IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 2, 2020, accepted October 11, 2020, date of publication October 15, 2020, date of current version October 29, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3031481

High-Level Penetration of Renewable Energy Sources Into Grid Utility: Challenges and Solutions

MD. SHAFIUL ALAM[1], FAHAD SALEH AL-ISMAIL[1,2,3], (Senior Member, IEEE),
ABOUBAKR SALEM[2], (Member, IEEE),
AND MOHAMMAD A. ABIDO[1,2], (Senior Member, IEEE)
[1]K.A.CARE Energy Research & Innovation Center (ERIC), King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[2]Department of Electrical Engineering, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[3]Center for Environmental & Water, Research Institute, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

Corresponding author: Md. Shafiul Alam (mdshafiul.alam@kfupm.edu.sa)

This work was supported in part by the Deanship of Scientific Research (DSR), King Fahd University of Petroleum & Minerals (KFUPM) under Project DF181035, and in part by the K.A.CARE Energy Research & Innovation Center (ERIC).

ABSTRACT The utilization of renewable energy sources (RESs) has become significant throughout the world, especially over the last two decades. Although high-level RESs penetration reduces negative environmental impact compared to conventional fossil fuel-based energy generation, control issues become more complex as the system inertia is significantly decreased due to the absence of conventional synchronous generators. Some other technical issues, high uncertainties, low fault ride through capability, high fault current, low generation reserve, and low power quality, arise due to RESs integration. Renewable energy like solar and wind are highly uncertain due to the intermittent nature of wind and sunlight. Cutting edge technologies including different control strategies, optimization techniques, energy storage devices, and fault current limiters are employed to handle those issues. This paper summarizes several challenges in the integration process of high-level RESs to the existing grid. The respective solutions to each challenge are presented and discussed. A comprehensive list of challenges and solutions, for both wind and solar energy integration cases, are well documented. Finally, the future recommendations are provided to solve the several problems of renewable energy integration which could be key research areas for the industry personnel and researchers.

INDEX TERMS Renewable energy resources, solar and wind energy conversion, virtual inertia, fault ride through capability, fault current limiter, control of converter.

NOMENCLATURE

AGC	Automatic generation control
ANN	Artificial neural network
BESS	Battery energy storage system
BFCL	Bridge fault current limiter
DE	Differential evolution
DVR	Dynamic voltage restorer
ED	Economic dispatch
ESS	Energy storage system
FACTS	Flexible alternating current transmission system
FLC	Fault current limiter
GA	Genetic Algorithm
HTS	High temperature superconducting
HVDC	High voltage direct current
IGDT	Information-gap decision theory
LMMN	Least mean mixed norm
LVRT	Low voltage ride through
MAE	Mean absolute error
MPC	Model predictive control
PFC	Primary frequency control
PFs	Passive filters
PLL	Phase locked loop
PMSG	Permanent magnet synchronous generator
PSO	Particle swarm optimization
ROCOF	Rate of change of frequency
SAPF	Shunt active power filter
SCIG	Squirrel case induction generator

The associate editor coordinating the review of this manuscript and approving it for publication was Qiuhua Huang.

SDBR	Series dynamic braking resistor
SMES	Superconducting magnetic energy storage
STATCOM	Static synchronous compensator
SVC	Static VAR compensator
TCSC	Thyristor-controlled series capacitor
UC	Unit commitment
UPFC	Unified power flow controller
UPQC	Unified power quality conditioner
VSC	Voltage source converter
WTPC	Wind turbine power curve

I. INTRODUCTION

Nowadays, several environmental concerns arise due to emission of carbon dioxide, Sulphur dioxide, and nitrogen oxide by the fossil fuel based generating stations. This environmental pollution causes global warming and acid rain [1]. On the other hand, renewable energy (RE) generation systems are considered clean and cheaper compared to traditional synchronous machine-based power generations. Thus, governments and several agencies are forced to increase the RE generation to replace fossil fuel-based power generation. As per international renewable energy agency [2], a roadmap for RE integration in the world upto 2030 is shown in Figure 1. It is expected that the world will meet total 36% of its energy demand from renewable energy sources (RESs) by 2030. Solar, wind, tide, wave, and geothermal heat are the main sources of RE generation. Among these sources, solar and wind systems are the most promising due their lower generation cost and their capability of maximum power point tracking over a wide range of wind and sunlight variations [3].

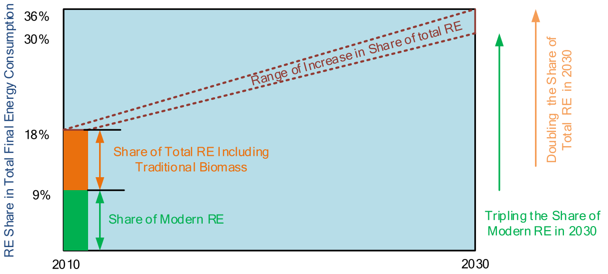

FIGURE 1. A roadmap for renewable power generation by 2030.

Figure 2 shows the global investment of power from wind and solar energy resources. As shown in Figure 2, more money was invested for power generation from wind until 2009. However, this scenario was reversed, since then [4], [5]. The global power generation in Giga Watt (GW) from wind and solar is depicted in Figure 3.

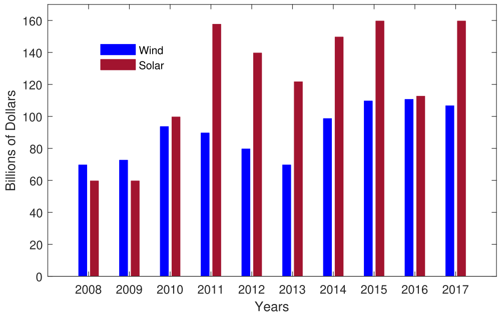

FIGURE 2. Wind and solar power worldwide investment.

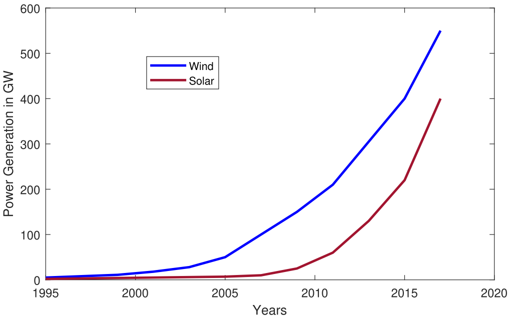

FIGURE 3. Wind and solar power worldwide power generation.

The high-level integration of RE to the utility grid may lead to concerns regarding stable and reliable operation of the system due to stochastic nature of power generation [6]. This is because of continuous wind speed and sunlight irradiance variations. The intermittent and unpredictable nature of renewable energy sources could be modeled properly to reduce the negative impact on stable operation of the system. Several methodologies [7]–[9] are presented in the literature to model uncertainties in RE in order to have minimal impact on the reliable and stable operation of the system. The proper control of the power electronic (PE) converters connected to the RESs is important to ensure the stable operation during the transients and AC system parameter variations. As per grid code requirement, renewable energy sources should stay connected during system faults. Thus, improvement of fault ride through (FRT) capability of renewable energy conversion system becomes vital. Several methods have been presented in the literature to improve the FRT capability of solar and wind energy systems connected to the grids [10], [11]. Renewable energy conversion systems employ costly PE converters for power conditioning. Protection of such converters is important from both economic and stability points of view. However, short-circuit power level increases with the enlarged RESs integration. Therefore, in order to restrict the fault current within acceptable limits, several strategies, such as fault current limiter, energy storage device, dynamic voltage restorer, are presented in the literature [11]–[14].

Uncertainty in renewable energy generation creates several problems like supply-demand mismatch and reserve generation reduction, posing frequency instability problem in the system. Also, large-scale RESs integrated system faces extremely low inertia which further degrades system frequency stability. The concept of virtual synchronous generator has evolved which imitates the behavior of prime mover to enhance inertia in the control loop virtually and accordingly stabilizing the system frequency [15], [16]. A central control scheme is presented in [17] to incorporate loads in primary frequency control (PFC). However, the control scheme fully depends on fast communication link which may pose threat due to cyber-attack. In order to avoid the need for fast communication channel, different schemes are presented in the literature for implementing local controllers for loads. However, for improvement of the local load controller, some parameters need to be determined in the main control center and transferred to the local controller through communication links. In [18], loads are categorized into different groups for primary frequency control with specific time-frequency control for each group of loads. During the unplanned islanding of the RESs, in case of disturbances, system frequency decreases gradually. To guarantee the frequency stability of the renewable energy system due to unplanned islanding, a control strategy of distributed generations (DGs), loads, and energy resources is presented in [19].

Integration of RESs degrades the power quality at the point of common coupling (PCC) and injects harmonic components, that must not exceeds specific limits, to electrical networks [20]. Power loss in the circuit and communication system interference are two major problems due to high-level harmonics injection by the PE converters of PV and wind generation systems [21]–[23]. It is imperative to improve the power quality by adopting several measures to ensure smooth system operation [24].

The high-level integration of the renewable energy sources to the utility grids reduces the system reliability [25], [26]. The amount of renewable energy integration must be restricted if the power system is not sufficiently flexible. For example, to meet the load demand in case of renewable energy uncertainty, the dispatchable generators can ramp quickly. However, fast ramping causes increased maintenance cost, which leads to plant closure and reduces system reliability [27]. The system with reduced inertia, due to high-level renewable energy integration, requires faster frequency control after disturbances. In such case, if the system fails to respond quickly, several issues arise such as under-frequency load-shedding, and generator damage which reduce system reliability [28], [29]. A high variation of irradiance for PV and extreme wind gust for wind turbine lead to the violation of low voltage ride through. Thus, the PV and wind generators may be disconnected from the system leading to degraded reliability [30], [31].

According to the aforementioned issues and their importances, this paper provides a broad view of the several challenges and opportunities in highly renewable integrated systems. Several challenges, such as total inertia reduction, low fault ride through capability, high uncertainties, voltage and frequency fluctuation, and low power quality, are well documented in this review article. In addition, several methodologies are also discussed to solve each of the above-mentioned problems. Some gaps are clearly mentioned in the current studies which could be filled by cutting edge technologies as form of new contribution from the researches and industry personnel.

The paper is organized as follows: Section II provides frequency instability issues of RESs integrated system and possible solution methodologies; fault ride through and stability issues are addressed in section III; power quality issues in RESs integration and several solution techniques are discussed in section IV; modeling of uncertainty and optimization techniques in uncertainty reduction are discussed in section V; current challenges for RESs integration and some future works are recommended in section VI; and finally, section VII summarizes the major conclusions of this review.

II. LOW INERTIA AND FREQUENCY ISSUES

Integration of renewable energy resources (RESs), both solar photovoltaic (PV) and wind, reduces the total inertia of the system due to the replacement of conventional synchronous generators [32]. Although the variable speed wind turbines have inertia, it is effectively decoupled from the system; thus, it cannot assist improving frequency response, due to the connection of wind turbine to the network through the power electronic converters. Moreover, solar PV plants cannot provide any inertia to the power system, which further degrades the frequency response. Therefore, high-level penetration of RESs to the system with the replacement of conventional synchronous generator reduces overall inertia and increases the rate of change of frequency (ROCOF) which activates load-shedding controller, even at small load-generation mismatch [33]. Furthermore, reduction in reserve power, due to replacement of reserve generating units, causes frequency deviation [34]. Thus, it is imperative to design new controllers for RESs to emulate the behavior of synchronous generator in order to improve frequency response of the system. The following subsections describe different control techniques of solar PV and wind systems to improve the frequency response for stable operation.

A. WIND BASED SYSTEM

The dynamic behavior of the power system is studied with the swing equation of machine as below [35].

$$P_{mech} - P_{elet} = J\omega \frac{d\omega}{dt} \tag{1}$$

where, P_{mech} is the mechanical power input to the machine, P_{elet} is the electrical power, J is the moment of inertia, ω is the system frequency in rad/sec. The strength of the power system, either weak or strong, can be understood with the total inertia of the system as represented by the following equation.

$$H = \frac{J\omega}{2S} \tag{2}$$

where, S is the summation of the apparent power of all generators. Now, simplifying equation (1) and (2), following equations are obtained.

$$\frac{2H}{\omega}\frac{d\omega}{dt} = \frac{P_{mech} - P_{elet}}{S} \tag{3}$$

$$\frac{2H}{f}\frac{df}{dt} = \frac{P_{mech} - P_{elet}}{S} \tag{4}$$

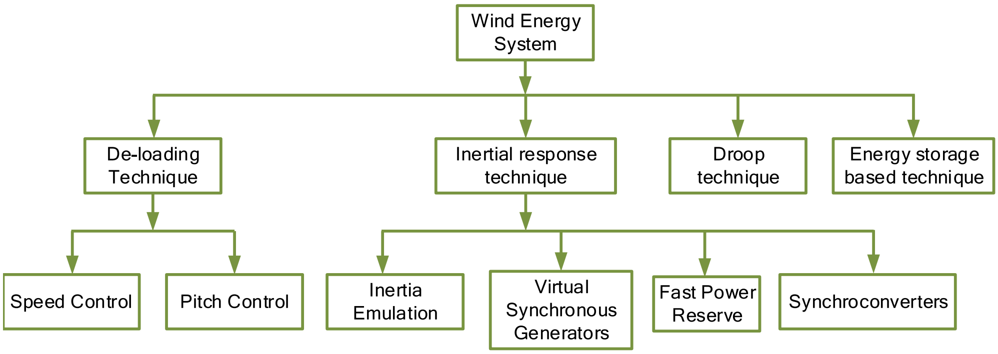

FIGURE 4. Inertia and frequency support techniques by wind system.

where, f is the system frequency in Hz and $\frac{df}{dt}$ is the ROCOF. Thus, ROCOF is inversely proportional to the system inertia. In order to meet the stability criteria, the system requires additional inertia while integrating more RESs. The concept of virtual inertia technologies, using PE converters, energy storage systems (ESSs), and control algorithms, which release the stored kinetic energy of wind turbine, are presented in the literature to support the frequency of RESs integrated system. The wind energy system can help stabilizing grid frequency with different techniques such as de-loading technique, inertial response technique, and droop technique. Each of these techniques can be sub-categorized into different techniques [36]. Classification of inertia and frequency support techniques by wind turbine is presented in Figure 4.

1) DE-LOADING TECHNIQUE

De-loading technique, the ability of the wind system to provide reserve power, is evolved to address the frequency deviation [37]. This technique shifts the optimal operating point of wind turbine to the reduced power level point; as a result, wind system provides some reserve generation, which can participate in frequency regulation [38]. De-loading technique mainly consists of two operating modes: pitch-angle control mode and speed control mode. The former one shifts the pitch angle from zero to some higher values and the latter one shifts the turbine speed left or right from the maximum power point, as shown in Figure 5 and 6, respectively.

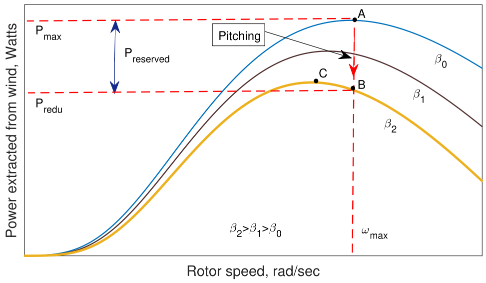

FIGURE 5. De-loading techniques for wind turbine by pitch control.

As shown in Figure 5, pitch control is achieved by increasing pitch angle from some lower value, β_0, to some higher value, β_2, for a constant wind speed, corresponding to rotor speed at maximum power point, ω_{max}. In this way, operating point shifts from point A to B instead of C, which can provide reserve power $P_{reserved}$, during frequency deviation of the system [36], [38], [39].

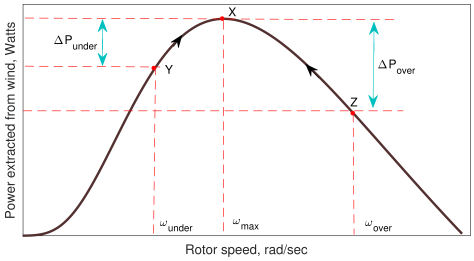

FIGURE 6. De-loading techniques for wind turbine by speed control.

Speed control mode de-loading technique has two possibilities, such as over-speed control and under-speed control. In former one, rotor speed controller adjusts the rotor speed at somewhat higher value, for example, ω_{over}, for a constant pitch angle. In case of wind system to participate in frequency regulation, rotor speed is adjusted back to the point corresponding to maximum power point, ω_{max}. Thus, shifting the operating point from Z to X provides additional reserve power, ΔP_{over}, during frequency instability due to generation and load mismatch. In latter one, see Figure 6, rotor speed is controlled to somewhat lower value, ω_{under}, which is below the maximum power point speed, ω_{max}. Thus, operation of wind generator at this point has a reserve power, ΔP_{over}. However, over-speed control mode is preferable than under-speed control mode, since in latter one, speed is increased from ω_{under} to ω_{max} utilizing some power extracted from the turbine. This shows opposite behavior during the first interval of the frequency response and is considered as 'detrimental strategy' [40], [41].

