving frequency regulation to the network due to the absence of inertia [124]. This results in decreased frequency nadir in DFIG based OWPPs with lacking inertia [125].

TABLE VI
FREQUENCY BOUNDS IN GLOBAL GRID STANDARDS

Country	Frequency limits (Hz) (f_{min} - f_{max})	Duration
Australia	49.5 - 50.0	continuous
($F_0 = 50$)	49.0 - 51.0	10 min
	48.0 - 51.0	2 min
	47.5 - 52.0	9 sec
Canada	59.4 - 60.6	continuous
($F_0 = 60$)	58.5 - 60.5	11 min
	57.5 - 61.7	1.5 min
	57.0 - 61.7	10 sec
Denmark	48.5 - 51.0	continuous
($F_0 = 50$)	48.0 - 51.0	25 min
	47.5 - 52.0	5 min
	47.0 - 52.0	10 sec
Germany	49.0 - 50.5	continuous
($F_0 = 50$)	48.5 - 51.5	30 min
	47.5 - 51.5	10 min
	46.5 - 53.5	10 sec
Ireland	49.5 - 50.5	continuous
($F_0 = 50$)	47.5 - 52.0	60 min
	47.0 - 52.0	20 sec
UK	47.5 - 52.0	continuous
($F_0 = 50$)	47.0 - 52.0	20 sec
US	59.5 – 60.0	continuous
($F_0 = 60$)	59.3 - 59.5	10 min
	58.7 - 59.3	10 sec

Active and reactive power requirements should be met in all grid codes to maintain load voltage and power factor levels at the PCC. Under nominal power generation, recommended practice is to operate the wind turbines in a way to retain 0.95 power factor leading or lagging. In UK grid codes, gradual reduction in reactive power is required, as the plant achieves 20% to 50% of rated power. However, the German grid codes demand a continuous reactive power at different power plant generations. With the Danish grid codes, it is requisite to reach a power factor set point with a tenacity of 0.01. Table VII compares operating limits of power factor in global grid codes for which OWPP are required to remain connected to grid [126].

TABLE VII
POWER FACTOR REQUIREMENTS IN INTERNATIONAL GRID CODES

Country	Power Factor	
	Leading	Lagging
Canada	0.90	0.95
Germany	0.95	0.92
UK	0.95	0.95
Denmark	0.95	0.95
Australia	0.93	0.93
New Zealand	0.95	0.95
US	0.95	0.95
Ireland	0.95	0.95
Spain	0.91	0.91

V. POWER QUALITY IMPROVEMENTS TECHNIQUES IN OWPP

Mitigation of PQ and stability issues attracted the researchers or operators attention due to the increased penetration of OWPP in the grid. Various devices and control techniques have been developed recently to improve the PQ of the interconnected power grid in general.

A. DFIG CONVERTERS BASED CONTROL TECHNIQUES

PQ improvement and harmonic current mitigation have been reported in the literature to be achieved by applying control algorithms on DFIG converters [39]. In [127], the grid side control (GSC) of the wind energy system has been adjusted to regulate the dc link voltage by using d-q transformation method. In addition to DC link voltage modification through active filtering, mitigation of harmonic currents is achieved. A DFIG-based wind energy system with nonlinear loads at PCC is shown in Fig. 10 [128]. This DFIG based system works as an active filter as well as source of real power generation. The harmonic current caused by the nonlinear loads is mitigated by GSC control. The rotor side control (RSC) is based on voltage-oriented reference frame for achieving unity power factor at the stator side as well as MPPT.

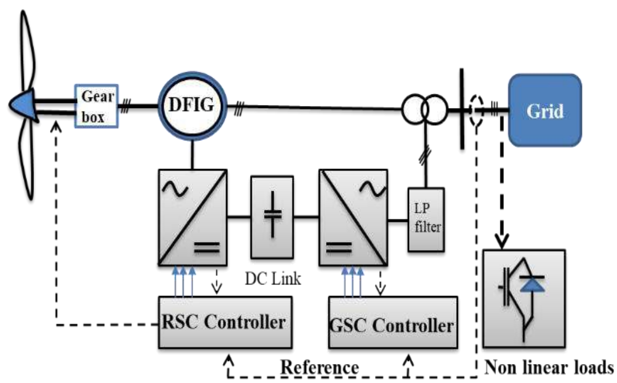

FIGURE 10. RSC and GSC configuration in DFIG based grid system

A sensorless stator field oriented technique is used to control the RSC, which eventually reduces the harmonics levels at the grid [129]. In [128], the control of GSC is implemented such that the signal fed to power switches is bounded by a hysteresis current method. The experimental results show significant improvement of total harmonic distortion (THD) at the grid after filtering. H. Nian et al [130] proposed an impedance reshaping control method for a 2MW DFIG system. This control strategy enables the system to suppress the high frequency resonance thereby avoiding the unstable condition. Furthermore an active damping strategy that can compensate for the matrix converter LC filter under different operating conditions is presented in [131]. Here, a small signal stability analysis has been performed and it is shown that the input filter resonance issue becomes severe as the DFIG operates at sub-synchronous speed with unity power factor.

B. FACTS based Active Power Filter Techniques

Flexible Alternating Current Transmission Systems or FACTS are power electronic based devices that can control and regulate the active and reactive power in a power network. These compensating devices can be coupled in series, or in combined topology, contingent on specific requirements when connecting to the power system grid [132]. FACTS based on series connection include thyristor controlled series capacitors (TCSC) as well as static synchronous series compensator (SSSC) [133], while Shunt based FACTS comprise of static VAR compensator (SVC) and static synchronous compensator (STATCOM). Unified power flow controller (UPFC) are hybrid FACTS i.e. series-shunt devices are capable to control voltage and power flow simultaneously [134]. Table VIII specifies comparison of various FACTS effects on PQ parameters in electric power grid [135].

TABLE VIII
FACTS DEVICES EFFECT ON PQ PARAMETERS (HIGHER * IS BETTER)

Parameters	SVC	STATCOM	TCSC	UPFC
Reactive Power control	***	****	**	****
Active Power control	---	*	**	---
Voltage stability	***	****	***	****
Flicker reduction	***	****	---	****
Harmonics	---	*	---	****

The principle of the STATCOM is to either consume or deliver the reactive power based on the estimated RMS value at the PCC. Consequently, it mitigates voltage drops and improves the active and reactive power flow in the transmission line. A scheme of modified STATCOM controller with synchronous frame reference controller for minimizing some of the PQ issues of a hybrid wind and PV based system is proposed in [136]. The proposed controller manages to achieve 25.35% improvement in system's THD. Voltage variations have been reduced and active power flow significantly improves using the proposed scheme. Kamel et al in [37] studied two cases for improving the PQ in OWPP connected to power grid. That include sharing of the STATCOM reactive power with the electric grid as well as regulating the voltage at the PCC, as shown in Fig. 11.