The de-loading techniques provide reserve power to support the frequency of the system. However, the amount of power is not specific. In [42], [43], a combined pitch angle and over-speed controller is proposed to participate in frequency regulation based on the request from the system operator for specific amount of power. Further improvement in frequency control is achieved with the pitch and over-speed control, coordinated with droop control [43].

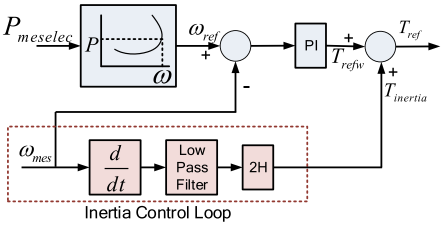

FIGURE 7. Inertia emulation techniques one-loop control.

This control topology is tested for doubly fed induction generator (DFIG) based wind system. Most of the de-loading techniques involve operation of wind turbine in de-loaded mode for long-term, which is responsible for economic loss for the wind turbine owners. To minimize this economic loss, a coordinated strategy is presented in [44]. In this strategy, DFIG does not need to operate in de-loaded mode for long-term; instead, it can operate in maximum power point tracking (MPPT) mode while there is no need for frequency support of the system.

2) INERTIAL RESPONSE TECHNIQUE

Conventional synchronous generator can release the kinetic energy, which is stored in the rotating mass, automatically to the grid; however, renewable energy resources (RESs) cannot do the same due to the decoupling between rotating mass and grid through the power electronic converters. To resolve this issue, inertial response techniques are evolved, which can be categorized into different ones such as inertia emulation, virtual synchronous generator, fast power reserve, and synchroconverter. The main idea behind these techniques is to emulate the behavior of conventional synchronous generators through the RESs.

In inertia emulation technique, the kinetic energy stored in the rotating mass is released with the new control loops [45]. Generally, one-loop and two-loop control strategies are used for inertia emulation by the wind systems. In one-loop control strategy, kinetic energy stored in the rotating blades is released based on ROCOF with a single loop only, while the latter one does the similar task with two loops for better frequency response.

As shown in Figure 7, MPPT controller loop determines the reference speed of the rotor, ω_{ref}, which is processed by the PI controller to provide torque reference, T_{refw}, corresponding to maximum power in normal operating condition. However, during frequency deviation, inertia control loop is enabled to provide additional torque, $T_{inertia}$. Due to this additional torque, generator speed is slowed down, and the kinetic energy stored in the rotor is released [46], [47]. However, the main disadvantage of this method is that the amount of torque provided by the additional control loop is constant, which is responsible for rapid reduction of rotor speed as well as delay in controller operation. To overcome this issue, in [48], an inertia response technique is presented to dynamically adapt the inertia constant during frequency response support with an idea to increase the inertia constant as long as the frequency of the system continues to decline. This strategy is applied for DFIG based system in [49] and compared for different values of K_{in} and K_f as shown in Figure 8.

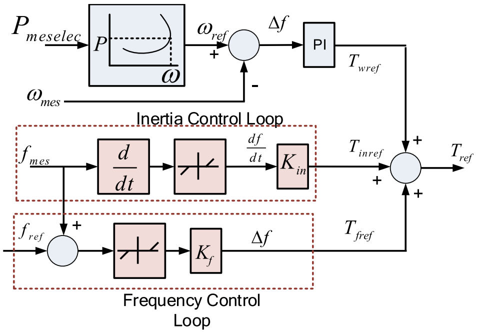

FIGURE 8. Inertia emulation techniques two-loop control.

Most of the inertial response techniques adopt modification of vector control, which is based on conventional phase locked loop (PLL) and voltage source converter (VSC). For example, in [47], [50], [51], some techniques are presented to allow the wind turbines to emulate inertia by providing additional signals based on ROCOF. However, the conventional synchronizing device, PLL, may have some negative impacts on system stability, which is reported in the literature [52], [53]. To resolve this issue, another inertial response technique is developed which is called synchroconverter. The synchroconverter topology, which adopts the synchronous generator model based topology, is evolved to support the frequency of weak grid by the wind generation system. The synchroconverter provides an enhanced PLL or a sinusoid-locked loop, which makes wind system inherently capable to maintain synchronism through the active power control [54], [55]. Detailed control strategy of synchroconverter is shown in Figure 9.

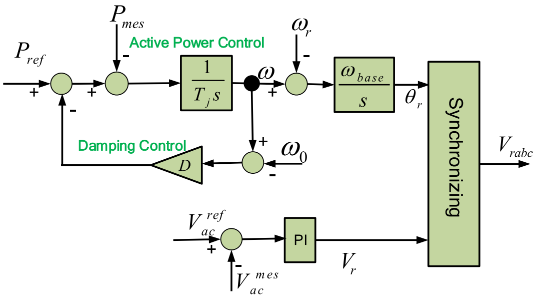

FIGURE 9. Synchroconverter control for DFIG based wind system for inertia support.

Since there is no damper winding in DFIG and the resistances in rotor and stator windings are low, it requires additional damping controller as depicted in Figure 9. As shown in Figure 9, the DFIG based wind system is synchronized with the grid based on active power control scheme without relying on PLL. The error between measured and reference active power causes the regulation of ω via the virtual inertia. Phase angle i.e. the rotor voltage angle, for synchronization, is obtained by direct integration of slip frequency, ω_{slip}.

Another method for inertial response is fast power reserve technique, which is based on supplying the stored kinetic energy of the rotating turbine to the grid by means of some modified control strategies [56]–[58]. However, detailed control strategies are not documented in references [56], [57]. In fast power reserve technique, frequency deviation is used as input to the detection and triggering circuit [58]. In normal system operation, detection and triggering circuits enable the MPPT control loop and bypass the power shaping loop. However, in abnormal condition, when the system frequency deviation is more than the threshold level, power shaping loop is enabled and MPPT loop is disabled as shown in Figure 10. At this level, the wind generation system enters overproduction mode until the kinetic energy of the wind turbine is completely discharged. Afterward, wind generation system returns to MPPT mode. It is worth mentioning that, transition between overproduction to MPPT mode may lead to underproduction phase, in which power is reversed from grid to turbine. To avoid this unexpected operation, instead of sharp transition, a sloped transition is presented as shown in Figure 10.

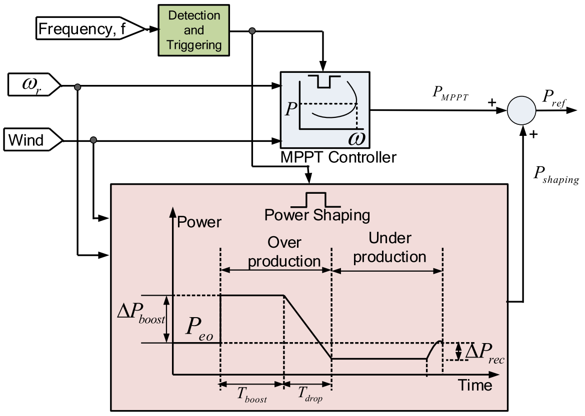

FIGURE 10. Fast power reserve technique for frequency support.

3) DROOP CONTROL TECHNIQUE

The droop controller, which adjust the output power with the variation of system frequency based on the droop setting, is evolved to support primary frequency control [59]. The droop gain and power relation is given by the following equation.

$$\Delta P_{droop} = K_{droop} \Delta f \tag{5}$$

In this work, the droop controller is only enabled when the system frequency deviation exceeds a specific limit ($|\Delta f| > |a| = 0.075$). The droop gain (ΔK_{droop}) is optimized by perturb and observe method. Sufficient power is kept as reserved by de-loading technique, as discussed in section II-A1, which is then used by the centralized droop controller in response to the frequency deviation. Similar to conventional synchronous generator equipped with speed governor for frequency regulation, wind energy system can support frequency by adjusting active power according to droop setting [60], [61]. Active power is adjusted with the frequency deviation given by the following equation.

$$\Delta P = P_{low} - P_{high} = -\frac{\omega_{high} - \omega_{low}}{R} \tag{6}$$

where, R is the droop constant, P_{low} is the low power, P_{high} is the high power, ω_{low} is the low frequency, ω_{high} is the high frequency. Detailed droop control structure is shown in Figure 11.

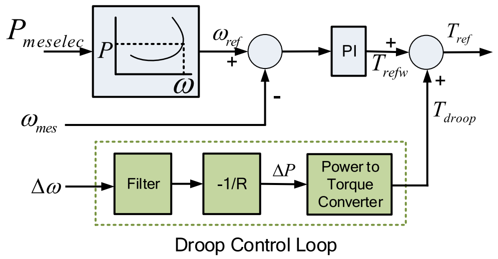

FIGURE 11. Droop control technique for wind system.

As shown in Figure 11, the reference torque is generated as a sum of MPPT controller loop torque and droop control loop torque. Depending on the frequency deviation of the system, torque command is modified by the droop controller to stabilize system frequency.

4) ENERGY STORAGE BASED TECHNIQUE

Modification of the existing control strategies as well as introduction of several new strategies are presented in the literature to solve low inertia and frequency issues of variable speed wind system as discussed in the previous sections. However, it is worth mentioning that the strategies discussed earlier have low reliability issue due to varying nature of wind. A potential solution to this problem is to integrate wind energy to the grid through energy storage systems (ESSs), such as battery, superconducting magnetic energy storage (SMES), fly wheel energy storage, super capacitors [62], [63], [63]–[65]. Frequency response is improved for wind energy system using battery energy storage system (BESS) in [66] and a combined BESS and automatic generation control (AGC) strategy is presented in [67] for improved frequency response. Some of the ESSs has higher energy density whereas some of them has higher power density. Thus, in [68], [69], hybrid ESS based frequency support technique is presented to harness both high power and energy densities.

Since the natural inertia of variable speed wind generator is much lower than conventional synchronous generator, SMES, which is fast responding compared to other energy storage device, is presented to improve primary frequency response of permanent magnet synchronous generator (PMSG) system [70]. The improvement in frequency response of PMSG

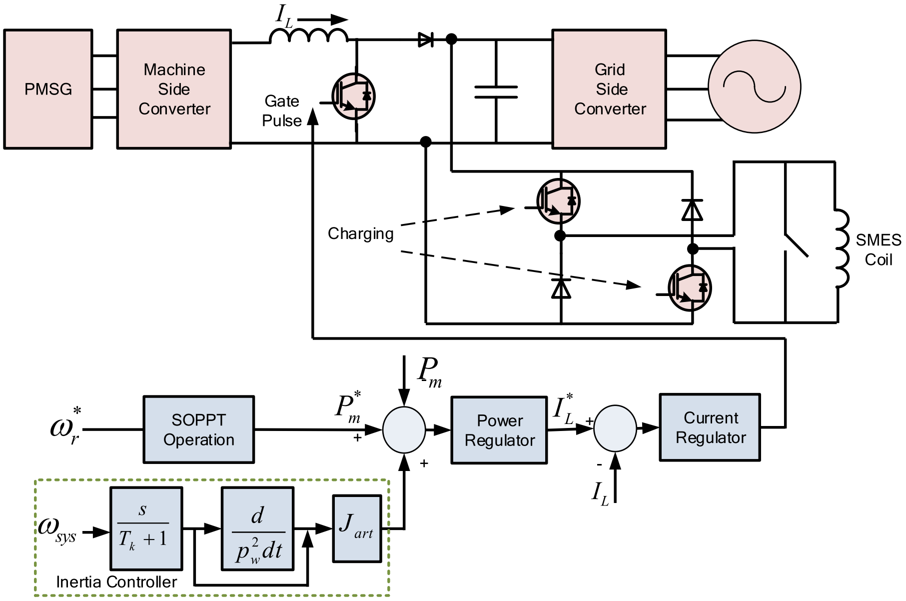

FIGURE 12. Energy storage based frequency support for PMSG wind system.

wind system is achieved with artificial inertial controller which controls the boost controller in the DC link as shown in Figure 12. In stable operation, the difference between electromagnetic torque and mechanical torque is zero; however, in worst case scenario, the system frequency deviates, and change in the reference torque reduces the rotor speed to emulate the inertia. The inertia controller provides duty to the boost converter, which adjusts the power output and torque for primary frequency support by controlling the current through the reactor, I_L. DFIG based wind system frequency response improvement is presented in [71] with battery and flywheel energy storage. In [71], flywheel based storage is considered as an integral part of wind power plant to provide reserve power indicated by the system operator for primary frequency control as shown in Figure 13. Total power reserve required by the system is distributed between the wind turbine and flywheel energy storage. Power reserves of wind turbine and energy storage are activated by the local controls immediately after the frequency deviation exceeds a predefined value. The central control is employed to supervise the activation of local controls.

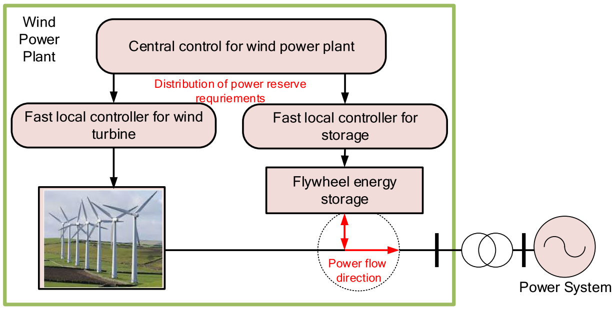

FIGURE 13. Frequency regulation by wind farm and flywheel energy storage.

B. SOLAR BASED SYSTEM

Grid connected solar photovoltaic (PV) system can participate in frequency regulation during positive frequency excursion, increase in system frequency due to higher generation than load, by reducing the output of PV. However, it cannot participate in frequency regulation during negative frequency excursion, since it operates at maximum power point having no reserve margin. For the PV system to participate in frequency regulation during negative frequency excursion, some reserve must be kept by de-loading or some other techniques. Mainly, three possible techniques are presented in the literature: charging energy storage devices [72], [73], operating PV system in reduced power output mode by de-loading [74]–[77] and inertial response technique [78]. Several techniques presented in the literature for frequency and inertial support from PV system is shown in Figure 14.

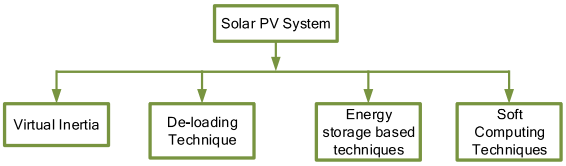

FIGURE 14. Frequency and inertia support by PV system.

1) INERTIAL RESPONSE TECHNIQUE

Primary frequency control by PV system is presented in [78] with inertia emulation technique. The inner and outer control loops are implemented to generate duty cycle for the DC/DC

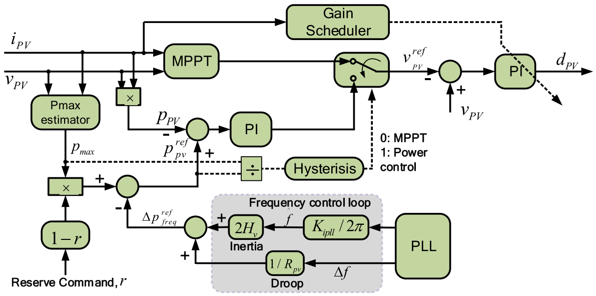

FIGURE 15. **Primary frequency regulation and inertia emulation by PV.**

converter of PV system as shown in Figure 15. The former regulates the PV array voltage to its reference value while the latter regulates the PV power to the reference value either by MPPT controller or power controller. The reference power for the outer controller is given by the following equation.

$$p_{pv}^{ref} = (1-r).p_{max} - \Delta p_{freq}^{ref} \tag{7}$$

where r is the reserve power set by the system operator, P_{max} is the estimate of maximum available power, Δp_{freq}^{ref} is the output of frequency controller. The frequency controller, which comprises proportional and derivative terms, gives the following frequency dependent PV power reference.

$$\Delta p_{freq}^{ref} = \Delta f/R_{pv} + 2H_{pv}\hat{f} \tag{8}$$

where, R_{pv} is the droop constant, H_{pv} is the virtual inertia gain and $\hat{f}$ is the rate of change of frequency.

2) DE-LOADING TECHNIQUE

The PV system can provide reserve and support system frequency by de-laoding technique which involves operation of PV system beyond the MPP as shown in Figure 16. The maximum power corresponds to point MPP with a voltage of V_{MPP}. As shown, instead of operating at MPP, the PV system operates at point B having a total reserve of $P_{max} - P_{delaoded}$.

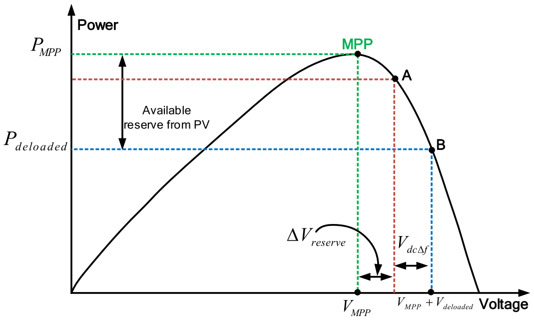

FIGURE 16. **PV system de-loading power-voltage curve.**

The de-loading technique as presented in [79] is shown in Figure 17. As shown, the PV output power depends on both V_{MPP} and system frequency deviation Δf which is given by the following equation.

$$V_{dcref} = V_{MPP} + V_{deloaded} - V_{dc\Delta f} \tag{9}$$

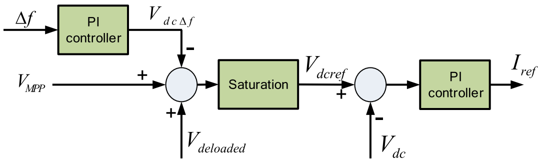

FIGURE 17. **PV system deloading controller.**

However, the controller presented in Figure 17 has non-uniform distribution of frequency regulation. This mainly happens for same amount of power release from the PV units having different reserve level. So, the PV units with less reserve reach MPP faster than other PV units with higher reserve and further frequency regulation cannot be achieved by these units due to their operation at MPP. In order to address this issue, a modified controller is presented in [76], in which, the output power delivered from each unit depends on the reserve, instead of delivering same amount of power from each unit. The modified reference voltage for this new controller is given by the following equation.

$$V_{dcref} = V_{MPP} + V_{deloaded} - V_{dc\Delta f} - (\Delta f * \Delta V_{reserve} * K_p) \tag{10}$$

where, Δf is the system frequency deviation, $V_{reserve}$ is the voltage corresponding to reserve power, and K_p is the gain of the proportional controller.

Another de-loading technique is presented in [80] which is named as adaptive de-loading technique having three controller loops: droop controller, active power-voltage matching controller, and vector controller. This technique provides a reserve power in PV system with a possibility to adjust quickly the output power of PV for frequency regulation of the grid.

3) ENERGY STORAGE BASED TECHNIQUE

Energy storage devices can be used to mitigate the negative impact of high penetration of PV to the grid [81], [82] by reducing the active power variation. In [82], droop and step response controllers with energy storage are presented to improve frequency response of two high PV system united states power grids. Performance of step response controller with energy-constrained high-power-density storage system is found slightly better than droop controller in this study. In [83], a battery energy storage system (BESS) is designed to support grid frequency, by BESS input current regulation, with an efficient DC-DC converter control. Additionally, the presented controller is capable to improve fault ride through capability in case of different transients in the system.

4) SOFT COMPUTING TECHNIQUES

The output power fluctuation of the PV system, as a change of the weather conditions, season, and geographic location, cause high-level frequency deviation of the power system. In [84], [85], soft commuting methods are applied in the PV system to reduce power fluctuation from the PV system for improving the frequency response. Depending on frequency deviation and average insolation of PV system, output power command is generated in [85] using fuzzy logic controller. The method is capable to operate the PV system to near maximum power point which is better than the de-loading technique. Another soft computing technique similar to the reference [85] is presented in [86] which combines fuzzy logic controller and particle swarm optimization to generate output power command in order to improve frequency response of PV system.

C. GRID-FORMING CONTROL TECHNIQUES

Generally, inverter-based distributed energy resources, such as PV and wind, have very low or no inertia. Also, such sources operate at the rated power and are unable to respond dynamically to the system frequency variations. The grid-forming control techniques of such inverter-based PV and wind generators can damp the frequency oscillations, mainly, when they are tied to the weak grid system [87]. Unlike the conventional synchronous generators, the inverters can respond faster before any load shedding is triggered if the proper controller is designed for the inverters. The grid-forming inverter controls the voltage and frequency with droop characteristics. During contingencies, the grid-forming inverters control the output power instantaneously based on droop setting to balance the power and restore the system frequency. Such control technique is advantageous for low inertia PV and wind systems. The positive impact of grid-forming inverters with droop control to support system frequency is addressed in [88] for O'ahu power system in Hawaii. It is indicated that the PV connected grid-forming inverters are capable to support system frequency during huge loss of synchronous generators. The AC grid-forming control techniques for offshore wind integrated system are discussed in [89]. The dynamic frequency stability of PV integrated system can be improved with grid-forming inverters control strategy which provides sufficient reserve margin [90].

III. FAULT RIDE THROUGH (FRT) CAPABILITY ISSUES

A quick disconnection of PV and wind plants, in case of disturbances, badly affects the stability of the system. Therefore, FRT capability requires that the PV/wind plants must remain connected to the grid during faults for a specific period. This requirement is mainly imposed by the modern grid code, which varies from country to country depending on different factors, [91] as shown in Figure 18.

Since the grid fault is responsible for low voltage of the system, it is important for the renewable sources to continue its operation to maintain continuity of the power flow and improve system reliability during contingencies. To achieve this goal, different improved control strategies are adopted and auxiliary devices are installed and controlled with the renewable energy sources [92]–[94]. In the literature, FRT capability issues are discussed for three different system such as PV system, wind system, hybrid PV/wind system. Different techniques are presented for each of these systems as categorized in Figure 19. Mainly, FRT capability of PV/wind system is augmented without and with auxiliary devices. Improved control strategies and soft computing techniques are presented in the literature. In [95], a hybrid control technique is presented for improving both low voltage and high voltage FRT capability of DFIG wind system. A Sugeno fuzzy logic controller is presented in [96] which has less overshoot and steady state error compared to the conventional controller. In order to augment FRT of PV system, a model predictive control strategy is presented in [97] which has fast and robust control features. However, in this method, additional controller is needed to switch between LVRT mode and normal mode which, in turn, increases cost of the controller. A detailed list of different control techniques without auxiliary devices is presented in Table 1. In the table, the advantages as well as different gaps in current study are well documented which can be a great source for the researchers for further study and improvement of FRT of renewable sources.

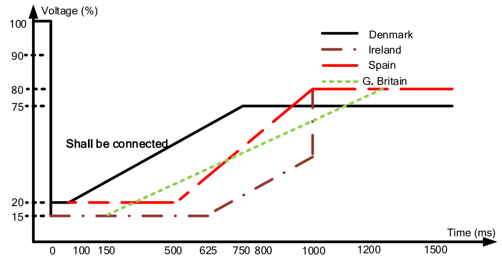

FIGURE 18. Grid code for different countries.

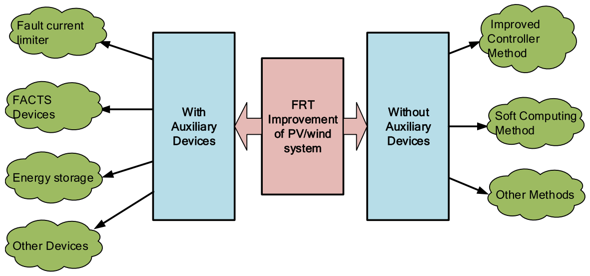

FIGURE 19. FRT improvement techniques of different renewable energy systems.

As shown in Figure 19, different auxiliary devices, such as fault current limier, energy storage, and FACTS devices, can be employed with RESs to augment FRT. The improvement of FRT for different PV and wind energy systems with the application of fault current limiters is shown in Figure 20. Among the several auxiliary devices, fault current limiters (FCLs) are widely studied and implemented due to low cost, low loss in stand-by mode, high voltage withstanding capability. Mainly two types of FCLs are dominating for application in power system: superconducting and non-superconducting [122]–[124].

FRT capability enhancement of PV system, fixed speed wind, DFIG, PMSG, squirrel case induction generator (SCIG), wind integrated high voltage DC (HVDC), and

TABLE 1. FRT improvement techniques for different renewable energy systems.

Type [references]	Methods	Advantages	Disadvantages
DFIG [95], [98]–[101]	Fuzzy based slide mode control	Current and voltage within the limit Continuation of DFIG operation in non-ideal voltage case	Additional energy storage needed
	Combined active and passive compensator method	Reduced oscillation of DC link voltage and torque	Increased cost and complexity
	Combined feed-forward and feed-back control	Improved transient performance	Dynamic voltage restorer (DVR) needed in grid side
	Hybrid control	Improvement of both low and high voltage ride through	PI parameters are not optimized
PMSG [96], [102]–[106]	Fault reconfigurable parallel control	improved reliablity Multi-leg FRT capability Only faulty leg is isolated	The system needs one additional controller Complex fault detection method
	Active power limitation controller	Peak current within safe limit DC link over voltage suppression removal second-order active power fluctuation	Not applicable for low inertia PMSG Additional pitch angle controller needed
	Combined vector and direct torque control	Fast transient and smooth steady-state performance Reduction of rotor speed oscillation	High cost due to use of two controllers
	Composite control structure	Reactive power support for grid voltage recovery Less stress on DC link capacitor	Crowbar circuit is mandatory Wind turbine must have 10% over speed capability
	Sugeno fuzzy logic controller	Quick response, less overshoot, negligible steady-state error	High power loss in gearbox
	Coordinated controller	Full use of each unit of a hybrid wind farm Improved stability and adaptability No communication required among the wind farms	Complex and costly controller Real-time current and voltage measurements required
PV [97], [107]–[113]	A novel LVRT control	Protection of inverter during voltage dip AC over-current and DC-link over voltage suppression	A fast, automatic, and precise fault detection is mandatory for the controller A DC-chopper barker is needed to absorb energy
	Model predictive controller	Fast and robust current control feature Low overshoot and fast tracking of reference signals	It needs additional controller for switching between normal mode and LVRT mode
	Comprehensive LVRT strategy	DC link over voltage reduction Converter over current reduction and higher reliability of PV system	It can not track maximum power during fault Complex control structure due to synthesis of positive and negative sequences
	Nonlinear controller	Improved recovery performance DC-link voltage remains within predefined limit during faults	It needs two controller which increase cost MPPT controller is switched off during fault
	Model current predictive controller (MCPC)	DC link harmonic reduction AC current is suppressed to preset value positive and negative sequence separation algorithm can all be removed	Complexity arises due to coordination between MCPC and non-MPPT controller
	Robust control	Improved DC bus voltage protection due to decoupling Improved AC voltage profile	Estimation error of inductor current may cause unsatisfactory performance
	An adaptive control strategy	PI controller has adaptive tuning feature DC link voltage fluctuation is reduced Power oscillation is well damped	Initial assumption of PI parameter may deteriorate controller performance
	Synchronous frame method	Overcurrent protection for the converter No hard switching required between MPPT and non-MPPT controller	Unsatisfactory performance for deep voltage sag Controller has negative impact on utility system
SCIG [114]–[117]	Combinational voltage booster technique	Proper voltage is maintained during serious sag by controlling thyristor Excessive fault energy is dissipated in the braking resistor Active power loss is minimized	Complex control due to switching different operational modes
	Hybrid pitch angle controller	Hybrid controller is superior over PI controller Power and frequency oscillations are well damped	High cost than PI due to extra controller
	Coordinated FRT control	Abnormal rise of DC link voltage is limited Smoothing of injected reactive power during symmetrical fault	Double frequency oscillations in reactive power during unsymmetrical fault
	Distributed compensation controller	Reduction of torque ripple Improvement of wind farm reliability and stability Independent control of positive and negative sequence voltages	For deeper voltage dip, higher current rating of constant power load is required Higher cost than centralized compensation controller
Combined PV and Wind [118]–[121]	Coordinative LVRT control	Power imbalance reduction between faulted grid and renewable source Capable to handle transient voltage faults	Requirement of four controllers increases cost More stress on DC-link capacitor and rotating mass
	Reactive power injection method	PCC voltage profile is improved The controller has feasibility to implement in hardware in loop	PV array DC link voltage has overshoot
	Auto-tuned fuzzy PI approach	Less cost and simple design Minimization rotor over current Voltage, power and torque fluctuation reduction	Switching is needed for grid side converter controller
	Modified controller	Converter protection against over voltage Reactive power support during faults	Switching among different controllers takes long time

combined wind and PV systems is observed with different FCLs such as bridge type fault current limiter (BFCL), series dynamic braking resistor (SDBR), modified BFCL, super conducting FCL, and variable resistive FCL [125], [126]. As shown in Figure 20, FRT improvement of DFIG systems are achieved with almost all types of FCLs, whereas only few of them are studied and implemented in other renewable systems. This helps the novice researchers to find out the gaps in current study and fill-up those gaps with different cutting-edge technologies.

An alternative solution to keep the renewable energy resources to be connected with the grid during disturbances is to use different FACTS devices such as static VAR compensator (SVC), thyristor-controlled series capacitor (TCSC), and static synchronous compensator (STATCOM). In [127], a STATCOM based control strategy is proposed for the FRT improvement of fixed speed wind energy generation system. The hybrid PV/wind system FRT capability improvement is studied in [128] with combined control of SVC and SDBR. In general, all these mentioned devices can help mitigate the fault problems of PV/wind system; however, integration of such devices increases both control complexity and cost. As an alternative to addition of the external devices, other methodologies are also presented in the literature to reduce cost and complexity. For instance, in [129], dynamic current limitation method is presented to augment FRT as well as save inverter of a small-scale solar system. It is worth mentioning that the modification or improvement of such method is needed for large-scale PV system or hybrid PV/wind systems. This gap, FRT improvement of large-scale hybrid wind/PV system, could be filled-up by cutting-edge technologies.

Another approach of improving FRT of RESs is to use energy storage systems (ESSs) such as battery, supercapacitor, and fly wheel energy storage. The main function of the energy storage is to absorb energy from the system during disturbances so that the negative impact of faults is minimized. In [130], capacitor energy storage system is investigated for FRT improvement of distributed renewable energy generator. Since the supercapacitor has high power density, it is proposed as a potential solution to reduce short term power fluctuation in PV system during normal condition [131]. Also, during the grid side faults, energy generated by PV is

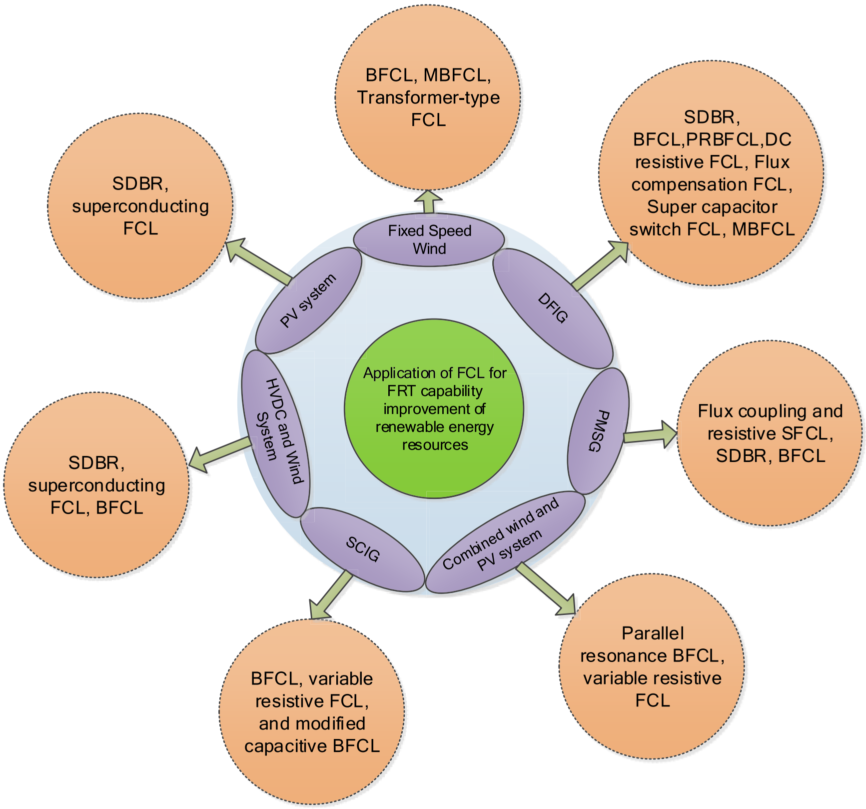

FIGURE 20. FRT improvement of renewable systems with FCLs.

stored in the supercapacitor to augment FRT capability of PV system. In general, energy storage is a costly solution to the FRT problems of renewable energy system. Further investigation is needed to minimize the cost by optimal sizing of ESSs as well as combined FCL and ESSs could be a better solution for FRT of PV/wind system.