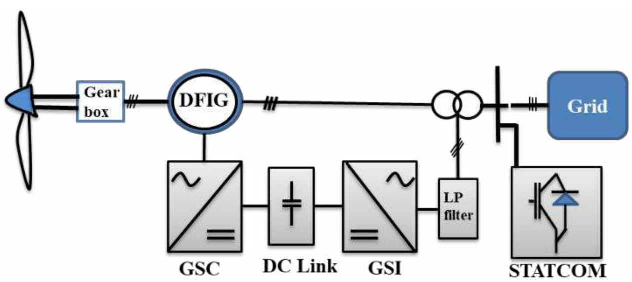

FIGURE 11. STATCOM placement of DFIG based OWPP

Another STATCOM compensation based PQ improvement study on a OWPP and PV hybrid power system has been presented in [137]. The simulation results show that load bus voltage is regulated at about 1.0 p.u. while THD in voltages and currents are maintained at 1%. The UPFC consists of series as well as shunt converters, coupled to a dc link capacitor as shown in Fig. 12. The series part provides the regulation of active and reactive powers while shunt part ensures the voltage support at PCC by regulating voltage at DC link of UPFC [138]. Dynamic performance of a DFIG based OWPP under wind gusts and disturbances is proposed in [139] using an adaptive model-free controller for UPFC. Uncertainties like voltage sag, voltage swell, wind gust and LVRT capability of the system significantly improved when suggested UPFC based adaptive controller is compared to conventional PI controller. The UPFC show promising results, while damping the SSR oscillations occur mostly in systems with series-capacitor compensated lines. One such hybrid steam turbine generator (STG) - DFIG based OWPP uses UPFC with its damping controller to mitigate SSR oscillations by improving transient stability of the system [140].

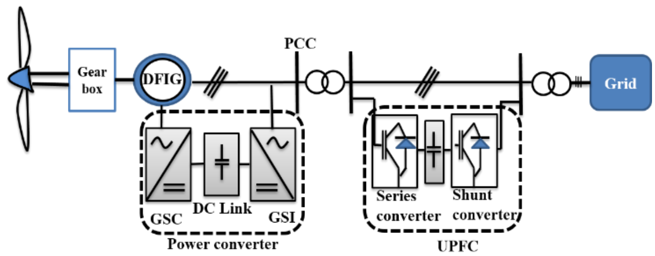

FIGURE 12. UPFC connected DFIG based system

C. ENERGY STORAGE SYSTEM BASED SOLUTIONS

The energy storage systems (ESS) play a significant role in PQ improvement of the generated power by regulating output voltage of the OWPP. The electrical power produced by the wind turbines is dependent upon the wind speed and affects both the PQ as well as system planning [141]. The ESS generally includes battery, flywheel, superconducting magnetic energy storage system SMES, super capacitor, compressed air system, pump hydro and hydrogen production. Usually the ESS connected to the intermediate DC link capacitor of back to back power electronic converters for power conversation as illustrated in Fig. 13. The battery energy storage system (BESS) in addition to storing the power, also regulates the active and reactive power at PCC, and maintains system stability [142].

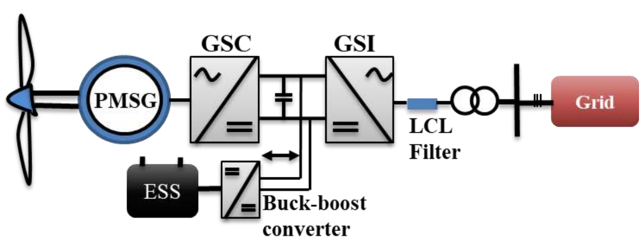

FIGURE 13. ESS connected to DFIG based wind energy system

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The control and stabilization scheme for grid connected wind farm with reactive power compensation by SMES is proposed in [143]. This multilevel control method enhances the transient stability by fast controllability of the SMES four-quadrant operation. Similarly, a fuzzy logic based controlled SMES in [144] shows an improved transients response and voltage regulation. In [145], authors presented a system of DFIG with fuel cell connected to the power grid. The proposed scheme used vector control on two back-to-back power electronic converters to regulate the power flow to the grid, fuel cell, and generator. Beside SMES, the flywheel energy storage (FES) systems are also effective in alleviating power surges occur during faults in OWPP connected to grid [146]. Another study reported in [147], exploits the ability of FES system to smooth out power fluctuation, where it is interfaced with 80 MW DFIG based OWPP. Super capacitor is another ESS based solution for voltage flicker issue in weak grid having wind energy integration. With appropriate filtering control algorithm, these systems achieve superior flicker mitigation as compared to the reactive power control techniques [148].

D. METHODOLOGIES FOR LVRT IN OWPP

Various schemes have been reported in literature for efficient fault ride through in offshore wind based generations [26]. The commonly used methods include simple protective circuits such as crowbar, stator damping resistor (SDR) and rotor current limiter (RCL). These schemes are mostly used in DFIG based systems. Other methods include VARs injection through FACTS based devices and the implementation of robust control strategies to enable system to ride through during fault conditions. Organization of different LVRT strategies in OWPP is illustrated in Fig. 14.

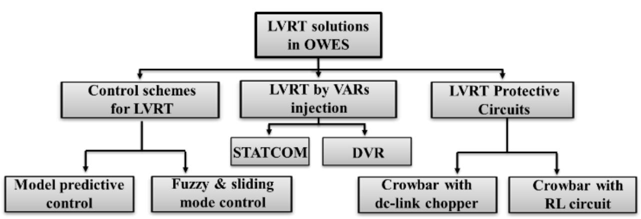

FIGURE 14. LVRT Schemes for wind turbines

1) LVRT PROTECTIVE CIRCUITS

Most common LVRT method for type III wind turbine is using crowbar (CB) protective circuit. Crowbar is a resistive circuit which is connected across rotor winding terminals [149]. In case a fault occurs, a large rotor current generates due to DFIG rotor and stator magnetic coupling. To counter this high current, resistor crowbar bank is installed to disable the rotor side converter during the fault, so that power flow can be controlled independently. For optimal value of crowbar resistance, $R_{C,\,opt}$, the following relation is applied [150]:

$$R_{C,opt} = \frac{\sqrt{2}\,(V_{max}\omega_S L_S)}{\sqrt{(3.2\,V^2 - 2V_{max}^2)}} \quad (8)$$

where ω_s is the synchronous speed, V is the stator voltage; V_{max} is the maximum rotor voltage while Ls is the stator inductance. An upgraded scheme make use of bidirectional switches connected to stator or rotor resistors is discussed in [42]. Whenever a fault occurs, switch turned OFF, connecting the resistors of RCL and SDR in series with rotor and stator as shown in Fig. 15. The advantage of these (RCL, SDR) circuits over crowbar implementation is the ability to limit high transient current while retaining the connection with GSC.

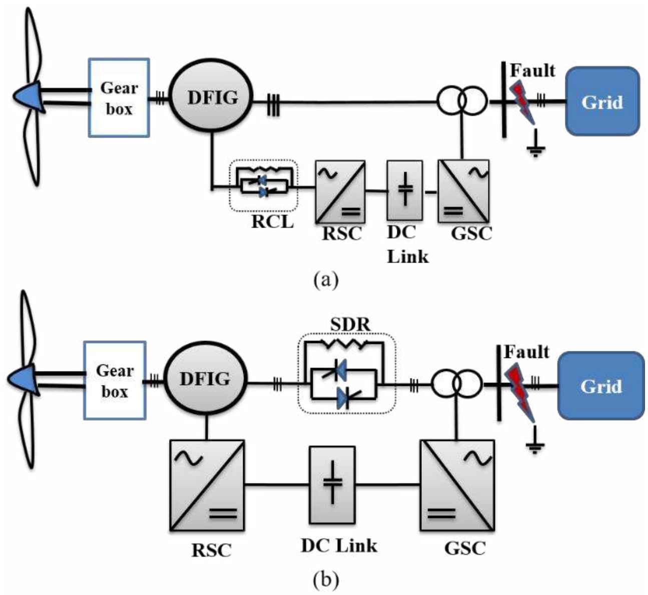

FIGURE 15. LVRT Improvements via (a) RCL, (b) SDR, for wind turbines

2) LVRT BY VARS INJECTION

The dynamic voltage restorer (DVR) is a series connected device usually linked with DFIG based wind generation systems at PCC to counter voltage sag or swell and PQ issues. In addition, it enhances the LVRT ability by injecting voltage and provides power compensation to the grid to clear faults [151], [152]. An onsite FRT testing methodology for OWPP prior to grid integration is presented in [153] combining with DVR control to maintain voltage swells for testing requirements. A flexible AC transmission system (FACTS) based device i.e. STATCOM is a shunt-connected, reactive power compensation scheme. It can mitigate harmonic resonance issues and provides load compensation to the grid [31]. Heydari et al [154] suggested an updated STATCOM based control method to improve LVRT ability of wind turbine in case of voltage fault. There proposed STATCOM compensator model enables the system to clear the maximum fault duration swiftly thereby improving the stability margin.

3) CONTROL SCHEMES FOR LVRT

Control techniques are crucial to the robust operation of OWPP in case, PQ issues happen. Proper tuned controllers stabilize the system by improving its LVRT capability. A fuzzy control technique is implemented in DFIG based OWPP to limit fault current by improving LVRT ability of the system [155]. A similar scheme with integrated terminal sliding mode control is proposed in [156] to enable DFIG to ride through deep voltage sag under different operating conditions. Direct-model predictive control (DMPC) technique developed in [157] optimize the LVRT ability of DFIG energy conversion systems by optimizing the switching states of the embedded power converter.

VI. CONCLUSION AND RECOMMENDATIONS

The unprecedented growth of offshore wind generation has paved an accelerated path towards a global decarbonized future with clean renewable energy. Nevertheless, the intermittent nature of wind power poses various challenges related to the integration and transmission systems of the wind turbine such as PQ and system stability challenges. Although AC transmission is most commonly used in OWPPs nowadays, the transmission voltage level constraints will encourage the use of HVDC transmission in near future. This paper reviewed PQ issues of OWPP integration into electric gird and discussed various solution methodologies. Statistics regarding OWPP installed capacity and future growth have been listed. Different types of wind turbine topologies with their distinguishing features, control algorithms and variability have been discussed. The mentioned challenges focused on PQ issues like flickers, harmonics, voltage sag and swells as well as voltage and frequency stability problems and recent control schemes with regard to OWPP. This article also sheds light on crucial aspects like LVRT methods and grid code requirements in different parts of the world. These grid codes are essentially intended for grid support in case of steady-state as well as grid faults conditions. In addition, this paper reviewed available solution approaches including DFIG controllers systems, filters, energy storage systems and customs power devices to deal with the challenges of PQ problems in OWPP. A performance comparison of these FACTS devices shows UPFC and STATCOM to be better options for solving PQ issues, followed by SVC and TCSC. A continuous renewal of grid standards in different countries depending upon wind variability, generation portfolio and LVRT requirements and schemes have been discussed thoroughly.

For the review topic under consideration, some recommendations with regard to PQ challenges, standards and solution methods for future improvements in the prevailing system are:

1. The need of a fast communication system to exchange and manage data between far-flung offshore and onshore stations. Latest protocols like internet of things (IoT) can help in this regard to mitigate any communication delays that may affect system stability.
2. Online impedance assessment analysis for OWPPs networks can be achieved by installing advanced synchronized waveform monitoring devices.
3. PQ issues like harmonics and flickers need to have precise grid codes for measurements and contribution of different stakeholders involved in the radial OWPPs.
4. SH mitigation with regards to OWPP is the area which still need researcher's attention with well-established grid regulations are required to solve this issue.
5. LVRT capability requirements need to contain information that is more detailed, because the FRT ability vary with wind farm rating as well as type of faults.
6. Detailed grid codes need to be implemented for integration of various ESS technologies, which can provide smooth output and system flexibility from wind generation for a specific duration in case of any fault.
7. A standardized and regulated policy from various countries to enhance OWPP development, while at the same time providing economic, environmental as well as social growth to those nations.

The above recommendations may be helpful in achieving improved PQ with regards to OWPP, which is fast growing power provider market and will dominate its peers in the near future. This review could be extended to further studies to enhance PQ and stability in OWPP by overcoming various system drawbacks.

REFERENCE

[1] R. M.Elavarasan *et al.*, "A Comprehensive Review on Renewable Energy Development, Challenges, and Policies of Leading Indian States with an International Perspective," *IEEE Access*, vol. 8. Institute of Electrical and Electronics Engineers Inc., pp. 74432–74457, 2020.

[2] Jean andD.Pitteloud, "Global Wind Power Statistics – Wind Energy International Platform," 2019. https://library.wwindea.org/global-statistics/ (accessed Jul. 03, 2020).

[3] E. P. P.Soares-Ramos, L.deOliveira-Assis, R.Sarrias-Mena, andL. M.Fernández-Ramírez, "Current status and future trends of offshore wind power in Europe," *Energy*, vol. 202, p. 117787, Jul.2020.

[4] L.Vinet andA.Zhedanov, "A 'missing' family of classical orthogonal polynomials," *J. Phys. A Math. Theor.*, vol. 44, no. 8, p. 085201, Feb.2011.

[5] Wind Europe, "Subtittle if needed. If not MONTH 2018 Offshore Wind in Europe," 2020.

[6] "Offshore - Statistics - Online access - The Wind Power." https://www.thewindpower.net/statistics_offshore_en.php (accessed Aug. 11, 2020).

[7] J.Lee andF.Zhao, "Global Offshore Wind Report 2020 - Global Wind Energy Council," *Contributing authors: Alastair Dutton, Ben Backwell, Liming Qiao, Shuxin Lim, Anjali Lathigaralead, Wanliang Liang*, 2020. https://gwec.net/global-offshore-wind-report-2020/ (accessed Aug. 11, 2020).