Furthermore, in order to improve FRT of RESs several industry standards and measures are applied. For example, North American Electric Reliability Corporation (NERC) and Electric Reliability Council of Texas (ERCOT) published several technical reports [132], [133] on FRT capability improvement of RESs system. As per the report [132], two faults occurred near Anaheim Hills, California resulted in the reduction of solar PV generation. For the first fault, 682 MW solar PV generation was lost, whereas, for the second fault 937 MW PV generation was lost. The key finding is that the inverter enters into momentary cessation mode: the inverter temporarily ceases to inject current into the grid during voltage excursion with the ability to immediately restore output when the voltage returns within the limits. The reports recommend that the momentary cessation should be mitigated to the greatest possible extent for existing resources for FRT capability enhancement.

IV. POWER QUALITY ISSUES

The heart of renewable energy system is the power electronic (PE) converters. These devices are responsible for the harmonic injection in the system. Furthermore, operation of these converters are highly dependent on the quality of the voltage signal. In order to improve the power quality of the RESs different measures are taken such as implementation of improved control strategies and use of different auxiliary devices [134]. The different approaches and cutting-edge technologies used for power quality improvement are visualized in Figure 21.

As shown in Figure 21, filters, flexible AC transmission systems (FACTS) devices, energy storages, and converter control can be sub-categorized into different ones in order to improve power quality. Some of these methods are also documented in the previous sections for reducing power fluctuation and frequency deviation. Power quality issues of PV/wind systems can be handled with more advanced filtering technologies such as active and passive filters [135]–[137]. However, the cost, size and weight of passive filters (PFs) increase with the increase of power rating of the converters. Thus, PFs are not a better solution for cutting-edge technology [138], [139]. On the other hand, one of the most attractive solutions is to employ the shunt active power filter (SAPF) in order to improve power quality, reactive power and current harmonics compensation [140], [141]. With the increase of the penetration of renewable energy, the active power filter size increases. In order to resolve this issue and minimize the filter size and cost, hybrid APF is proposed [142], [143]. In hybrid filter, lower order harmonics are eliminated by SAPF whereas the PF removes the higher order harmonics [144], [145]. The harmonics at

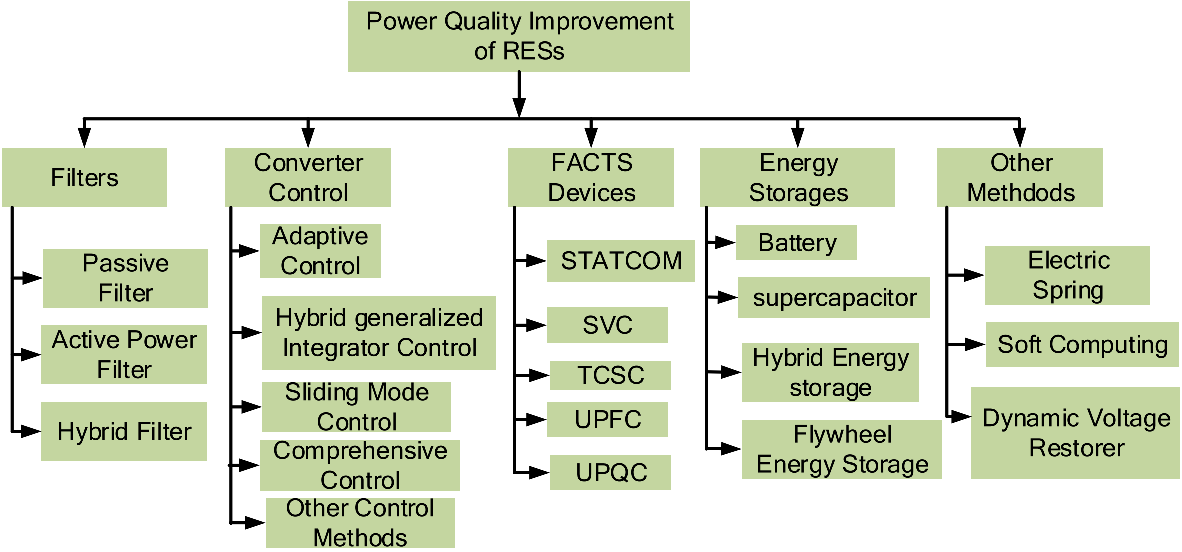

FIGURE 21. Power quality improvement techniques for RESs.

TABLE 2. FACTS devices for power quality improvement.

FACTS Devices	Contirbutions	Comments
D-FACTS [152], [155]	These methods improve dynamic voltage stabilization Harmonics mitigation is achieved and power factor is improved	Further improvement is possible by systematic D-FACTS design
SSFC [154]	Harmonics mitigation and voltage stabilization Losses reduction and power factor improvement	
STATCOM [156]–[158]	Point of common coupling harmonic mitigation Voltage deviaton reduced by 73.4% in [158]	Voltage controller parameters can be tuned with any optimization technique The strategy presented in [158] only considers linear load
TCSC [159], [160]	Machine electrical torque deviation is reduced	In some cases, damping of oscillation is slower than traditional controller [159] Optimal placement of TCSC is not considered [160]
SVC [161], [162]	Wind and PV systems voltage profile is improved Large-scale DFIG harmonic reduction is observed in [162]	Harmonics minimization is not considered in optimization [161]
UPFC [163]–[165]	Voltage profile and harmonics are improved	UPFC can mitiage more harmonics with phase shifting capability [165]
UPQC [24], [166]–[168]	Voltage sag and current harmonics are mitigated Interharmonics, noise and DC offset are improved	Mitigation of higher order harmonics requires further research

switching frequency and the multiple of switching frequency are problematic for the converters of renewable energy system. In order to mitigate these harmonics with less voltage drop and small component size, another higher order active filter is presented in [146].

The different advanced control methodologies of converter of renewable energy system are presented in order for harmonic mitigation [147]–[150]. An improved high frequency harmonics rejection technique is presented in [147] with hybrid generalized integrator controller. Although the controller has a trade-off between accuracy and speed of convergence, it eliminates both interharmonics, subharmonics and disturbances. In [148], a dynamic state estimation based slide mode control is proposed for grid connected DFIG wind farm, which is capable to alleviate unnecessary switching of converters as well as improve power quality. Some control techniques are proposed for the hybrid PV/wind systems in [149], [151], for the improvement of power quality, without any filter or auxiliary devices. As reported in [149], harmonics compensation and fundamental load component extraction are achieved with a new least mean mixed norm (LMMN) control strategy.

The flexible AC transmission systems (FACTS) devices play an important role to improve different aspects of power quality, like harmonics, power factor, oscillations in electrical quantities, voltage dip, in highly renewable penetrated systems [152]–[154]. Various FACTS devices, such thyristor-controlled series capacitor (TCSC), static VAR compensator (SVC), and static synchronous compensator (STATCOM), are presented in the literature to handle harmonics issues of renewable energy system. A detail documentations on harmonic mitigation with different FACTS devices are visualized in table 2. Several gaps on different approaches are clearly mentioned which can be a good source for future research.

Different energy storage devices, such as battery, supercapacitor, and flywheel energy storage, are employed to improve power quality of renewable energy system, especially for the purpose of power smoothing [169]–[173]. A sophisticated power allocation method between PV and battery storage is developed in [169] to mitigate over voltage at PCC and support wide range of reactive power. Improvement of power quality for a PV system is observed in [171] with battery storage which is connected with the DC link of the PV energy conversion system. However, the battery storage is not suitable for frequent charging and discharging applications due to its low power density and small life cycle. In order to resolve this issue, a hybrid energy storage, battery and supercapacitor, is proposed in [174] to smooth the power fluctuation in a wind energy integrated system. Both high energy density of battery and high power density of supercapacitor are harnessed in this new approach. This work mainly employs self-adaptive wavelet packet decomposition and two-level power reference signal distribution technique to reduce grid power fluctuation due to wind speed variations. The parameters of battery and supercapacitor are given by experience in this study; however, the economic optimization can be employed for further power quality improvement. Power quality improvement of PV and DFIG systems is presented [175], [176] with superconducting magnetic energy storage (SMES). The high temperature superconducting (HTS) coil is charged and discharged based on PV array output and utility power quality [175]. Although the power quality of DFIG wind system is improved in [176], extreme high current flows through the SMES coil which may be problematic for practical implementation of such device. To resolve this issue, improved control strategy can be proposed, or several SMES can be connected in parallel as a future research. Moreover, the power quality improvement of renewable energy systems (RESs) is also achieved with some other methodologies like electric spring, dynamic voltage restorer (DVR), soft computing based methods [177]–[180]. A hybrid PV/DFIG system harmonics mitigation is presented in [178] with a fuzzy logic controlled DVR. However, the proposed technique does not take the voltage deviation at the PCC and harmonic contents of voltage signals as input to fuzzy controller. Further harmonics improvement may be possible with the consideration of these facts.

Finally, the modular multilevel converter (MMC) can be employed for RESs system to improve the power quality [181], [182]. The multi-phase synchronous generator is superior over the conventional three phase generator due to its high reliability and less torque ripple. In [183], a six-phase permanent magnet synchronous generator (PMSG) based variable speed offshore wind farm is presented with MMC to reduce voltage ripple and harmonics. In addition, the voltage fluctuation is reduced with the voltage balancing and averaging of sub-modules of MMC. In [184], a second harmonic reference injection in the modulation process of MMC is used to mitigate circulating current and achieve stable operation of MMC during grid integration of RESs. Also, a capacitor voltage balancing algorithm is incorporated in the control strategy to keep the voltage of each sub-module within the acceptable limits. In [185], the arm voltages total harmonic distortion (THD), voltage ripple of the capacitors, harmonic contents of grid current are analyzed with different modulation techniques of medium voltage MMC for renewable energy integration. This work suggests that further optimization is required to determine several factors those affect the selection of modulation strategies.

V. UNCERTAINTY ISSUES

In power systems, uncertainty means inaccurate parameters which cannot be predicted with 100% certainty and which affects the smooth operation. Nowadays, renewable energy sources are considered as main source of uncertainty in power system due to their intermittent nature [186]. With the high-level integration of intermittent renewable sources to the grid, the main question remain; how do the system operators manage the uncertainty from these sources? However, vast majority of the optimization techniques, soft computing and advanced control algorithms, energy storage devices are employed to mitigate the uncertainty issues. Numerous methods are implemented to fully or partially mitigate the uncertainties in RESs integration. Of them, the key approaches are shown in Figure 22 and summarized below.

- **Modeling Uncertainties:** The probabilistic pattern of wind and solar power generation systems are caused by different operational challenges, which stem from uncertainty in weather, wind speed, and solar irradiation [187]. The uncertainty in loads, correlated wind, solar distributed energy resources, and plug-in hybrid electric vehicles are modeled in [188] with possibilitic method. The uncertainty modeling of wind energy conversion adopts dynamic model which is further partitioned into stochastic and deterministic components [189]. A dynamic empirical wind turbine power curve (WTPC) model is developed based on Langevin model and maximum principle method [190]. Another probabilistic WTPC model, based on normal distribution, varying mean and constant standard deviation, is proposed in [191] to minimize uncertainty. Hitherto, most of the mentioned methods simulate WTPC uncertainty based on known distribution and statistical parameters, which may not be consistent with real situation. Furthermore, the evaluation of probabilistic model is more complicated than deterministic one; thus, it requires a new evaluation criteria. To address these issues, a probabilistic WTPC model is proposed [192] with new model inputs, such as pitch angle and wind direction, and evaluation criteria, to quantify the uncertainties of energy conversion. The uncertainty modeling of a distribution network, comprising solar and wind generation systems, is presented [193] in which deterministic and uncertain components are calculated based on fitted power characteristic and probability distribution, respectively. The uncertainty management to assist high-level RESs integration process is also achieved with robust optimization techniques as presented in the literature [194]–[196]. There is extreme need for new long-term planning models of power system to incorporate uncertainty resulted from large-scale renewable energy integration. In order to address this issue, in [194], a new generation and transmission expansion planning model is proposed based on robust optimization. The key feature of the model is that daily uncertainty is represented by the concept of uncertainty sets

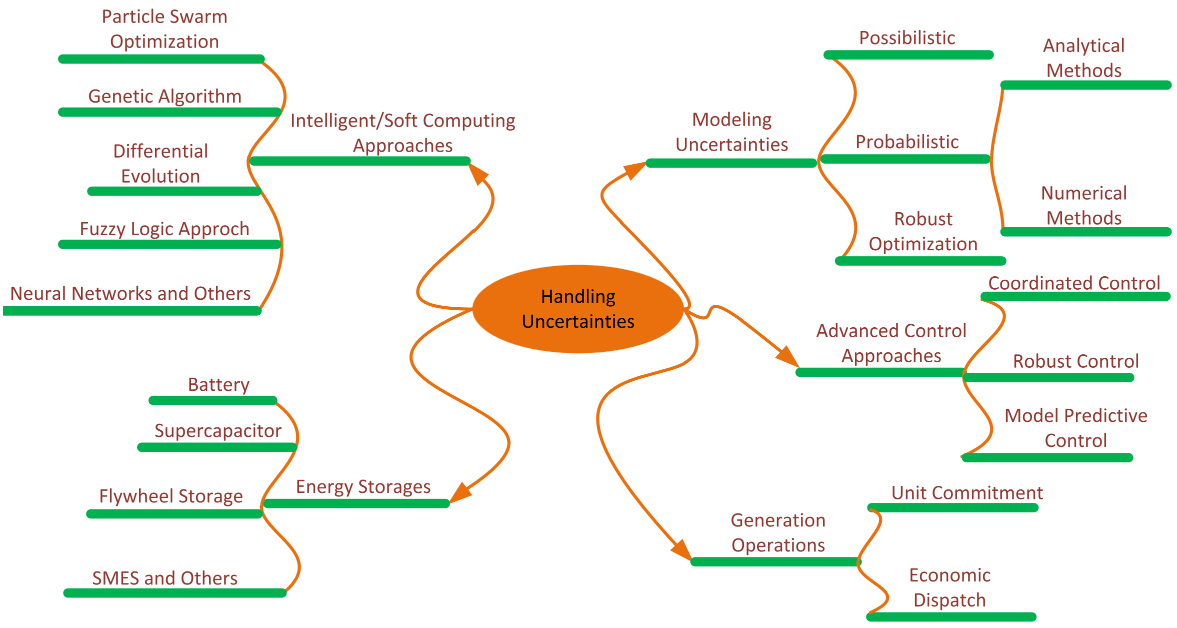

FIGURE 22. **Pictorial elaboration of uncertainty mitigation methods.**

of representative days, which measures loads and renewable generations over such days.

- **Generation Operations:** Another approach to alleviate the risk of uncertainty is to implement improved and intelligent generation operations with the help of unit commitment (UC) and economic dispatch (ED). Several mathematical programming methods are used to solve optimization problems such as UC, ED, optimal power flow, and state estimation [197]. The UC helps to provide optimal schedule of the generation operations in power system [198]. A comparative study of renewable uncertainty integration into stochastic security-constrained UC is performed in [199]. Both stochastic and deterministic models are studied where the stochastic model demonstrates more robust performance. Due to the fact that the gas-fired generating units are capable of ramping up quickly, which can mitigate uncertainty of renewable energy, many countries are installing more gas-fired units [200]. Higher the uncertainty in renewable energy, higher the dependency of the power system on traditional gas-fired generation, which transfers the uncertainties from renewable source to gas flow network. Thus, it necessitates an integrated unit commitment problem for electricity network and gas network. To come up with this issue, a new integrated unit commitment problem is formulated for electric and gas networks and solved with mixed integer non-linear optimization technique in [201]. Most of the studies mainly focus on one or two aspects of uncertainties; however, inclusion of all possible uncertainties is required for better system operation. Some unit commitment methodologies are presented in [202]–[204], dealing with the mitigation process of both forecast and outages uncertainties of solar and wind power generation. Another new multiobjective unit commitment optimization technique, utilizing information-gap decision theory (IGDT), is proposed in [205] considering both wind power and load demand uncertainties. A robust UC for thermal generators is proposed in a day-ahead market considering wind output uncertainties [206] which minimizes the total cost under worst wind output power. The cost effective UC is important while maintaining the system reliability in case of high-level integration of renewable energy. In practice, the renewable energy generations do not follow specific distributions and some historical data are available. Thus, a data driven risk-averse stochastic UC model is proposed for wind integrated system [207]. In order to capture the uncertainty of UC problems, two-stage stochastic programming can be applied [208]. The impact of variability of wind and solar power can also be minimized with economic dispatch (ED), short-term optimal output power scheduling from a number of generation units to meet the load demand subject to network and other constraints. A model, through Weibull distribution evaluated on a linearized power curve of the wind farm, is developed in [209] to solve ED problem considering wind power generation uncertainty. A similar model is proposed [210] in which wind generation is considered as constraint in optimization problem and is analyzed with Lagrange multiplier approach. A combined UC and ED solution method, which is described by the probability distribution function of thermal generators' output power, excess electricity, energy not served, and spinning reserve, is reported in [211] to reduce uncertainty impacts of high-level RESs integration. In this method, combination of priority list and ED solution is used to solve UC problems. Another unified UC and ED is solved [212] for RESs system having energy storage devices for short-term operation scheduling. This work may be further extended to include more electricity generation mix, which includes more gas-fired units and renewable sources. Furthermore, complex optimization of UC and ED can be solved with semidefinite programming [213].