[8] "Wind power is crucial for combating climate change. Wind energy can be deployed anywhere in the world."

[9] R.Ferdinand, P.Melzer, andA.Monti, "Power Quality Issues at the Grid Connection Point of HVDC Connected Offshore Wind Farms and Their Influence on the Production," Dec. 2018.

[10] C.Qin, P.Ju, F.Wu, Y.Jin, Q.Chen, andL.Sun, "A coordinated control method to smooth short-term power fluctuations of hybrid offshore renewable energy conversion system (HORECS)," Aug. 2015.

[11] P.Sørensen *et al.*, "Power quality issues on wind power installations in Denmark," 2007.

[12] R.Li, L.Yu, L.Xu, andG. P.Adam, "Coordinated Control of Parallel DR-HVDC and MMC-HVDC Systems for Offshore Wind Energy Transmission," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 8, no. 3, pp. 2572–2582, Sep.2020.

[13] A. W.Korai andI.Erlich, "Mitigation of harmonic instability in offshore wind farms using supplementary signals in the HVDC control," in *IEEE Power and Energy Society General Meeting*, Jan. 2018, vol. 2018-January, pp. 1–5.

[14] M. L.Rahman, S.Oka, andY.Shirai, "Hybrid power generation system using offshore-wind turbine and tidal turbine for power fluctuation compensation (HOT-PC)," *IEEE Trans. Sustain. Energy*, vol. 1, no. 2, pp. 92–98, Jul.2010.
[15] A.Egea-Alvarez, F.Bianchi, A.Junyent-Ferre, G.Gross, andO.Gomis-Bellmunt, "Voltage control of multiterminal VSC-HVDC transmission systems for offshore wind power plants: Design and implementation in a scaled platform," *IEEE Trans. Ind. Electron.*, vol. 60, no. 6, pp. 2381–2391, 2013.
[16] Z.Lu, Y.Ye, andY.Qiao, "An Adaptive Frequency Regulation Method with Grid-Friendly Restoration for VSC-HVDC Integrated Offshore Wind Farms," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 3582–3593, Sep.2019.
[17] Y.Pipelzadeh, N. R.Chaudhuri, B.Chaudhuri, andT. C.Green, "Coordinated Control of Offshore Wind Farm and Onshore HVDC Converter for Effective Power Oscillation Damping," *IEEE Trans. Power Syst.*, vol. 32, no. 3, pp. 1860–1872, May2017.
[18] H.Liu andJ.Sun, "Voltage stability and control of offshore wind farms with AC collection and HVDC transmission," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 2, no. 4, pp. 1181–1189, 2014.
[19] A.Xue, J.Zhang, L.Zhang, Y.Sun, J.Cui, andJ.Wang, "Transient frequency stability emergency control for the power system interconnected with offshore wind power through VSC-HVDC," *IEEE Access*, vol. 8, pp. 53133–53140, 2020.
[20] L.Harnefors, A. G.Yepes, A.Vidal, andJ.Doval-Gandoy, "Passivity-based controller design of grid-connected VSCs for prevention of electrical resonance instability," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 702–710, Feb.2015.
[21] M.Cheah-Mane, L.Jun, N.Jenkins, andL.Sainz, "Electrical resonance instability study in HVDC-connected Offshore Wind Power Plants," in *IEEE Power and Energy Society General Meeting*, Nov. 2016, vol. 2016-November.
[22] Ł. H.Kocewiak, J.Hjerrild, andC. L.Bak, "Wind turbine converter control interaction with complex wind farm systems," in *IET Renewable Power Generation*, 2013, vol. 7, no. 4, pp. 380–389.
[23] L. P.Kunjumuhammed, B. C.Pal, C.Oates, andK. J.Dyke, "Electrical oscillations in wind farm systems: Analysis and insight based on detailed modeling," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 51–62, Jan.2016.
[24] C.Sourkounis andP.Tourou, "Grid Code Requirements for Wind Power Integration in Europe," *Conf. Pap. Energy*, vol. 2013, pp. 1–9, 2013.
[25] T.Kristian Vrana *et al.*, "Wind Power within European Grid Codes: Evolution, Status and Outlook."
[26] M. T.Hagh andT.Khalili, "A review of fault ride through of PV and wind renewable energies in grid codes," *International Journal of Energy Research*, vol. 43, no. 4. John Wiley and Sons Ltd, pp. 1342–1356, Mar.25, 2019.
[27] D. W.Gao, E.Muljadi, T.Tian, M.Miller, andW.Wang, "Comparison of Standards and Technical Requirements of Grid-Connected Wind Power Plants in China and the United States," Golden, CO (United States), Sep.2016.
[28] B.Rona andÖ.Güler, "Power system integration of wind farms and analysis of grid code requirements," *Renewable and Sustainable Energy Reviews*, vol. 49. Elsevier Ltd, pp. 100–107, Sep.01, 2015.
[29] H.Hamlaoui andB.Francois, "Interest of storage based STATCOM systems to the power quality enhancement of thyristors based LCC HVDC links for offshore wind farm," in *Proceedings of the IEEE International Conference on Industrial Technology*, Apr. 2018, vol. 2018-February, pp. 1702–1707.
[30] H. M.Huang, G. W.Chang, C. K.Chen, H. J.Su, andT. C.Wu, "A study of low voltage ride-through capability for offshore wind power plant," in *2011 IEEE International Conference on Smart Grid Communications, SmartGridComm 2011*, 2011, pp. 517–521.
[31] O.Prakash Mahela andA.Gafoor Shaik, "Topological aspects of power quality improvement techniques: A comprehensive overview," *Renewable and Sustainable Energy Reviews*, vol. 58. Elsevier Ltd, pp. 1129–1142, May01, 2016.
[32] K. N. B. M.Hasan, K.Rauma, A.Luna, J. I.Candela, andP.Rodríguez, "Harmonic compensation analysis in offshore wind power plants using hybrid filters," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 2050–2060, 2014.
[33] G. S.Chawda, A. G.Shaik, O. P.Mahela, S.Padmanaban, andJ. B.Holm-Nielsen, "Comprehensive Review of Distributed FACTS Control Algorithms for Power Quality Enhancement in Utility Grid with Renewable Energy Penetration," *IEEE Access*, vol. 8, pp. 107614–107634, 2020.
[34] A.Sajadi, R. M.Kolacinski, andK. A.Loparo, "Impact of wind turbine generator type in large-scale offshore wind farms on voltage regulation in distribution feeders," Jun. 2015.
[35] X.Chen, L.Yan, X.Zhou, andH.Sun, "A Novel DVR-ESS-Embedded Wind-Energy Conversion System," *IEEE Trans. Sustain. Energy*, vol. 9, no. 3, pp. 1265–1274, Jul.2018.
[36] A. O.Ibrahim, T. H.Nguyen, D. C.Lee, andS. C.Kim, "A fault ride-through technique of DFIG wind turbine systems using dynamic voltage restorers," *IEEE Trans. Energy Convers.*, vol. 26, no. 3, pp. 871–882, Sep.2011.
[37] K.Sayahi, A.Kadri, F.Bacha, andH.Marzougui, "Implementation of a D-STATCOM control strategy based on direct power control method for grid connected wind turbine," *Int. J. Electr. Power Energy Syst.*, vol. 121, p. 106105, Oct.2020.
[38] L.Wang, Z. H.Yang, X. Y.Lu, andA.V.Prokhorov, "Stability Analysis of a Hybrid Multi-Infeed HVdc System Connected Between Two Offshore Wind Farms and Two Power Grids," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 1824–1833, May2017.
[39] W. A.Hafez, M. A.ElSattar, A. H. K.Alaboudy, andA. A.Elbaset, "Power Quality Issues of Grid Connected Wind Energy System Focus on DFIG and Various Control Techniques of Active Harmonic Filter: A review," in *2019 21st International Middle East Power Systems Conference, MEPCOHafez, W. A., Sattar, M. A. El, Alaboudy, A. H. K., & Elbaset, A. A. (2019). Power Quality Issues of Grid Connected Wind Energy System Focus on DFIG and Various Control Techniques of Activ*, Dec. 2019, pp. 1006–1014.
[40] E. M.Molla andC. C.Kuo, "Voltage Sag Enhancement of Grid Connected Hybrid PV-Wind Power System Using Battery and SMES Based Dynamic Voltage Restorer," *IEEE Access*, vol. 8, pp. 130003–130013, 2020.
[41] J.Boyle, T.Littler, andA.Foley, "Review of frequency stability services for grid balancing with wind generation," *J. Eng.*, vol. 2018, no. 15, pp. 1061–1065, Oct.2018.
[42] A. M.Howlader andT.Senjyu, "A comprehensive review of low voltage ride through capability strategies for the wind energy conversion systems," *Renewable and Sustainable Energy Reviews*, vol. 56. Elsevier Ltd, pp. 643–658, Apr.01, 2016.
[43] Y. K.Wu, S. M.Chang, andP.Mandal, "Grid-connected wind power plants: A survey on the integration requirements in modern grid codes," in *Conference Record - Industrial and Commercial Power Systems Technical Conference*, May 2019, vol. 2019-May.
[44] L.Fan, *Control and dynamics in power systems and microgrids*. CRC Press, 2017.
[45] S.Chatterjee andS.Chatterjee, "Review on the techno-commercial aspects of wind energy conversion system," *IET Renew. Power Gener.*, vol. 12, no. 14, pp. 1581–1608, Oct.2018.
[46] Y.Li, L.Fan, andZ.Miao, "Stability Control for Wind in Weak Grids," *IEEE Trans. Sustain. Energy*, vol. 10, no. 4, pp. 2094–2103, Oct.2019.
[47] E. C.Navarrete, M.Trejo Perea, J. C.Jáuregui Correa, R.V.Carrillo Serrano, andG. J. R.Moreno, "Expert Control Systems Implemented in a Pitch Control of Wind Turbine: A Review," *IEEE Access*, vol. 7, pp. 13241–13259, 2019.
[48] L.Xiong, P.Li, andJ.Wang, "High-order sliding mode control of DFIG under unbalanced grid voltage conditions," *Int. J. Electr. Power Energy Syst.*, vol. 117, p. 105608, May2020.
[49] S.Kihwele, "On control and operating strategies for maximizing the controllability of the DFIG wind turbine during grid disturbance," Sep. 2016.
[50] A. P.Neumann, M. J.Mulroy, andC.Ebden, "The use of 66kV technology for offshore wind demonstration sites," in *IET Conference Publications*, 2014, vol. 2014, no. CP651.
[51] Q.Wei, B.Wu, D.Xu, andN. R.Zargari, "Medium frequency transformer based configuration for voltage source converter based offshore wind farm," in *2016 IEEE 8th International Power Electronics and Motion Control Conference, IPEMC-ECCE Asia 2016*, Jul. 2016, pp. 3521–3525.

[52] S.Liu, X.Wang, L.Ning, B.Wang, M.Lu, andC.Shao, “Integrating Offshore Wind Power Via Fractional Frequency Transmission System,” *IEEE Trans. Power Deliv.*, vol. 32, no. 3, pp. 1253–1261, Jun.2017.

[53] M.Huang, X.Wang, S.Liu, X.Wang, Y.Meng, andR.Ye, “Technical and Economic Analysis on Fractional Frequency Transmission System for Integration of Long-distance Offshore Wind Farm,” *Dianli Xitong Zidonghua/Automation Electr. Power Syst.*, vol. 43, no. 5, pp. 167–174, Mar.2019.

[54] E.Pan, B.Yue, X.Li, Z.Zhao, andQ.Zhu, “Integration technology and practice for long-distance offshore wind power in China,” *Energy Convers. Econ.*, vol. 1, no. 1, pp. 4–19, Sep.2020.

[55] Imdadullah, S. M.Amrr, M. S.Jamil Asghar, I.Ashraf, andM.Meraj, “A comprehensive review of power flow controllers in interconnected power system networks,” *IEEE Access*, vol. 8. Institute of Electrical and Electronics Engineers Inc., pp. 18036–18063, 2020.

[56] A.-K.Skytt, P.Holmberg, andL.-E.Juhlin, “Presented at Second International Workshop on Transmission Networks for Off shore Wind Farms Royal Institute of Technology HVDC Light for connection of wind farms,” Mar.

[57] C. J.Chou, Y. K.Wu, G. Y.Han, andC. Y.Lee, “Comparative evaluation of the HVDC and HVAC links integrated in a large offshore wind farm - An actual case study in Taiwan,” 2011.

[58] D.Lamsal, V.Sreeram, Y.Mishra, andD.Kumar, “Output power smoothing control approaches for wind and photovoltaic generation systems: A review,” *Renewable and Sustainable Energy Reviews*, vol. 113. Elsevier Ltd, p. 109245, Oct.01, 2019.

[59] L.Fan, S.Yuvarajan, andR.Kavasseri, “Harmonic analysis of a DFIG for a wind energy conversion system,” *IEEE Trans. Energy Convers.*, vol. 25, no. 1, pp. 181–190, Mar.2010.

[60] S.Liang, Q.Hu, andW. J.Lee, “A survey of harmonic emissions of a commercial operated wind farm,” 2010.

[61] E.Hamatwi, I. E.Davidson, M. N.Gitau, andG. P.Adam, “Modeling and control of voltage source converters for grid integration of a wind turbine system,” in *IEEE PES PowerAfrica Conference, PowerAfrica 2016*, Aug. 2016, pp. 98–106.

[62] M.Jamil, R.Gupta, andM.Singh, “A review of power converter topology used with PMSG based wind power generation,” 2012.