- **Advanced Control Approaches:** Several control approaches are also presented in the literature to handle the uncertainties stem from the variation of wind speed and solar irradiation [214], [215]. The presented control approach in [215] combines the virtual inertia concept and pitch angle control to dynamically shift the maximum power tracking curve of DFIG wind generation system. The output power smoothing for wind generation systems, DFIG and PMSG, is presented in [216]–[218] with coordinated control approaches. The voltage control, rotor speed control, and pitch angle control are coordinated in hierarchical manner to reduce the impact of uncertainties due to wind speed variation [216]. Most of the control approaches do not deal with multi disruption and unknown parameters. However, the model predictive control (MPC) approach has the ability to consider both of them. In order to take these advantages, MPC-based control approaches are presented in [219], [220] for uncertainty mitigation of wind and solar energy systems. A robust nonlinear controller is presented in [221] for grid connected solar PV system. The partial feedback linearization approach is adopted and the robustness is guaranteed with wide range of uncertainties in solar system.
- **Intelligent/Soft Computing Approaches:** The reliability of network performance is degraded due to large scale stochastic renewable energy integration to the grid. Soft computing approaches are extensively employed in power system for reduction of uncertainty impact resulted from stochastic renewable energy sources. Although the soft computing techniques face the challenges in global optimality, uncertainties in renewable energy integration are managed with soft computing approaches. In [222], genetic algorithm-particle swarm optimization (GA-PSO) based hybrid technique is reported for wind and solar system. The load uncertainty and random change of demand are considered in [223] in optimization problem which is solved by modified PSO. Due to the efficacy to solve the optimization problem with many operational constraints, differential evolution (DE) is reported in [224], [225] for the renewable system in which generation uncertainties are on the top of load variations. In order to minimize the renewable energy prediction, artificial neural network (ANN) is trained with uncertain parameters like solar irradiance and wind speed [226]. Afterwords, eco-static objective function, reliability criteria, and battery management strategy are modeled and optimized with weighted improved PSO algorithm for further minimization of impact of uncertainty.
- **Energy Storages:** In RESs integration, uncertainty resulted from unavailability of exact information causes several unexpected system behaviors. As mentioned before, several optimization/soft computing approaches enable the development of RES models that are resilient to uncertainties; however, implicit considerations are required to build such models in case of intense presence of uncertainties. Still, the RES model needs to be designed systematically considering its high-level inherently fluctuating phenomena. To address this issue, several storage devices are the best candidates to be integrated within the system model [227], [228]. A systematic design approach to include highest level of flexibility in RES model is proposed considering hourly demand response, energy storage devices, and fast ramping unit [229]. To harness the energy-shifting and fast ramping capabilities of batteries, stochastic unit commitment and energy scheduling with economic dispatch are presented [230]. Further investigation on comprehensive set of real-time operation strategies of batteries could be new research direction and or more detailed lifetime degradation impact of batteries on uncertainty of RESs can be investigated. The source and load uncertainties management scheme is developed in [231] considering a hybrid energy storage system, comprising battery and supercapacitor. The performance of this hybrid scheme is also evaluated with other possible hybrid schemes, like superconducting magnetic energy storage and batteries (SMES-batteries) and flywheel-batteries. As per present discussions, energy storage system (ESS) plays an important role in mitigating and managing uncertainties; however, determination of size of ESS related to uncertainty mitigation process is imperative. A theoretical ESS sizing method is proposed in [232] considering stochastic nature of uncertainties and analyzed by mean absolute error (MAE). Different approaches, probabilistic [233], optimization [234], frequency domain [235], in evaluating the size of ESS are also adopted for mitigation of uncertainties in RESs integration.

VI. CURRENT CHALLENGES AND FUTURE RECOMMENDATIONS

Nowadays, several economic and technical benefits are gained from high-level integration of converter based renewable energy sources, such as low cost energy, less carbon emission, less operational and maintenance cost. However, many technical issues, very low inertia causing frequency instability, high fault current resulting from the short circuit, intensive uncertainties due to varying nature of wind speed and irradiance, degraded power quality, are raised due to high-level renewable energy integration. It is challenging for the researchers, system planners and operators to maintain flexible, reliable, and stable operations of such systems. Among the several issues, the reduction of system inertia is the most detrimental to the the power system. Since the frequency control is directly affected by the low system inertia. If the frequency of the power system starts declining without any remedial actions, several generating stations may be discontented due to frequency relay settings, and the system black-out may happen consequently. FRT capability may have impact on the inertia or frequency control of the power system. For example, if the PV and wind generators are disconnected due to their low FRT capability, the system frequency control becomes difficult as a result of generation and load mismatch. Likewise, uncertainty in PV and wind power generations leads to power mismatch, which exasperates frequency control. Although the power quality of renewable energy is weakly connected to the frequency control and FRT capability, several devices, such as FACTS, and energy storages, used for power quality improvement may help to control frequency and FRT capability. Thus, the academic researchers and engineers should consider the new strategy/control development for renewable energy system from the aggregated point of view of these issues.

Nowadays, several cutting-edge technologies and techniques are used and being continuously developed to deal with new challenges resulted from renewable energy integration. For instance, virtual inertia control, fault current limiters, advanced filters, energy storage devices, optimization techniques are adopted to handle those issues. Nevertheless, as still there are possibilities to develop better strategies to deal with the several challenges of high-level renewable energy integration, the future researches are likely to be conducted in the areas summarized below.

- Advanced control methodologies (such as predictive, adaptive, intelligence, robust, optimal, hierarchical control) can be redesigned/improved/implemented considering high power rating of converters and improved power sharing among the converters in order to facilitate high-level RES integration. Nevertheless, efficient power sharing of RES is often overlooked with the ideal voltage source assumption to the input of the converters.
- Even with the advanced control strategies, RES system is still vulnerable to the faults. Some auxiliary devices, such as recently developed non-superconducting fault current limiters, can be analyzed, and applied to RES system, and their feasibility studies can be conducted.
- Application of advanced control strategy highly depends on proper modeling of the system. Thus, improved and or novel model can be developed considering stochastic nature of renewable sources. Furthermore, importance should be given to reduce the complexity of such models in order for easy practical implementation.
- Low inertia is the serious concern for high-level RES integration. Although some methodologies, such as virtual inertia controllers, and droop controller, are present in the literature to ease the problem, still there are opportunities to contribute in this direction by designing improved inertia controller. Especially, the amount of virtual inertia needed for stable operation of high RES system can be optimized with advanced algorithms, and then this amount could be supported with improved virtual controller.
- There are few research studies that deal with the inertia/frequency support of RES system without auxiliary system. The DC side of converters of RES consists capacitors and AC side consists inductors. These two elements have built-in energy storing capability and mimic the behavior of rotating mass. Thus, voltage and current control of these elements can be hot research topic for short-term frequency support from them, similar to the frequency support from rotating mass inertia of a synchronous generator.
- Energy storage devices are important to support frequency, and voltage profile. However, few researches consider the impact of lifetime of energy storages when they are applied for frequency and voltage support, power quality improvement, and uncertainty management.

VII. CONCLUSION

Although high-level RES integration to the grid has advantages, it still raises several serious concerns like low inertia, degraded power quality, and high-level uncertainties. The aim of this article is to offer a comprehensive and in-depth review on challenges and solutions of high-level RES integration to the grid. Several challenges, such as low inertia, high fault current, low power quality, high uncertainty, are clearly pointed out and discussed. Besides, potential solution to each challenge is well documented with recent research articles. The detailed analysis of several technical problems of high-level RES integration is well documented with necessary graphical representations. Several gaps in the current study are clearly pointed out as challenges which can be filled up with cutting-edge technologies and novel researches. It is expected that this article can be an excellent reference for researchers of all level, beginner to high-level, to realize major challenges and opportunities in RES integration to the grid. Finally, a complete list of future works are highlighted for further improvement in control and operation of renewable energy systems.

REFERENCES

[1] K. J. Warner and G. A. Jones, "The 21st century coal question: China, India, development, and climate change," *Atmosphere*, vol. 10, no. 8, p. 476, Aug. 2019.

[2] *Remap 2030: A Renewable Energy Roadmap*, IRENA, Abu Dhabi, United Arab Emirates, 2014.

[3] M. K. Hossain and M. H. Ali, "Transient stability augmentation of PV/DFIG/SG-based hybrid power system by parallel-resonance bridge fault current limiter," *Electr. Power Syst. Res.*, vol. 130, pp. 89–102, Jan. 2016.

[4] M. Eckhart, "Renewables 2018 global status report," Worldwatch, Washington, DC, USA, Tech. Rep. REN21, 2018.

[5] M. A. Hossain, H. R. Pota, M. J. Hossain, and F. Blaabjerg, "Evolution of microgrids with converter-interfaced generations: Challenges and opportunities," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 160–186, Jul. 2019.

[6] M. Hossain, H. Pota, W. Issa, and M. Hossain, "Overview of AC microgrid controls with inverter-interfaced generations," *Energies*, vol. 10, no. 9, p. 1300, Aug. 2017.

[7] Z.-J. Wang and Z.-Z. Guo, "Uncertain models of renewable energy sources," *J. Eng.*, vol. 2017, no. 13, pp. 849–853, Jan. 2017.

[8] K. P. Kumar and B. Saravanan, "Recent techniques to model uncertainties in power generation from renewable energy sources and loads in microgrids—A review," *Renew. Sustain. Energy Rev.*, vol. 71, pp. 348–358, May 2017.

[9] M. H. Athari and Z. Wang, "Modeling the uncertainties in renewable generation and smart grid loads for the study of the grid vulnerability," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Sep. 2016, pp. 1–5.

[10] G. Rashid and M. H. Ali, "Bridge-type fault current limiter for asymmetric fault ride-through capacity enhancement of doubly fed induction machine based wind generator," in *Proc. IEEE Energy Convers. Congr. Exposit. (ECCE)*, Sep. 2014, pp. 1903–1910.

[11] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter," *Int. J. Electr. Power Energy Syst.*, vol. 86, pp. 104–119, Mar. 2017.

[12] X.-Y. Xiao, R.-H. Yang, X.-Y. Chen, Z.-X. Zheng, and C.-S. Li, "Enhancing fault ride-through capability of DFIG with modified SMES-FCL and RSC control," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 1, pp. 258–266, Jan. 2018.

[13] M. I. Daoud, A. M. Massoud, A. S. Abdel-Khalik, A. Elserougi, and S. 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, May 2016.

[14] A. R. Fereidouni, B. Vahidi, and T. H. Mehr, "The impact of solid state fault current limiter on power network with wind-turbine power generation," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1188–1196, Jun. 2013.

[15] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: A review," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 144–155, Mar. 2017.

[16] G. Magdy, G. Shabib, A. A. Elbaset, and Y. Mitani, "Renewable power systems dynamic security using a new coordination of frequency control strategy based on virtual synchronous generator and digital frequency protection," *Int. J. Electr. Power Energy Syst.*, vol. 109, pp. 351–368, Jul. 2019.

[17] S. A. Pourmousavi and M. H. Nehrir, "Real-time central demand response for primary frequency regulation in microgrids," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1988–1996, Dec. 2012.

[18] A. Molina-Garcia, F. Bouffard, and D. S. Kirschen, "Decentralized demand-side contribution to primary frequency control," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 411–419, Feb. 2011.

[19] T. S. Borsche, J. de Santiago, and G. Andersson, "Stochastic control of cooling appliances under disturbances for primary frequency reserves," *Sustain. Energy, Grids Netw.*, vol. 7, pp. 70–79, Sep. 2016.

[20] M. Farhoodnea, A. Mohamed, H. Shareef, and H. Zayandehroodi, "Power quality impact of renewable energy based generators and electric vehicles on distribution systems," *Procedia Technol.*, vol. 11, pp. 11–17, Jan. 2013.

[21] B. N. Singh, B. Singh, A. Chandra, P. Rastgoufard, and K. Al-Haddad, "An improved control algorithm for active filters," *IEEE Trans. Power Del.*, vol. 22, no. 2, pp. 1009–1020, Apr. 2007.

[22] L. Asiminoael, F. Blaabjerg, and S. Hansen, "Detection is key–Harmonic detection methods for active power filter applications," *IEEE Ind. Appl. Mag.*, vol. 13, no. 4, pp. 22–33, Jul. 2007.

[23] A. Luo, Q. Xu, F. Ma, and Y. Chen, "Overview of power quality analysis and control technology for the smart grid," *J. Modern Power Syst. Clean Energy*, vol. 4, no. 1, pp. 1–9, Jan. 2016.

[24] E. Hossain, M. R. Tur, S. Padmanaban, S. Ay, and I. Khan, "Analysis and mitigation of power quality issues in distributed generation systems using custom power devices," *IEEE Access*, vol. 6, pp. 16816–16833, 2018.

[25] G. S. Seck, V. Krakowski, E. Assoumou, N. Maïzi, and V. Mazauric, "Embedding power system's reliability within a long-term energy system optimization model: Linking high renewable energy integration and future grid stability for France by 2050," *Appl. Energy*, vol. 257, Jan. 2020, Art. no. 114037.

[26] H. Su, E. Zio, J. Zhang, Z. Li, H. Wang, F. Zhang, L. Chi, L. Fan, and W. Wang, "A systematic method for the analysis of energy supply reliability in complex integrated energy systems considering uncertainties of renewable energies, demands and operations," *J. Cleaner Prod.*, vol. 267, Sep. 2020, Art. no. 122117.

[27] N. Kumar, P. Besuner, S. Lefton, D. Agan, and D. Hilleman, "Power plant cycling costs tech. rep," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/SR-5500-55433, 2012, vol. 119.

[28] T. S. Borsche, T. Liu, and D. J. Hill, "Effects of rotational inertia on power system damping and frequency transients," in *Proc. 54th IEEE Conf. Decis. Control (CDC)*, Dec. 2015, pp. 5940–5946.

[29] S. C. Johnson, D. J. Papageorgiou, D. S. Mallapragada, T. A. Deetjen, J. D. Rhodes, and M. E. Webber, "Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy," *Energy*, vol. 180, pp. 258–271, Aug. 2019.

[30] S. Yu, L. Zhang, H. H.-C. Lu, T. Fernando, and K. P. Wong, "A DSE-based power system frequency restoration strategy for PV-integrated power systems considering solar irradiance variations," *IEEE Trans. Ind. Informat.*, vol. 13, no. 5, pp. 2511–2518, Oct. 2017.

[31] A. M. S. Yunus, A. Abu-Siada, M. A. S. Masoum, M. F. El-Naggar, and J. X. Jin, "Enhancement of DFIG LVRT capability during extreme short-wind gust events using SMES technology," *IEEE Access*, vol. 8, pp. 47264–47271, 2020.

[32] J. Morren, S. W. H. de Haan, W. L. Kling, and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 433–434, Feb. 2006.

[33] M. Hajiakbari Fini and M. E. Hamedani Golshan, "Frequency control using loads and generators capacity in power systems with a high penetration of renewables," *Electr. Power Syst. Res.*, vol. 166, pp. 43–51, Jan. 2019.

[34] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proc. Volumes*, vol. 47, no. 3, pp. 7290–7297, 2014.

[35] U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual inertia: Current trends and future directions," *Appl. Sci.*, vol. 7, no. 7, p. 654, Jun. 2017.

[36] M. Hajiakbari Fini and M. E. Hamedani Golshan, "Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables," *Electr. Power Syst. Res.*, vol. 154, pp. 13–22, Jan. 2018.

[37] C. Pradhan and C. Bhende, "Enhancement in primary frequency contribution using dynamic deloading of wind turbines," *IFAC-PapersOnLine*, vol. 48, no. 30, pp. 13–18, 2015.

[38] H. T. Ma and B. H. Chowdhury, "Working towards frequency regulation with wind plants: Combined control approaches," *IET Renew. Power Gener.*, vol. 4, no. 4, pp. 308–316, Jul. 2010.

[39] A. Žertek, G. Verbič, and M. Pantoš, "Optimised control approach for frequency-control contribution of variable speed wind turbines," *IET Renew. Power Gener.*, vol. 6, no. 1, pp. 17–23, Jan. 2012.

[40] N. A. Janssens, G. Lambin, and N. Bragard, "Active power control strategies of DFIG wind turbines," in *Proc. IEEE Lausanne Power Tech*, Jul. 2007, pp. 516–521.

[41] G. Ramtharan, J. B. Ekanayake, and N. Jenkins, "Frequency support from doubly fed induction generator wind turbines," *IET Renew. Power Gener.*, vol. 1, no. 1, pp. 3–9, Mar. 2007.