[63] J. C. Y.Hui, A.Bakhshai, andP. K.Jain, “An Energy Management Scheme with Power Limit Capability and an Adaptive Maximum Power Point Tracking for Small Standalone PMSG Wind Energy Systems,” *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4861–4875, Jul.2016.

[64] M.Benadja andA.Chandra, “A new MPPT algorithm for PMSG based grid connected wind energy system with power quality improvement features,” 2012.

[65] C.Wei, Z.Zhang, W.Qiao, andL.Qu, “An Adaptive Network-Based Reinforcement Learning Method for MPPT Control of PMSG Wind Energy Conversion Systems,” *IEEE Trans. Power Electron.*, vol. 31, no. 11, pp. 7837–7848, Nov.2016.

[66] S.W. andM.V., “Power Quality and Grid Code Issues in Wind Energy Conversion System,” in *An Update on Power Quality*, InTech, 2013.

[67] X.Liang, “Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources,” *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 855–866, Mar.2017.

[68] E.Hossain, M. R.Tur, S.Padmanaban, S.Ay, andI.Khan, “Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices,” *IEEE Access*, vol. 6, pp. 16816–16833, Mar.2018.

[69] Z.Chen, “Issues of connecting wind farms into power systems,” in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2005, vol. 2005, pp. 1–6.

[70] M.Mroz, K.Chmielowiec, andZ.Hanzelka, “Voltage fluctuations in networks with distributed power sources,” in *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, 2012, pp. 920–925.

[71] A. F. Z.Zobaa andS. H. A. A.Abdel Aleem, Eds., *Power Quality in Future Electrical Power Systems*. Institution of Engineering and Technology, 2017.

[72] “IEC 61400-21:2008 | IEC Webstore | rural electrification, wind power.” https://webstore.iec.ch/publication/5434 (accessed Jul. 22, 2020).

[73] T.Sun, Z.Chen, andF.Blaabjerg, “Flicker study on variable speed wind turbines with doubly fed induction generators,” *IEEE Trans. Energy Convers.*, vol. 20, no. 4, pp. 896–905, Dec.2005.

[74] I. A.Ahmed andA. F.Zobaa, “Comparative Power Quality Study of Variable Speed Wind Turbines,” *Int. J. Energy Convers.*, vol. 4, no. 4, p. 97, Jul.2016.

[75] R.Sinvula, K. M.Abo-Al-Ez, andM. T.Kahn, “Harmonic Source Detection Methods: A Systematic Literature Review,” *IEEE Access*, vol. 7. Institute of Electrical and Electronics Engineers Inc., pp. 74283–74299, 2019.

[76] B.Zolett andR. C.Leborgne, “Propagation of supraharmonics generated by PMSG wind power plants into transmission systems,” in *2020 IEEE PES Transmission and Distribution Conference and Exhibition - Latin America, T and D LA 2020*, Sep. 2020, pp. 1–6.

[77] A. A.Alkahtani *et al.*, “Power Quality in Microgrids including Supraharmonics: Issues, Standards, and Mitigations,” *IEEE Access*, vol. 8, pp. 127104–127122, 2020.

[78] S. D.Dhakulkar, V. A.Manwar, S. G.Banole, P. B. S.Rakhonde, andE.Engineering, “Inspection of Voltage Sags and Voltage Swells Incident in Power Quality Problems- a Review,” 2017. Accessed: Aug.22, 2020. [Online]. Available: https://irjet.net/archives/V4/i1/IRJET-V4I1346.pdf.

[79] Y.Han, Y.Feng, P.Yang, L.Xu, Y.Xu, andF.Blaabjerg, “Cause, Classification of Voltage Sag, and Voltage Sag Emulators and Applications: A Comprehensive Overview,” *IEEE Access*, vol. 8, pp. 1922–1934, 2020.

[80] “P1159/D7, Apr 2019 - IEEE Approved Draft Recommended Practice for Monitoring Electric Power Quality - IEEE Standard.” https://ieeexplore.ieee.org/document/8707146/versions#versions (accessed Aug. 23, 2020).

[81] M.Naguib Eskander andS. I.Amer, “Mitigation of voltage dips and swells in grid-connected wind energy conversion systems,” *IETE J. Res.*, vol. 57, no. 6, pp. 515–524, Nov.2011.

[82] A. A.Alkahtani *et al.*, “Power Quality in Microgrids Including Supraharmonics: Issues, Standards, and Mitigations,” *IEEE Access*, vol. 8, pp. 127104–127122, 2020.

[83] C. B. M.M.K. Deshmukh, “Review on Stability Analysis of Grid Connected Wind Power,” 2014. .

[84] C.Buchhagen, C.Rauscher, A.Menze, andJ.Jung, “BorWin1 - First Experiences with harmonic interactions in converter dominated grids,” *undefined*, 2016.

[85] “Wind Energy Systems Sub-Synchronous Oscillations: Events and Modeling.” https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR80_AMPS_WSSO_070920.html (accessed Nov. 19, 2020).

[86] M.Beza andM.Bongiorno, “On the risk for subsynchronous control interaction in type 4 based wind farms,” *IEEE Trans. Sustain. Energy*, vol. 10, no. 3, pp. 1410–1418, Jul.2019.

[87] J.Machowski, J. W.Bialek, andJ. R.Bumby, “POWER SYSTEM DYNAMICS Stability and Control Second Edition.”

[88] Prabha Kundur, “Power System Stability and Control - Prabha Kundur - McGraw-Hill Education,” 1994. https://www.mheducation.co.in/html/9780070635159.html (accessed Mar. 28, 2021).

[89] S.Ahmed Raza, A.Rahim, andS.Arabia, “An Adaptive Pitch Control Strategy for a Doubly Fed Wind Generation System.”

[90] A.Sajadi, S.Zhao, K.Clark, andK. A.Loparo, “Small-Signal Stability Analysis of Large-Scale Power Systems in Response to Variability of Offshore Wind Power Plants,” *IEEE Syst. J.*, vol. 13, no. 3, pp. 3070–3079, Sep.2019.

[91] W.Du, J.Bi, T.Wang, andH.Wang, “Impact of grid connection of large-scale wind farms on power system small-signal angular stability,” *CSEE J. Power Energy Syst.*, vol. 1, no. 2, pp. 83–89, Jul.2015.

[92] Y.Pan *et al.*, “Towards the Robust Small-Signal Stability Region of Power Systems under Perturbations Such as Uncertain and Volatile Wind Generation,” *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1790–1799, Mar.2018.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3098705, IEEE Access

[93] F.Wu, X. P.Zhang, andP.Ju, "Small signal stability analysis and control of the wind turbine with the direct-drive permanent magnet generator integrated to the grid," *Electr. Power Syst. Res.*, vol. 79, no. 12, pp. 1661–1667, Dec.2009.

[94] X.Li, Z.Zeng, J.Zhou, andY.Zhang, "Small signal stability analysis of large scale variable speed wind turbines integration," *Proceedings of the 11th International Conference on Electrical Machines and Systems, ICEMS 2008*, 2008. .