[42] Z. Wu, W. Gao, J. Wang, and S. Gu, "A coordinated primary frequency regulation from permanent magnet synchronous wind turbine generation," in *Proc. IEEE Power Electron. Mach. Wind Appl.*, Jul. 2012, pp. 1–6.

[43] C. Zhangjie, W. Xiaoru, and T. Jin, "Control strategy of large-scale DFIG-based wind farm for power grid frequency regulation," in *Proc. 31st Chin. Control Conf.*, Jul. 2012, pp. 6835–6840.

[44] B. Peng, F. Zhang, J. Liang, L. Ding, Z. Liang, and Q. Wu, "Coordinated control strategy for the short-term frequency response of a DFIG-ES system based on wind speed zone classification and fuzzy logic control," *Int. J. Electr. Power Energy Syst.*, vol. 107, pp. 363–378, May 2019.

[45] T. Kerdphol, F. Rahman, Y. Mitani, K. Hongesombut, and S. Küfeoglu, "Virtual inertia control-based model predictive control for microgrid frequency stabilization considering high renewable energy integration," *Sustainability*, vol. 9, no. 5, p. 773, May 2017.

[46] J. Morren, J. Pierik, and S. W. H. de Haan, "Inertial response of variable speed wind turbines," *Electr. Power Syst. Res.*, vol. 76, no. 11, pp. 980–987, Jul. 2006.

[47] J. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," *IEEE Trans. Energy Convers.*, vol. 19, no. 4, pp. 800–802, Dec. 2004.

[48] L. Wu and D. G. Infield, "Towards an assessment of power system frequency support from wind plant—Modeling aggregate inertial response," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2283–2291, Jan. 2013.

[49] Z. Zhang, Y. Wang, H. Li, and X. Su, "Comparison of inertia control methods for DFIG-based wind turbines," in *Proc. IEEE ECCE Asia Downunder*, Jun. 2013, pp. 960–964.

[50] F. M. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, "Control of DFIG-based wind generation for power network support," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1958–1966, Nov. 2005.

[51] O. Göksu, R. Teodorescu, P. Rodriguez, and L. Helle, "A review of the state of the art in control of variable-speed wind turbines," in *Proc. 9th Int. Workshop Large-Scale Integr. Wind Power Power Syst.*, Aarhus, Denmark, 2010, pp. 1–8.

[52] D. Jovcic, L. A. Lamont, and L. Xu, "VSC transmission model for analytical studies," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, vol. 3, Jul. 2003, pp. 1737–1742.

[53] T. Midtsund, J. A. Suul, and T. Undeland, "Evaluation of current controller performance and stability for voltage source converters connected to a weak grid," in *Proc. 2nd Int. Symp. Power Electron. Distrib. Gener. Syst.*, Jun. 2010, pp. 382–388.

[54] Q.-C. Zhong and T. Hornik, *Control of Power Inverters in Renewable Energy and Smart Grid Integration*, vol. 97. Hoboken, NJ, USA: Wiley, 2012.

[55] S. Wang, J. Hu, and X. Yuan, "Virtual synchronous control for grid-connected DFIG-based wind turbines," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 4, pp. 932–944, Dec. 2015.

[56] N. R. Ullah, T. Thiringer, and D. Karlsson, "Temporary primary frequency control support by variable speed wind turbines—Potential and applications," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 601–612, 2008.

[57] A. D. Hansen, M. Altin, I. D. Margaris, F. Iov, and G. C. Tarnowski, "Analysis of the short-term overproduction capability of variable speed wind turbines," *Renew. Energy*, vol. 68, pp. 326–336, Aug. 2014.

[58] S. El Itani, U. D. Annakkage, and G. Joos, "Short-term frequency support utilizing inertial response of DFIG wind turbines," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–8.

[59] E. Jahan, M. R. Hazari, S. M. Muyeen, A. Umemura, R. Takahashi, and J. Tamura, "Primary frequency regulation of the hybrid power system by deloaded PMSG-based offshore wind farm using centralised droop controller," *J. Eng.*, vol. 2019, no. 18, pp. 4950–4954, Jul. 2019.

[60] W. Yao and K. Y. Lee, "A control configuration of wind farm for load-following and frequency support by considering the inertia issue," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–6.

[61] R. L. Josephine and S. Suja, "Estimating PMSG wind turbines by inertia and droop control schemes with intelligent fuzzy controller in Indian development," *J. Electr. Eng. Technol.*, vol. 9, no. 4, pp. 1196–1201, Jul. 2014.

[62] M. Y. Worku, M. A. Abido, and R. Iravani, "Power fluctuation minimization in grid connected photovoltaic using supercapacitor energy storage system," *J. Renew. Sustain. Energy*, vol. 8, no. 1, Jan. 2016, Art. no. 013501.

[63] L. Miao, J. Wen, H. Xie, C. Yue, and W.-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.

[64] H. Ye, Y. Liu, W. Pei, and L. Kong, "Efficient droop-based primary frequency control from variable-speed wind turbines and energy storage systems," in *Proc. IEEE Transp. Electrific. Conf. Expo, Asia–Pacific (ITEC Asia-Pacific)*, Aug. 2017, pp. 1–5.

[65] S. Zhang, Y. Mishra, and M. Shahidehpour, "Fuzzy-logic based frequency controller for wind farms augmented with energy storage systems," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1595–1603, Mar. 2016.

[66] M. Khalid and A. V. Savkin, "An optimal operation of wind energy storage system for frequency control based on model predictive control," *Renew. Energy*, vol. 48, pp. 127–132, Dec. 2012.

[67] H. Zhao, Q. Wu, S. Hu, H. Xu, and C. N. Rasmussen, "Review of energy storage system for wind power integration support," *Appl. Energy*, vol. 137, pp. 545–553, Jan. 2015.

[68] A. Esmaili, B. Novakovic, A. Nasiri, and O. Abdel-Baqi, "A hybrid system of li-ion capacitors and flow battery for dynamic wind energy support," *IEEE Trans. Ind. Appl.*, vol. 49, no. 4, pp. 1649–1657, Jul. 2013.

[69] N. Mendis, K. M. Muttaqi, and S. Perera, "Management of low- and high-frequency power components in demand-generation fluctuations of a DFIG-based wind-dominated RAPS system using hybrid energy storage," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 2258–2268, May 2014.

[70] M. N. Musarrat, M. R. Islam, K. M. Muttaqi, and D. Sutanto, "Enhanced frequency support from a PMSG-based wind energy conversion system integrated with a high temperature SMES in standalone power supply systems," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, pp. 1–6, Mar. 2019.

[71] F. Díaz-González, M. Hau, A. Sumper, and O. Gomis-Bellmunt, "Coordinated operation of wind turbines and flywheel storage for primary frequency control support," *Int. J. Electr. Power Energy Syst.*, vol. 68, pp. 313–326, Jun. 2015.

[72] N. Sa-ngawong and I. Ngamroo, "Intelligent photovoltaic farms for robust frequency stabilization in multi-area interconnected power system based on PSO-based optimal Sugeno fuzzy logic control," *Renew. Energy*, vol. 74, pp. 555–567, Feb. 2015.

[73] C. A. Hill, M. C. Such, D. Chen, J. Gonzalez, and W. M. Grady, "Battery energy storage for enabling integration of distributed solar power generation," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 850–857, Jun. 2012.

[74] N. Kakimoto, S. Takayama, H. Satoh, and K. Nakamura, "Power modulation of photovoltaic generator for frequency control of power system," *IEEE Trans. Energy Convers.*, vol. 24, no. 4, pp. 943–949, Dec. 2009.

[75] H. Xin, Y. Liu, Z. Wang, D. Gan, and T. Yang, "A new frequency regulation strategy for photovoltaic systems without energy storage," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 985–993, Oct. 2013.

[76] P. P. Zarina, S. Mishra, and P. C. Sekhar, "Exploring frequency control capability of a PV system in a hybrid PV-rotating machine-without storage system," *Int. J. Electr. Power Energy Syst.*, vol. 60, pp. 258–267, Sep. 2014.

[77] H. Alatrash, A. Mensah, E. Mark, G. Haddad, and J. Enslin, "Generator emulation controls for photovoltaic inverters," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 996–1011, Jun. 2012.

[78] S. I. Nanou, A. G. Papakonstantinou, and S. A. Papathanassiou, "A generic model of two-stage grid-connected PV systems with primary frequency response and inertia emulation," *Electr. Power Syst. Res.*, vol. 127, pp. 186–196, Oct. 2015.

[79] P. P. Zarina and S. Mishra, "Power oscillation reduction contribution by PV in deloaded mode," in *Proc. IEEE 6th Int. Conf. Power Syst. (ICPS)*, Mar. 2016, pp. 1–4.

[80] G. Yan, S. Liang, Q. Jia, and Y. Cai, "Novel adapted de-loading control strategy for PV generation participating in grid frequency regulation," *J. Eng.*, vol. 2019, no. 16, pp. 3383–3387, Mar. 2019.

[81] S. Showers and A. Raji, "Frequency regulation of grid connected solar pv system using battery storage system," in *Proc. Int. Conf. Domestic Use Energy (DUE)*, 2019, pp. 176–182.

[82] S. You, Y. Liu, Y. Liu, A. Till, H. Li, Y. Su, J. Zhao, J. Tan, Y. Zhang, and M. Gong, "Energy storage for frequency control in high photovoltaic power grids," in *Proc. 18th Int. Conf. Smart Technol. (EUROCON)*, Jul. 2019, pp. 1–6.

[83] X. Wang and M. Yue, "Design of energy storage system to improve inertial response for large scale PV generation," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2016, pp. 1–5.

[84] P. K. Ray and A. Mohanty, "A robust firefly–swarm hybrid optimization for frequency control in wind/PV/FC based microgrid," *Appl. Soft Comput.*, vol. 85, Dec. 2019, Art. no. 105823.

[85] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and C.-H. Kim, "A frequency-control approach by photovoltaic generator in a PV–Diesel hybrid power system," *IEEE Trans. Energy Convers.*, vol. 26, no. 2, pp. 559–571, Jun. 2011.

[86] B. Sakeen, N. K. Bachache, and S. Wang, "Frequency control of PV-diesel hybrid power system using optimal fuzzy logic controller," in *Proc. IEEE 11th Int. Conf. Dependable, Autonomic Secure Comput.*, Dec. 2013, pp. 174–178.

[87] R. H. Lasseter, Z. Chen, and D. Pattabiraman, "Grid-forming inverters: A critical asset for the power grid," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 925–935, Jun. 2020.

[88] M. E. Elkhatib, W. Du, and R. H. Lasseter, "Evaluation of inverter-based grid frequency support using frequency-watt and grid-forming PV inverters," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2018, pp. 1–5.

[89] R. Ramachandran, S. Poullain, A. Benchaib, S. Bacha, and B. François, "AC grid forming by coordinated control of offshore wind farm connected to diode rectifier based HVDC link-review and assessment of solutions," in *Proc. 20th Eur. Conf. Power Electron. Appl. (EPE ECCE Europe)*, 2018, pp. P–1.

[90] B.-I. Crăciun, T. Kerekes, D. Séra, and R. Teodorescu, "Frequency support functions in large PV power plants with active power reserves," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 849–858, Dec. 2014.

[91] L. A. Fajardo R, F. Iov, J. Aurelio Medina R, A. D. Hansen, and F. Blaabjerg, "Induction generator model in phase coordinates for fault ride-through capability studies of wind turbines," in *Proc. Eur. Conf. Power Electron. Appl.*, 2007, pp. 1–10.

[92] M. Alam, M. Abido, A. Hussein, and I. El-Amin, "Fault ride through capability augmentation of a DFIG-based wind integrated VSC-HVDC system with non-superconducting fault current limiter," *Sustainability*, vol. 11, no. 5, p. 1232, Feb. 2019.

[93] E. Munkhchuluun, L. Meegahapola, and A. Vahidnia, "Long-term voltage stability with large-scale solar-photovoltaic (PV) generation," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105663.

[94] M. S. El Moursi, J. L. Kirtley, and W. Xiao, "Fault ride through capability for grid interfacing large scale PV power plants," *IET Gener., Transmiss. Distrib.*, vol. 7, no. 9, pp. 1027–1036, Sep. 2013.

[95] M. Mohseni, M. A. S. Masoum, and S. M. Islam, "Low and high voltage ride-through of DFIG wind turbines using hybrid current controlled converters," *Electr. Power Syst. Res.*, vol. 81, no. 7, pp. 1456–1465, Jul. 2011.

[96] M. H. Qais, H. M. Hasanien, and S. Alghuwainem, "Whale optimization algorithm-based sugeno fuzzy logic controller for fault ride-through improvement of grid-connected variable speed wind generators," *Eng. Appl. Artif. Intell.*, vol. 87, Jan. 2020, Art. no. 103328.

[97] E. Zangeneh Bighash, S. M. Sadeghzadeh, E. Ebrahimzadeh, and F. Blaabjerg, "Improving performance of LVRT capability in single-phase grid-tied PV inverters by a model-predictive controller," *Int. J. Electr. Power Energy Syst.*, vol. 98, pp. 176–188, Jun. 2018.

[98] M. J. Morshed and A. Fekih, "A new fault ride-through control for DFIG-based wind energy systems," *Electr. Power Syst. Res.*, vol. 146, pp. 258–269, May 2017.

[99] M. Benbouzid, B. Beltran, Y. Amirat, G. Yao, J. Han, and H. Mangel, "Second-order sliding mode control for DFIG-based wind turbines fault ride-through capability enhancement," *ISA Trans.*, vol. 53, no. 3, pp. 827–833, May 2014.

[100] J. Mohammadi, S. Afsharnia, and S. Vaez-Zadeh, "Efficient fault-ride-through control strategy of DFIG-based wind turbines during the grid faults," *Energy Convers. Manage.*, vol. 78, pp. 88–95, Feb. 2014.

[101] R. A. J. Amalorpavaraj, P. Kaliannan, S. Padmanaban, U. Subramaniam, and V. K. Ramachandaramurthy, "Improved fault ride through capability in DFIG based wind turbines using dynamic voltage restorer with combined feed-forward and feed-back control," *IEEE Access*, vol. 5, pp. 20494–20503, 2017.

[102] G. Chen and X. Cai, "Reconfigurable control for fault-tolerant of parallel converters in PMSG wind energy conversion system," *IEEE Trans. Sustain. Energy*, vol. 10, no. 2, pp. 604–614, Apr. 2019.

[103] M. Nasiri and R. Mohammadi, "Peak current limitation for grid side inverter by limited active power in PMSG-based wind turbines during different grid faults," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 3–12, Jan. 2017.

[104] M. Jahanpour-Dehkordi, S. Vaez-Zadeh, and J. Mohammadi, "Development of a combined control system to improve the performance of a PMSG-based wind energy conversion system under normal and grid fault conditions," *IEEE Trans. Energy Convers.*, vol. 34, no. 3, pp. 1287–1295, Sep. 2019.

[105] P. Xing, L. Fu, G. Wang, Y. Wang, and Y. Zhang, "A compositive control method of low-voltage ride through for PMSG-based wind turbine generator system," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 1, pp. 117–125, Jan. 2018.

[106] J. Yao, J. Pei, D. Xu, R. Liu, X. Wang, C. Wang, and Y. Li, "Coordinated control of a hybrid wind farm with DFIG-based and PMSG-based wind power generation systems under asymmetrical grid faults," *Renew. Energy*, vol. 127, pp. 613–629, Nov. 2018.

[107] A. Q. Al-Shetwi, M. Z. Sujod, and F. Blaabjerg, "Low voltage ride-through capability control for single-stage inverter-based grid-connected photovoltaic power plant," *Sol. Energy*, vol. 159, pp. 665–681, Jan. 2018.

[108] G. B. Huka, W. Li, P. Chao, and S. Peng, "A comprehensive LVRT strategy of two-stage photovoltaic systems under balanced and unbalanced faults," *Int. J. Electr. Power Energy Syst.*, vol. 103, pp. 288–301, Dec. 2018.

[109] A. Mojallal and S. Lotfifard, "Enhancement of grid connected PV arrays fault ride through and post fault recovery performance," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 546–555, Jan. 2019.

[110] F. Zheng, Y. Chen, T. Ye, Y. Zhang, F. Guo, and Y. Zhang, "Design of hybrid control algorithm for fault ride-through of photovoltaic system," *IEEE Access*, vol. 7, pp. 124196–124206, 2019.

[111] Y. Wang and B. Ren, "Fault ride-through enhancement for grid-tied PV systems with robust control," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2302–2312, Mar. 2018.

[112] H. M. Hasanien, "An adaptive control strategy for low voltage ride through capability enhancement of grid-connected photovoltaic power plants," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 3230–3237, Jul. 2016.

[113] H. Wen and M. Fazeli, "A new control strategy for low-voltage ride-through of three-phase grid-connected PV systems," *J. Eng.*, vol. 2019, no. 18, pp. 4900–4905, Jul. 2019.

[114] F. Jiang, C. Tu, Z. Shuai, F. Xiao, and Z. Lan, "Combinational voltage booster technique for fault ride-through capability enhancement of squirrel-cage induction generator," *Electr. Power Syst. Res.*, vol. 136, pp. 163–172, Jul. 2016.

[115] K. A. Naik and C. P. Gupta, "Improved fluctuation behavior of SCIG based wind energy system using hybrid pitch angle controller," in *Proc. IEEE Uttar Pradesh Sect. Int. Conf. Electr., Comput. Electron. Eng. (UPCON)*, Dec. 2016, pp. 508–514.

[116] H. Ahuja, S. Sharma, G. Singh, A. Sharma, and A. Singh, "Coordinated fault ride through strategy for SCIG based WECS," in *Proc. 2nd Int. Conf. Comput. Intell. Commun. Technol. (CICT)*, Feb. 2016, pp. 424–429.

[117] N. Jelani and M. Molinas, "Asymmetrical fault ride through as ancillary service by constant power loads in grid-connected wind farm," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1704–1713, Mar. 2015.

[118] Y. He, M. Wang, and Z. Xu, "Coordinative low-voltage-ride-through control for the wind-photovoltaic hybrid generation system," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1503–1514, Jun. 2020.

[119] V. Pagola-Torres, R. Pena-Gallardo, and J. Segundo-Ramirez, "Low voltage ride-through analysis in real time of a PV-wind hybrid system," in *Proc. IEEE Int. Autumn Meeting Power, Electron. Comput. (ROPEC)*, Nov. 2015, pp. 1–6.

[120] M. J. Morshed and A. Fekih, "A novel fault ride through scheme for hybrid Wind/PV power generation systems," *IEEE Trans. Sustain. Energy*, vol. 11, no. 4, pp. 2427–2436, Oct. 2020.

[121] O. Noureldeen and A. M. A. Ibrahim, "Low-voltage ride-through capability enhancement of a grid-connected photovoltaic/wind hybrid power system," in *Proc. 19th Int. Middle East Power Syst. Conf. (MEPCON)*, Dec. 2017, pp. 786–795.

[122] M. Alam, M. Abido, and I. El-Amin, "Fault current limiters in power systems: A comprehensive review," *Energies*, vol. 11, no. 5, p. 1025, Apr. 2018.

[123] M. S. Alam, M. A. Abido, and Z. M. Al-Hamouz, "Model predictive control approach for bridge-type fault current limiter in VSC-HVDC system," *Arabian J. Sci. Eng.*, vol. 44, no. 3, pp. 2079–2089, Mar. 2019.

[124] H. Liu and X. Xie, "Impedance network modeling and quantitative stability analysis of sub-/super-synchronous oscillations for large-scale wind power systems," *IEEE Access*, vol. 6, pp. 34431–34438, 2018.

[125] C. Huang, X. Y. Xiao, Z. Zheng, and Y. Wang, "Cooperative control of SFCL and SMES for protecting PMSG-based WTGs under grid faults," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, pp. 1–6, Mar. 2019.

[126] A. Q. Al-Shetwi, M. Z. Sujod, F. Blaabjerg, and Y. Yang, "Fault ride-through control of grid-connected photovoltaic power plants: A review," *Sol. Energy*, vol. 180, pp. 340–350, Mar. 2019.

[127] H. Heydari-doostabad, M. R. Khalghani, and M. 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, May 2016.

[128] A. Ayvaz and M. Özdemir, "A combined usage of sdbr and svc to improve the transient stability performance of a pv/wind generation system," in *Proc. Nat. Conf. Electr., Electron. Biomed. Eng. (ELECO)*, 2016, pp. 76–80.

[129] C. H. Benz, W.-T. Franke, and F. W. Fuchs, "Low voltage ride through capability of a 5 kW grid-tied solar inverter," in *Proc. 14th Int. Power Electron. Motion Control Conf. (EPE-PEMC)*, Sep. 2010, pp. T12–T13.

[130] N. Saadat, S. S. Choi, and D. M. Vilathgamuwa, "A statistical evaluation of the capability of distributed renewable generator-energy-storage system in providing load low-voltage ride-through," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1128–1136, Jun. 2015.

[131] M. Y. Worku and M. A. Abido, "Grid-connected PV array with supercapacitor energy storage system for fault ride through," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2015, pp. 2901–2906.

[132] J. NERC and W. S. Report, "900 mw fault induced solar photovoltaic resource interruption disturbance report," North Amer. Electr. Rel. Corp. (NERC), Atlanta, GA, USA, Tech. Rep. 404-446-2560, Feb. 2018.

[133] E. Rehman, M. Miller, J. Schmall, and S. H. Huang, "Dynamic stability assessment of high penetration of renewable generation in the ERCOT grid," ERCOT, Austin, TX, USA, Tech. Rep. 144927, 2018. [Online]. Available: http://www.ercot.com/content/wcm/lists/144927

[134] X. Liang and C. Andalib-Bin- Karim, "Harmonics and mitigation techniques through advanced control in grid-connected renewable energy sources: A review," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3100–3111, Jul. 2018.

[135] H. Djeghloud, A. Bentounsi, and H. Benalla, "Sub and super-synchronous wind turbine-doubly fed induction generator system implemented as an active power filter," *Int. J. Power Electron.*, vol. 3, no. 2, pp. 189–212, 2011.

[136] K. Ishaque and Z. Salam, "A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 475–488, Mar. 2013.

[137] M. M. Elkholy, M. A. El-Hameed, and A. A. El-Fergany, "Harmonic analysis of hybrid renewable microgrids comprising optimal design of passive filters and uncertainties," *Electr. Power Syst. Res.*, vol. 163, pp. 491–501, Oct. 2018.

[138] M. Tali, A. Obbadi, A. Elfajri, and Y. Errami, "Passive filter for harmonics mitigation in standalone PV system for non linear load," in *Proc. Int. Renew. Sustain. Energy Conf. (IRSEC)*, Oct. 2014, pp. 499–504.

[139] W. U. Tareen, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, "Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system," *Renew. Sustain. Energy Rev.*, vol. 70, pp. 635–655, Apr. 2017.

[140] K. Ravinder and H. O. Bansal, "Investigations on shunt active power filter in a PV-wind-FC based hybrid renewable energy system to improve power quality using hardware-in-the-loop testing platform," *Electric Power Syst. Res.*, vol. 177, Dec. 2019, Art. no. 105957.

[141] J. W. Kolar, T. Friedli, J. Rodriguez, and P. W. Wheeler, "Review of three-phase PWM AC–AC converter topologies," *IEEE Trans. Ind. Electron.*, vol. 58, no. 11, pp. 4988–5006, Nov. 2011.

[142] H. Yamada, E. Hiraki, and T. Tanaka, "A starting method of the harmonic current compensator using a hybrid active filter for wind power generation systems with soft starters," in *Proc. Int. Power Electron. Conf. (ECCE ASIA)*, Jun. 2010, pp. 317–322.

[143] S. P. Litrán and P. Salmerón, "Analysis and design of different control strategies of hybrid active power filter based on the state model," *IET Power Electron.*, vol. 5, no. 8, pp. 1341–1350, Sep. 2012.

[144] N. Hui, D. Wang, and Y. Li, "An efficient hybrid filter-based phase-locked loop under adverse grid conditions," *Energies*, vol. 11, no. 4, p. 703, Mar. 2018.

[145] L. Qian, D. A. Cartes, and H. Li, "An improved adaptive detection method for power quality improvement," *IEEE Trans. Ind. Appl.*, vol. 44, no. 2, pp. 525–533, Mar. 2008.

[146] A. Anzalchi, M. Moghaddami, A. Moghadasi, M. M. Pour, and A. I. Sarwat, "Design and analysis of a higher order power filter for grid-connected renewable energy systems," *IEEE Trans. Ind. Appl.*, vol. 53, no. 5, pp. 4149–4161, Sep. 2017.

[147] F. Chishti, S. Murshid, and B. Singh, "Weak grid intertie WEGS with hybrid generalized integrator for power quality improvement," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1113–1123, Feb. 2020.

[148] S. S. Yu, G. Zhang, T. Fernando, and H. H.-C. Iu, "A DSE-based SMC method of sensorless DFIG wind turbines connected to power grids for energy extraction and power quality enhancement," *IEEE Access*, vol. 6, pp. 76596–76605, 2018.

[149] F. Chishti, S. Murshid, and B. Singh, "LMMN-based adaptive control for power quality improvement of grid intertie wind–PV system," *IEEE Trans. Ind. Informat.*, vol. 15, no. 9, pp. 4900–4912, Sep. 2019.

[150] A. S. Bubshait, A. Mortezaei, M. G. Simões, and T. 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, Jun. 2017.

[151] B. Seghir, A. Chandra, and R. Miloud, "A new control strategy for power quality improvement using MPPT from hybrid PV-wind connected to the grid," in *Proc. IEEE Can. Conf. Electr. Comput. Eng. (CCECE)*, May 2018, pp. 1–6.

[152] A. H. Elmetwaly, A. A. Eldesouky, and A. A. Sallam, "An adaptive D-FACTS for power quality enhancement in an isolated microgrid," *IEEE Access*, vol. 8, pp. 57923–57942, 2020.

[153] F. H. Gandoman, A. Ahmadi, A. M. Sharaf, P. Siano, J. Pou, B. Hredzak, and V. G. Agelidis, "Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 502–514, Feb. 2018.

[154] A. A. Abdelsalam and A. M. Sharaf, "A novel facts compensation scheme for power quality improvement in wind smart grid," in *Proc. 25th IEEE Can. Conf. Electr. Comput. Eng. (CCECE)*, Apr. 2012, pp. 1–4.

[155] P. Jyotishi and P. Deeparamchandani, "Mitigate voltage sag/swell condition and power quality improvement in distribution line using d-statcom," *Int. J. Eng. Res. Appl.*, vol. 3, no. 6, pp. 667–674, 2013.

[156] T. Sunil and N. Loganathan, "Power quality improvement of a grid-connected wind energy conversion system with harmonics reduction using FACTS device," in *Proc. IEEE Int. Conf. Adv. Eng. Sci. Manage. (ICAESM)*, Mar. 2012, pp. 415–420.

[157] P. M. Chavan and G. R. Walke, "Using STATCOM interfacing of renewable energy source to grid and power quality improvement," in *Proc. Int. Conf. Energy Syst. Appl.*, Oct. 2015, pp. 329–332.

[158] E. Jamil, S. Hameed, and B. Jamil, "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.

[159] K. C. S. Thampatty, "Design of MRAC based TCSC for damping sub-synchronous oscillations in SCIG based wind farm," in *Proc. IEEE Region 10 Conf. (TENCON)*, Oct. 2019, pp. 1846–1852.

[160] H. Kuang, L. Zheng, S. Li, and X. Ding, "Voltage stability improvement of wind power grid-connected system using TCSC-STATCOM control," *IET Renew. Power Gener.*, vol. 13, no. 2, pp. 215–219, Feb. 2019.

[161] A. Savic and Ž. Đurišic, "Optimal sizing and location of SVC devices for improvement of voltage profile in distribution network with dispersed photovoltaic and wind power plants," *Appl. Energy*, vol. 134, pp. 114–124, Dec. 2014.

[162] T. Tayyebifar, M. Shaker, and M. Aghababaie, "Performance comparison of STATCOM versus SVC to improve reactive power control in wind power based DFIG under short circuit fault," in *Proc. 9th Int. Conf. Ecol. Vehicles Renew. Energies (EVER)*, Mar. 2014, pp. 1–7.

[163] S. F. Panah, T. F. Panah, and G. A. Ghannad, "Reactive power compensation in wind power plant with short circuit in power plant line via UPFC," in *Proc. IEEE Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Nov. 2016, pp. 173–176.

[164] V. Chaudhary, A. Bhargava, and S. Verma, "Power quality enhancement using unified power flow controller in grid connected hybrid PV/Wind system," in *Proc. Int. Conf. Commun. Electron. Syst. (ICCES)*, Jul. 2019, pp. 2064–2069.

[165] A. Kalair, N. Abas, A. R. Kalair, Z. Saleem, and N. Khan, "Review of harmonic analysis, modeling and mitigation techniques," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 1152–1187, Oct. 2017.

[166] R. Bhavani, N. R. Prabha, and C. Kanmani, "Fuzzy controlled UPQC for power quality enhancement in a DFIG based grid connected wind power system," in *Proc. Int. Conf. Circuits, Power Comput. Technol. [ICCPCT]*, Mar. 2015, pp. 1–7.

[167] M. V. Chaudhary, P. C. Tapre, and C. Veeresh, "Enhancement of power quality using UPQC in hybrid wind/diesel system with energy storage," in *Proc. Int. Conf. Signal Process., Commun., Power Embedded Syst. (SCOPES)*, Oct. 2016, pp. 732–735.

[168] A. Rashad, S. Kamel, F. Jurado, and K. Mahmoud, "Performance improvement of various types of induction-based wind farms using center-node unified power flow controller," *Int. J. Control, Autom. Syst.*, vol. 16, no. 6, pp. 2644–2655, Dec. 2018.

[169] L. Liu, H. Li, Z. Wu, and Y. Zhou, "A cascaded photovoltaic system integrating segmented energy storages with self-regulating power allocation control and wide range reactive power compensation," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3545–3559, Dec. 2011.

[170] V. Behravesh, R. Keypour, and A. A. Foroud, "Control strategy for improving voltage quality in residential power distribution network consisting of roof-top photovoltaic-wind hybrid systems, battery storage and electric vehicles," *Sol. Energy*, vol. 182, pp. 80–95, Apr. 2019.

[171] L. Djamel and B. Abdallah, "Power quality control strategy for grid-connected renewable energy sources using PV array, wind turbine and battery," in *Proc. 4th Int. Conf. Power Eng., Energy Electr. Drives*, May 2013, pp. 1671–1675.

[172] H.-R. Seo, G.-H. Kim, S.-Y. Kim, N. Kim, H.-G. Lee, C. Hwang, M. Park, and I.-K. Yu, "Power quality control strategy for grid-connected renewable energy sources using PV array and supercapacitor," in *Proc. Int. Conf. Electr. Mach. Syst.*, 2010, pp. 437–441.

[173] M. Y. Worku and M. A. Abido, "Fault ride-through and power smoothing control of PMSG-based wind generation using supercapacitor energy storage system," *Arabian J. Sci. Eng.*, vol. 44, no. 3, pp. 2067–2078, Mar. 2019.

[174] M. Ding and J. Wu, "A novel control strategy of hybrid energy storage system for wind power smoothing," *Electr. Power Compon. Syst.*, vol. 45, no. 12, pp. 1265–1274, Jul. 2017.

[175] H. R. Seo, A. R. Kim, M. Park, and I. K. Yu, "Power quality enhancement of renewable energy source power network using SMES system," *Phys. C, Supercond. Appl.*, vol. 471, nos. 21–22, pp. 1409–1412, Nov. 2011.

[176] P. Mukherjee and V. V. Rao, "Effective location of SMES for power fluctuation mitigation of grid connected doubly fed induction generator," *J. Energy Storage*, vol. 29, Jun. 2020, Art. no. 101369.

[177] J. Soni and S. K. Panda, "Electric spring for voltage and power stability and power factor correction," *IEEE Trans. Ind. Appl.*, vol. 53, no. 4, pp. 3871–3879, Jul. 2017.

[178] A. Benali, M. Khiat, T. Allaoui, and M. Denai, "Power quality improvement and low voltage ride through capability in hybrid wind-PV farms grid-connected using dynamic voltage restorer," *IEEE Access*, vol. 6, pp. 68634–68648, 2018.

[179] A. Latif, S. M. S. Hussain, D. C. Das, and T. S. Ustun, "State-of-the-art of controllers and soft computing techniques for regulated load frequency management of single/multi-area traditional and renewable energy based power systems," *Appl. Energy*, vol. 266, May 2020, Art. no. 114858.

[180] A. Moeed Amjad and Z. Salam, "A review of soft computing methods for harmonics elimination PWM for inverters in renewable energy conversion systems," *Renew. Sustain. Energy Rev.*, vol. 33, pp. 141–153, May 2014.

[181] Z. Liu, K. Li, Y. Sun, J. Wang, Z. Wang, K. Sun, and M. Wang, "A steady-state analysis method for modular multilevel converters connected to permanent magnet synchronous generator-based wind energy conversion systems," *Energies*, vol. 11, no. 2, p. 461, Feb. 2018.

[182] J.-H. Fey, F. Hinrichsen, and R. Mallwitz, "Study on the total harmonic distortion of a 5-mw wind turbine with modular multilevel converter and development of a demonstrator," in *Proc. Conf. Sustain. Energy Supply Energy Storage Syst. (NEIS)*, 2017, pp. 1–5.