[95] H.Liu andZ.Chen, "Impacts of large-scale offshore wind farm integration on power systems through VSC-HVDC," 2013.

[96] Q.Hui, J.Yang, X.Yang, Z.Chen, Y.Li, andY.Teng, "A robust control strategy to improve transient stability for AC-DC interconnected power system with wind farms," *CSEE J. Power Energy Syst.*, Jun.2019.

[97] M.Tajdinian, A. R.Seifi, andM.Allahbakhshi, "Transient stability of power grids comprising wind turbines: New formulation, implementation, and application in real-time assessment," *IEEE Syst. J.*, vol. 13, no. 1, pp. 894–905, Mar.2019.

[98] W.Guo, F.Liu, J.Si, D.He, R.Harley, andS.Mei, "Approximate dynamic programming based supplementary reactive power control for DFIG wind farm to enhance power system stability," *Neurocomputing*, vol. 170, pp. 417–427, Dec.2015.

[99] R.Yousefian, R.Bhattarai, andS.Kamalasadan, "Transient Stability Enhancement of Power Grid with Integrated Wide Area Control of Wind Farms and Synchronous Generators," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4818–4831, Nov.2017.

[100] P.Kundur *et al.*, "Definition and classification of power system stability," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1387–1401, Aug.2004.

[101] A.Jalali andM.Aldeen, "Short-Term Voltage Stability Improvement via Dynamic Voltage Support Capability of ESS Devices," *IEEE Syst. J.*, vol. 13, no. 4, pp. 4169–4180, Dec.2019.

[102] N.Chen *et al.*, "A coordinated reactive power and voltage control system for wind farm grid integration," 2012.

[103] Z. H.Rather, Z.Chen, P.Thogersen, andP.Lund, "Dynamic Reactive Power Compensation of Large-Scale Wind Integrated Power System," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2516–2526, Sep.2015.

[104] L.Wang, M. H.Hsieh, C. T.Wu, andC. L.Lu, "Analysis of voltage variations of Taiwan power system connected with a large-scale offshore wind farm," in *1st International Future Energy Electronics Conference, IFEEC 2013*, 2013, pp. 548–552.

[105] S.Asadollah, R.Zhu, andM.Liserre, "Analysis of voltage control strategies for wind farms," *IEEE Trans. Sustain. Energy*, vol. 11, no. 2, pp. 1002–1012, Apr.2020.

[106] V.Gevorgian, Y.Zhang, andE.Ela, "Investigating the Impacts of Wind Generation Participation in Interconnection Frequency Response," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1004–1012, Jul.2015.

[107] X.Yingcheng andT.Nengling, "Review of contribution to frequency control through variable speed wind turbine," *Renewable Energy*, vol. 36, no. 6. Pergamon, pp. 1671–1677, Jun.01, 2011.

[108] Z.Wu *et al.*, "State-of-the-art review on frequency response of wind power plants in power systems," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 1, Jan.2018.

[109] D.Lee, J.Kim, andR.Baldick, "Stochastic optimal control of the storage system to limit ramp rates of wind power output," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2256–2265, Dec.2013.

[110] ENERGINET, "Regulations for grid connection," *Technical regulation 3.3.1 for battery plants*, 2017. https://en.energinet.dk/Electricity/Rules-and-Regulations/Regulations-for-grid-connection (accessed Apr. 04, 2021).

[111] "GB/T 1040.2-2006, PDF in English." https://www.chinesestandard.net/PDF.aspx/GBT1040.2-2006 (accessed Apr. 04, 2021).

[112] O. P.Mahela, N.Gupta, M.Khosravy, andN.Patel, "Comprehensive Overview of Low Voltage Ride Through Methods of Grid Integrated Wind Generator," *IEEE Access*, vol. 7, pp. 99299–99326, Jul.2019.

[113] P.Systems, E.Committee, I.Industry, andA.Society, "IEEE Trial-Use Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V," *IEEE Std 1668-2014*, 2014. https://standards.ieee.org/standard/1668-2014.html (accessed Sep. 26, 2020).

[114] C. 21IEEE Standards Coordinating, "IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems," *IEEE Std 1547.4-2011*, 2011. http://ieeexplore.ieee.org/servlet/opac?punumber=5960749 (accessed Sep. 26, 2020).

[115] D. M. F. G.Roger, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," *IEEE Std. 519-2014*, 2014. https://standards.ieee.org/standard/519-2014.html (accessed Sep. 26, 2020).

[116] M.Nazarudin andZ.Abidin, "IEC 61000-3-2 Harmonics Standards Overview." Accessed: Sep.26, 2020. [Online]. Available: www.schaffner.com.

[117] "IEC 61000-4-7:2002 | IEC Webstore," 2016. https://webstore.iec.ch/publication/4226 (accessed Aug. 03, 2020).

[118] International Electrotechnical Commission, "IEC Functional Safety and IEC 61508," 2018. https://www.iec.ch/functionalsafety/ (accessed Sep. 25, 2020).

[119] "IEC 60050-415 - International Electrotechnical Vocabulary - Part 415: Wind Turbine Generator Systems | Engineering360." https://standards.globalspec.com/std/517411/iec-60050-415 (accessed Sep. 25, 2020).

[120] "IEC 61000-4-7:2002 | IEC Webstore," 2016. https://webstore.iec.ch/publication/4226 (accessed Sep. 25, 2020).

[121] "IEC 61000-4-7:2002 | IEC Webstore," 2016. https://webstore.iec.ch/publication/4226 (accessed Oct. 20, 2020).

[122] F.Díaz-González, M.Hau, A.Sumper, andO.Gomis-Bellmunt, "Participation of wind power plants in system frequency control: Review of grid code requirements and control methods," *Renewable and Sustainable Energy Reviews*, vol. 34. Pergamon, pp. 551–564, Jun.01, 2014.

[123] A. K.Pathak, M. P.Sharma, andM.Bundele, "A critical review of voltage and reactive power management of wind farms," *Renewable and Sustainable Energy Reviews*, vol. 51. Elsevier Ltd, pp. 460–471, Jun.29, 2015.

[124] L.Miao, J.Wen, H.Xie, C.Yue, andW. J.Lee, "Coordinated Control Strategy of Wind Turbine Generator and Energy Storage Equipment for Frequency Support," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 2732–2742, Jul.2015.

[125] I.Ngamroo, "Review of DFIG wind turbine impact on power system dynamic performances," *IEEJ Trans. Electr. Electron. Eng.*, vol. 12, no. 3, pp. 301–311, May2017.

[126] M.Mohseni andS. M.Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6. Pergamon, pp. 3876–3890, Aug.01, 2012.

[127] N.Mesbahi, A.Ouari, andT.Mesbahi, "Active Filtering of Wind Energy Conversion System with DFIG for Nonlinear or Unbalanced Load." .

[128] N. K.Swami Naidu andB.Singh, "Doubly Fed Induction Generator for Wind Energy Conversion Systems with Integrated Active Filter Capabilities," *IEEE Trans. Ind. Informatics*, vol. 11, no. 4, pp. 923–933, Aug.2015.

[129] A. S.Bubshait, A.Mortezaei, M. G.Simoes, andT. D. C.Busarello, "Power Quality Enhancement for a Grid Connected Wind Turbine Energy System," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2495–2505, May2017.

[130] H.Nian andB.Pang, "Stability and Power Quality Enhancement Strategy for DFIG System Connected to Harmonic Grid with Parallel Compensation," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 1010–1022, Jun.2019.

[131] S.Mondal andD.Kastha, "Input Reactive Power Controller with a Novel Active Damping Strategy for a Matrix Converter Fed Direct Torque Controlled DFIG for Wind Power Generation," *IEEE J. Emerg. Sel. Top. Power Electron.*, pp. 1–1, Aug.2019.

[132] A.Kapetanaki, V.Levi, M.Buhari, andJ. A.Schachter, "Maximization of Wind Energy Utilization Through Corrective Scheduling and FACTS Deployment," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4764–4773, Nov.2017.

[133] A. R.Jordehi, "Particle swarm optimisation (PSO) for allocation of FACTS devices in electric transmission systems: A review,"

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3098705, IEEE Access

Renewable and Sustainable Energy Reviews, vol. 52. Elsevier Ltd, pp. 1260–1267, Aug.22, 2015.
[134] D. K. D.Satyendra Patel, "FACTS Controllers for Power Flow Control: A Brief Review." .
[135] W. U.Tareen, S.Mekhilef, M.Seyedmahmoudian, andB.Horan, "Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system," *Renewable and Sustainable Energy Reviews*, vol. 70. Elsevier Ltd, pp. 635–655, Apr.01, 2017.
[136] O. P.Mahela andA. G.Shaik, "Power quality improvement in distribution network using DSTATCOM with battery energy storage system," *Int. J. Electr. Power Energy Syst.*, vol. 83, pp. 229–240, Dec.2016.
[137] E.Jamil, S.Hameed, B.Jamil, andQurratulain, "Power quality improvement of distribution system with photovoltaic and permanent magnet synchronous generator based renewable energy farm using static synchronous compensator," *Sustain. Energy Technol. Assessments*, vol. 35, pp. 98–116, Oct.2019.
[138] Y. M.Alharbi, A. M. S.Yunus, andA. A.Siada, "Application of UPFC to improve the LVRT capability of wind turbine generator," *2012 22nd Australasian Universities Power Engineering Conference: "Green Smart Grid Systems", AUPEC 2012*, 2012. .
[139] M. I.Mosaad, A.Alenany, andA.Abu-Siada, "Enhancing the performance of wind energy conversion systems using unified power flow controller," *IET Gener. Transm. Distrib.*, vol. 14, no. 10, pp. 1922–1929, May2020.
[140] L.Wang *et al.*, "Damping of Subsynchronous Resonance in a Hybrid System with a Steam-Turbine Generator and an Offshore Wind Farm Using a Unified Power-Flow Controller," *IEEE Trans. Ind. Appl.*, vol. 57, no. 1, pp. 110–120, Jan.2021.
[141] N. Y.Abed, S.Teleke, andJ. J.Castaneda, "Planning and operation of dynamic energy storage for improved integration of wind energy," 2011.
[142] D. D.Banham-Hall, G. A.Taylor, C. A.Smith, andM. R.Irving, "Flow batteries for enhancing wind power integration," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1690–1697, 2012.
[143] M. G.Molina andP. E.Mercado, "Power flow stabilization and control of microgrid with wind generation by superconducting magnetic energy storage," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 910–922, 2011.
[144] M.Hasan Ali, T.Murata, andJ.Tamura, "Stabilization of Power System Including Wind Generator By Fuzzy Logic-Controlled Superconducting Magnetic Energy Storage," in *2005 International Conference on Power Electronics and Drives Systems*, vol. 2, pp. 1611–1616.
[145] B.Palle, M. G.Simoes, andF. A.Farret, "Dynamic interaction of an integrated doubly-fed induction generator and a fuel cell connected to grid," in *PESC Record - IEEE Annual Power Electronics Specialists Conference*, 2005, vol. 2005, pp. 185–190.
[146] M. I.Daoud, A. M.Massoud, A. S.Abdel-Khalik, A.Elserougi, andS.Ahmed, "A Flywheel Energy Storage System for Fault Ride Through Support of Grid-Connected VSC HVDC-Based Offshore Wind Farms," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 1671–1680, May2016.
[147] L.Wang *et al.*, "Study of a hybrid offshore wind and seashore wave farm connected to a large power grid through a flywheel energy storage system," 2011.
[148] M.Ammar andG.Joós, "A short-term energy storage system for voltage quality improvement in distributed wind power," *IEEE Trans. Energy Convers.*, vol. 29, no. 4, pp. 997–1007, 2014.
[149] S.Yang, T.Zhou, L.Chang, R.Shao, X.Zhen, andX.Zhang, "An analytical method for the response of DFIG under voltage dips," in *2015 IEEE Energy Conversion Congress and Exposition, ECCE 2015*, Oct. 2015, pp. 963–970.
[150] J.Yang, J. E.Fletcher, andJ.O'Reilly, "A series dynamic resistor based converter protection scheme for doubly-fed induction generator during various fault conditions," 2009.
[151] A.Rini Ann Jerin, P.Kaliannan, andU.Subramaniam, "Improved fault ride through capability of DFIG based wind turbines using synchronous reference frame control based dynamic voltage restorer," *ISA Trans.*, vol. 70, pp. 465–474, Sep.2017.
[152] V. P.Suppioni, A. P.Grilo, andJ. C.Teixeira, "Improving network voltage unbalance levels by controlling DFIG wind turbine using a dynamic voltage restorer," *Int. J. Electr. Power Energy Syst.*, vol. 96, pp. 185–193, Mar.2018.
[153] Z.Jiang andY.Liu, "Fault ride through testing method based on DVR for offshore wind turbines," in *Proceedings: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Dec. 2018, pp. 1813–1818.
[154] H.Heydari-Doostabad, M. R.Khalghani, andM. H.Khooban, "A novel control system design to improve LVRT capability of fixed speed wind turbines using STATCOM in presence of voltage fault," *Int. J. Electr. Power Energy Syst.*, vol. 77, pp. 280–286, May2016.
[155] G.Rashid andM. H.Ali, "Fault ride through capability improvement of DFIG based wind farm by fuzzy logic controlled parallel resonance fault current limiter," *Electr. Power Syst. Res.*, vol. 146, pp. 1–8, May2017.
[156] M. J.Morshed andA.Fekih, "A new fault ride-through control for DFIG-based wind energy systems," *Electr. Power Syst. Res.*, vol. 146, pp. 258–269, May2017.
[157] M.Abdelrahem andR.Kennel, "Direct-model predictive control for fault ride-through capability enhancement of DFIG," *PCIM Europe 2017 - International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2017. .