[183] Y. Gang, G. Yichang, Z. Lidan, L. Dongdong, and L. Xing, "Multi-phase permanent magnet synchronous generator variable speed constant frequency offshore wind system based on modular multilevel converter," in *Proc. IEEE Innov. Smart Grid Technol. Asia (ISGT Asia)*, May 2019, pp. 2127–2132.

[184] F. Shahnazian, J. Adabi, E. Pouresmaeil, and J. P. S. Catalão, "Interfacing modular multilevel converters for grid integration of renewable energy sources," *Electr. Power Syst. Res.*, vol. 160, pp. 439–449, Jul. 2018.

[185] A. António-Ferreira, C. Collados-Rodríguez, and O. Gomis-Bellmunt, "Modulation techniques applied to medium voltage modular multilevel converters for renewable energy integration: A review," *Electr. Power Syst. Res.*, vol. 155, pp. 21–39, Feb. 2018.

[186] Y. Wang, N. Zhang, C. Kang, M. Miao, R. Shi, and Q. Xia, "An efficient approach to power system uncertainty analysis with high-dimensional dependencies," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2984–2994, May 2018.

[187] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, "Application of RBF neural networks and unscented transformation in probabilistic power-flow of microgrids including correlated wind/PV units and plug-in hybrid electric vehicles," *Simul. Model. Pract. Theory*, vol. 72, pp. 51–68, Mar. 2017.

[188] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, "Fuzzy unscented transform for uncertainty quantification of correlated wind/PV microgrids: Possibilistic–probabilistic power flow based on RBFNNs," *IET Renew. Power Gener.*, vol. 11, no. 6, pp. 867–877, May 2017.

[189] A. Zakaria, F. B. Ismail, M. S. H. Lipu, and M. A. Hannan, "Uncertainty models for stochastic optimization in renewable energy applications," *Renew. Energy*, vol. 145, pp. 1543–1571, Jan. 2020.

[190] J. Gottschall and J. Peinke, "How to improve the estimation of power curves for wind turbines," *Environ. Res. Lett.*, vol. 3, no. 1, Jan. 2008, Art. no. 015005.

[191] T. Jin and Z. Tian, "Uncertainty analysis for wind energy production with dynamic power curves," in *Proc. IEEE 11th Int. Conf. Probabilistic Methods Appl. Power Syst.*, Jun. 2010, pp. 745–750.

[192] J. Yan, H. Zhang, Y. Liu, S. Han, and L. Li, "Uncertainty estimation for wind energy conversion by probabilistic wind turbine power curve modelling," *Appl. Energy*, vol. 239, pp. 1356–1370, Apr. 2019.

[193] X. Shang, Z. Li, J. Zheng, and Q. H. Wu, "Equivalent modeling of active distribution network considering the spatial uncertainty of renewable energy resources," *Int. J. Electr. Power Energy Syst.*, vol. 112, pp. 83–91, Nov. 2019.

[194] F. Verastegui, A. Lorca, D. E. Olivares, M. Negrete-Pincetic, and P. Gazmuri, "An adaptive robust optimization model for power systems planning with operational uncertainty," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 4606–4616, Nov. 2019.

[195] K. Tian, W. Sun, D. Han, and C. Yang, "Coordinated planning with predetermined renewable energy generation targets using extended two-stage robust optimization," *IEEE Access*, vol. 8, pp. 2395–2407, 2020.

[196] J. Yi, P. F. Lyons, P. J. Davison, P. Wang, and P. C. Taylor, "Robust scheduling scheme for energy storage to facilitate high penetration of renewables," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 797–807, Apr. 2016.

[197] A. Monticelli, "Electric power system state estimation," *Proc. IEEE*, vol. 88, no. 2, pp. 262–282, Feb. 2000.

[198] J. Ostrowski, M. F. Anjos, and A. Vannelli, "Tight mixed integer linear programming formulations for the unit commitment problem," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 39–46, Feb. 2012.

[199] H. Quan, D. Srinivasan, and A. Khosravi, "Integration of renewable generation uncertainties into stochastic unit commitment considering reserve and risk: A comparative study," *Energy*, vol. 103, pp. 735–745, May 2016.

[200] J. Devlin, K. Li, P. Higgins, and A. Foley, "The importance of gas infrastructure in power systems with high wind power penetrations," *Appl. Energy*, vol. 167, pp. 294–304, Apr. 2016.

[201] F. Fallahi and P. Maghouli, "Integrated unit commitment and natural gas network operational planning under renewable generation uncertainty," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105647.

[202] M. Melamed, A. Ben-Tal, and B. Golany, "A multi-period unit commitment problem under a new hybrid uncertainty set for a renewable energy source," *Renew. Energy*, vol. 118, pp. 909–917, Apr. 2018.

[203] H. Quan, D. Srinivasan, A. M. Khambadkone, and A. Khosravi, "A computational framework for uncertainty integration in stochastic unit commitment with intermittent renewable energy sources," *Appl. Energy*, vol. 152, pp. 71–82, Aug. 2015.

[204] C. Li, W. Wang, J. Wang, and D. Chen, "Network-constrained unit commitment with RE uncertainty and PHES by using a binary artificial sheep algorithm," *Energy*, vol. 189, Dec. 2019, Art. no. 116203.

[205] A. Ahmadi, A. Esmaeel Nezhad, P. Siano, B. Hredzak, and S. Saha, "Information-gap decision theory for robust security-constrained unit commitment of joint renewable energy and gridable vehicles," *IEEE Trans. Ind. Informat.*, vol. 16, no. 5, pp. 3064–3075, May 2020.

[206] R. Jiang, J. Wang, and Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 800–810, May 2012.

[207] C. Zhao and Y. Guan, "Data-driven stochastic unit commitment for integrating wind generation," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 2587–2596, Jul. 2016.

[208] C. C. Carøe, A. Ruszczynski, and R. Schultz, "Unit commitment under uncertainty via two-stage stochastic programming," Citeseer, Tech. Rep., 1997. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=3AD5502AE9A259756C1A6848B6B73057?doi=10.1.1.55.9828&rep=rep1&type=pdf

[209] J. Hetzer, D. C. Yu, and K. Bhattarai, "An economic dispatch model incorporating wind power," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 603–611, Jun. 2008.

[210] X. Liu and W. Xu, "Economic load dispatch constrained by wind power availability: A here-and-now approach," *IEEE Trans. Sustain. Energy*, vol. 1, no. 1, pp. 2–9, Apr. 2010.

[211] J. M. Lujano-Rojas, G. J. Osório, and J. P. S. Catalão, "New probabilistic method for solving economic dispatch and unit commitment problems incorporating uncertainty due to renewable energy integration," *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 61–71, Jun. 2016.

[212] E. A. Bakirtzis, C. K. Simoglou, P. N. Biskas, and A. G. Bakirtzis, "Storage management by rolling stochastic unit commitment for high renewable energy penetration," *Electr. Power Syst. Res.*, vol. 158, pp. 240–249, May 2018.
[213] J. Lavaei and S. H. Low, "Zero duality gap in optimal power flow problem," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 92–107, Feb. 2012.
[214] M. Wang-Hansen, R. Josefsson, and H. Mehmedovic, "Frequency controlling wind power modeling of control strategies," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 954–959, Oct. 2013.
[215] D. Ochoa and S. Martinez, "Frequency dependent strategy for mitigating wind power fluctuations of a doubly-fed induction generator wind turbine based on virtual inertia control and blade pitch angle regulation," *Renew. Energy*, vol. 128, pp. 108–124, Dec. 2018.
[216] X. Lyu, J. Zhao, Y. Jia, Z. Xu, and K. Po Wong, "Coordinated control strategies of PMSG-based wind turbine for smoothing power fluctuations," *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 391–401, Jan. 2019.
[217] J. Ouyang, M. Li, Z. Zhang, and T. Tang, "Multi-timescale active and reactive power-coordinated control of large-scale wind integrated power system for severe wind speed fluctuation," *IEEE Access*, vol. 7, pp. 51201–51210, 2019.
[218] Q. Jiang and H. Wang, "Two-Time-Scale coordination control for a battery energy storage system to mitigate wind power fluctuations," *IEEE Trans. Energy Convers.*, vol. 28, no. 1, pp. 52–61, Mar. 2013.
[219] X. Chen, W. Cao, Q. Zhang, S. Hu, and J. Zhang, "Martificial intelligence-aided model predictive control for a grid-tied wind-hydrogen-fuel cell system," *IEEE Access*, vol. 7, pp. 51301–51310, 2020.
[220] X. Liu, P. Paritosh, N. M. Awalgaonkar, I. Bilionis, and P. Karava, "Model predictive control under forecast uncertainty for optimal operation of buildings with integrated solar systems," *Sol. Energy*, vol. 171, pp. 953–970, Sep. 2018.
[221] M. A. Mahmud, M. J. Hossain, H. R. Pota, and N. K. Roy, "Robust nonlinear controller design for three-phase grid-connected photovoltaic systems under structured uncertainties," *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1221–1230, Jun. 2014.
[222] M. R. Mozafar, M. H. Moradi, and M. H. Amini, "A simultaneous approach for optimal allocation of renewable energy sources and electric vehicle charging stations in smart grids based on improved GA-PSO algorithm," *Sustain. Cities Soc.*, vol. 32, pp. 627–637, Jul. 2017.
[223] K. Gholami and E. Dehnavi, "A modified particle swarm optimization algorithm for scheduling renewable generation in a micro-grid under load uncertainty," *Appl. Soft Comput.*, vol. 78, pp. 496–514, May 2019.
[224] C. Bu, W. Luo, T. Zhu, R. Yi, and B. Yang, "Species and memory enhanced differential evolution for optimal power flow under double-sided uncertainties," *IEEE Trans. Sustain. Comput.*, vol. 5, no. 3, pp. 403–415, Jul. 2020.
[225] N. H. Awad, M. Z. Ali, R. Mallipeddi, and P. N. Suganthan, "An efficient differential evolution algorithm for stochastic OPF based active–reactive power dispatch problem considering renewable generators," *Appl. Soft Comput.*, vol. 76, pp. 445–458, Mar. 2019.
[226] A. Masoumi, S. Ghassem-zadeh, S. H. Hosseini, and B. Z. Ghavidel, "Application of neural network and weighted improved PSO for uncertainty modeling and optimal allocating of renewable energies along with battery energy storage," *Appl. Soft Comput.*, vol. 88, Mar. 2020, Art. no. 105979.
[227] R. R. Nejad, S. M. Hakimi, and S. M. M. Tafreshi, "Smart virtual energy storage control strategy to cope with uncertainties and increase renewable energy penetration," *J. Energy Storage*, vol. 6, pp. 80–94, May 2016.
[228] G. Giannakoudis, A. I. Papadopoulos, P. Seferlis, and S. Voutetakis, "Optimum design and operation under uncertainty of power systems using renewable energy sources and hydrogen storage," *Int. J. Hydrogen Energy*, vol. 35, no. 3, pp. 872–891, Feb. 2010.
[229] A. Nikoobakht, J. Aghaei, M. Shafie-Khah, and J. P. S. Catalao, "Assessing increased flexibility of energy storage and demand response to accommodate a high penetration of renewable energy sources," *IEEE Trans. Sustain. Energy*, vol. 10, no. 2, pp. 659–669, Apr. 2019.
[230] N. Li, C. Uckun, E. M. Constantinescu, J. R. Birge, K. W. Hedman, and A. Botterud, "Flexible operation of batteries in power system scheduling with renewable energy," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 685–696, Apr. 2016.
[231] U. Akram, R. Shah, and N. Mithulananthan, "Hybrid energy stoarage system for frequency regulation in microgrids with source and load uncertainties," *IET Gener., Transmiss. Distrib.*, vol. 13, no. 22, pp. 5048–5057, Nov. 2019.
[232] E. Oh and S.-Y. Son, "Theoretical energy storage system sizing method and performance analysis for wind power forecast uncertainty management," *Renew. Energy*, vol. 155, pp. 1060–1069, Aug. 2020.
[233] J. Wu, B. Zhang, H. Li, Z. Li, Y. Chen, and X. Miao, "Statistical distribution for wind power forecast error and its application to determine optimal size of energy storage system," *Int. J. Electr. Power Energy Syst.*, vol. 55, pp. 100–107, Feb. 2014.
[234] P. Yang and A. Nehorai, "Joint optimization of hybrid energy storage and generation capacity with renewable energy," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1566–1574, Jul. 2014.
[235] E. Oh and S.-Y. Son, "Energy-storage system sizing and operation strategies based on discrete Fourier transform for reliable wind-power generation," *Renew. Energy*, vol. 116, pp. 786–794, Feb. 2018.

MD. SHAFIUL ALAM received the B.Sc. degree in electrical and electronic engineering (EEE) from the Dhaka University of Engineering and Technology, Gazipur, Bangladesh, the M.Sc. degree in EEE from the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, and the Ph.D. degree in electrical engineering from the King Fahd University of Petroleum & Minerals (KFUPM), Saudi Arabia. He started his career as a Faculty Member at the Department of EEE, International Islamic University Chittagong (IIUC), Bangladesh, in August 2008, where his height rank was an Associate Professor in the Department. He is currently working as a Postdoctoral Fellow with the K.A.CARE Energy Research & Innovation Center (ERIC), KFUPM. He worked on several funded projects during Ph.D. research. His research interests include renewable energy sources integration into the utility grid, AC/DC microgrids, high voltage DC transmission, voltage source converter control, fault current limiter, optimization algorithms, such as PSO, GA, WOA, and so on, application in the power systems, fuzzy logic, neural networks, and machine learning. He is also a member of the Institution of Engineers Bangladesh (IEB). He received Best Paper Award in IEEE International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT) in 2014.

FAHAD SALEH AL-ISMAIL (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering from the King Fahd University of Petroleum & Minerals (KFUPM), Dhahran, Saudi Arabia, in 2009 and 2012, respectively, and the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in December 2016. He is currently the Director of the Center for Environment & Water (CEW), Research Institute (RI), and an Assistant Professor with the Department of Electrical Engineering, KFUPM. Before, he was appointed as the Director of CEW, he was the Director of Energy Research and Innovation Center, KFUPM, sponsored by the King Abdullah City for Atomic & Renewable Energy (K.A.CARE), from January 2019 to August 2020. He offers various courses on energy efficiency, demand-side management, power system operation and control, and power system planning. His research interests include power system planning and reliability, renewable energy integration, energy storage system planning and operation, demand-side management modeling with intermittent resources, and uncertainty representation of renewable energy.

ABOUBAKR SALEM (Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering from Helwan University, Egypt, in 2004 and 2009, respectively, and the Ph.D. degree from Ghent University, Belgium, in 2015. He is currently working as a Visiting Assistant Professor with the Department of EE, King Fahd University of Petroleum & Minerals. He is involved in several funded projects from KFUPM as a PI and a Co-I. He has participated as a Co-I in funded projects from European Union (i.e., STS-Med and Euro-Sun-Med) with a fund of € 20 million. His research interests include power electronic converters design and control, electrical drives applications, renewable energy integration, electrical vehicles, and smart grid applications.

MOHAMMAD A. ABIDO (Senior Member, IEEE) received the B.Sc. (Hons.) and M.Sc. degrees in electrical engineering from Menoufia University, Shebeen El-Kom, Egypt, in 1985 and 1989, respectively, and the Ph.D. degree from the King Fahd University of Petroleum & Minerals (KFUPM), Dhahran, Saudi Arabia, in 1997. He is currently a Distinguished University Professor with KFUPM and a Senior Researcher with the K.A.CARE Energy Research & Innovation Center, Dhahran. He has published two books and more than 350 articles in reputable journals and international conferences. He has participated in over 50 funded projects and supervised over 50 M.S. and Ph.D. students. His research interests include power system stability, planning, operation, and optimization techniques applied to power systems. He was a recipient of the KFUPM Excellence in Research Award in 2002, 2007, and 2012, the KFUPM Best Project Award in 2007 and 2010, the First Prize Paper Award of the Industrial Automation and Control Committee of the IEEE Industry Applications Society in 2003, the Abdel-Hamid Shoman Prize for Young Arab Researchers in Engineering Sciences in 2005, the Best Applied Research Award of the 15th GCC-CIGRE Conference, Abu Dhabi, United Arab Emirates, in 2006, and the Best Poster Award from the International Conference on Renewable Energies and Power Quality (ICREPQ'13), Bilbao, Spain, in 2013. He had been awarded the Almarai Prize for Scientific Innovation from 2017 to 2018, as a Distinguished Scientist, Saudi Arabia, in 2018, and the Khalifa Award for Higher Education from 2017 to 2018, as a Distinguished University Professor in Scientific Research, Abu Dhabi, in 2018.

• • •