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

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**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, and control of converter.

## Nomenclature

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

SCIG	Squirrel case induction generator
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

**N**OWADAYS, 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].

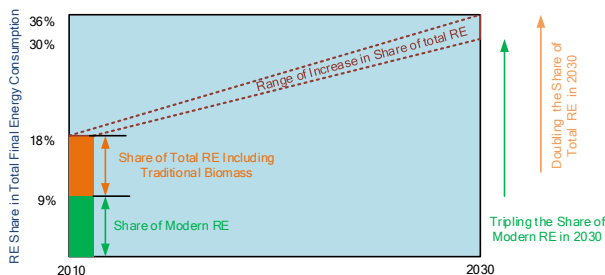


FIGURE 1. A roadmap for renewable power generation by 2030

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.

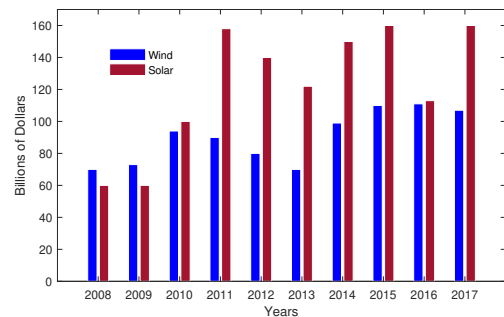


FIGURE 2. wind and solar power worldwide investment

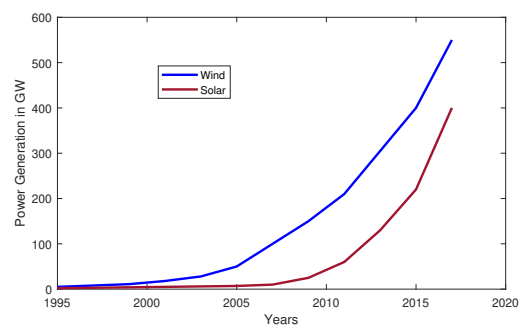


FIGURE 3. wind and solar power worldwide power generation

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 im-

portances, 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].

$$P_{mech} - P_{elet} = J\omega \frac{d\omega}{dt} \quad (1)$$

where,  $P_{mech}$  is the mechanical power input to the machine,  $P_{elet}$  is the electrical power,  $J$  is the moment of inertia,  $\omega$  is the system frequency in rad/sec. The strength of the power system, either weak or strong, can be understood with the

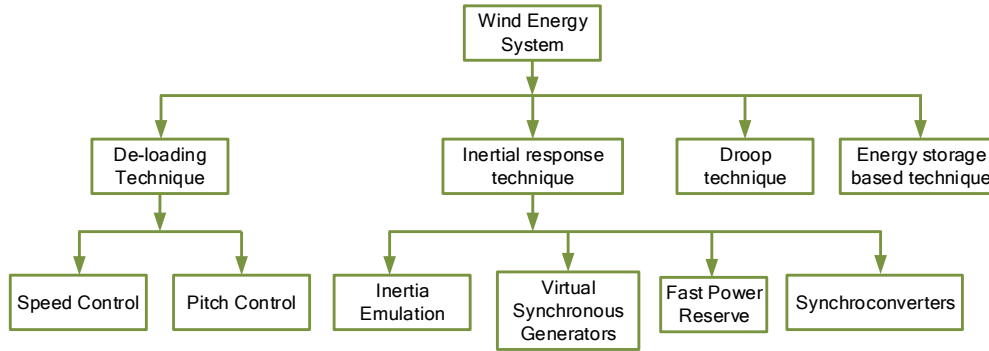


FIGURE 4. Inertia and frequency support techniques by wind system

total inertia of the system as represented by the following equation.

$$H = \frac{J\omega}{2S} \quad (2)$$

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

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

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

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.

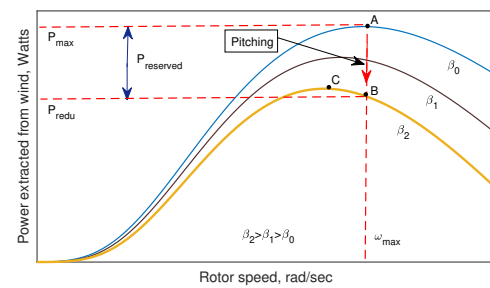


FIGURE 5. De-loading techniques for wind turbine by pitch control

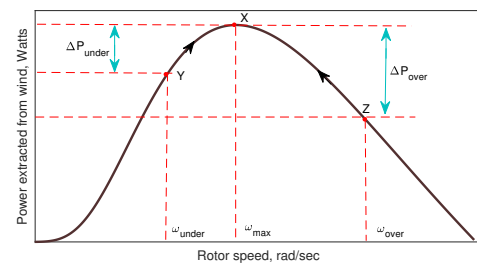


FIGURE 6. De-loading techniques for wind turbine by speed control

As shown in Figure 5, pitch control is achieved by increasing pitch angle from some lower value,  $\beta_0$ , to some higher value,  $\beta_2$ , for a constant wind speed, corresponding to rotor speed at maximum power point,  $\omega_{max}$ . 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].

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,  $\omega_{over}$ , 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,  $\omega_{max}$ . Thus, shifting the operating point from Z to X provides additional reserve power,  $\Delta P_{over}$ , during frequency instability due to generation and load mismatch. In latter one, see Figure 6, rotor speed is controlled to somewhat lower value,  $\omega_{under}$ , which is below the maximum power point speed,  $\omega_{max}$ . Thus, operation of wind generator at this point has a reserve power,  $\Delta P_{over}$ . However, over-speed control mode is preferable than under-speed control mode, since in latter one, speed is increased from  $\omega_{under}$  to  $\omega_{max}$  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]. 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.

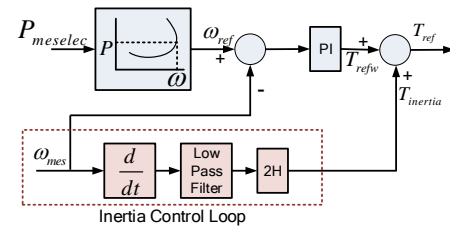


FIGURE 7. Inertia emulation techniques one-loop control

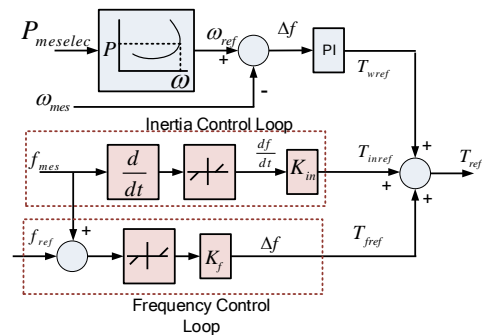


FIGURE 8. Inertia emulation techniques two-loop control

As shown in Figure 7, MPPT controller loop determines the reference speed of the rotor,  $\omega_{ref}$ , 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.

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.

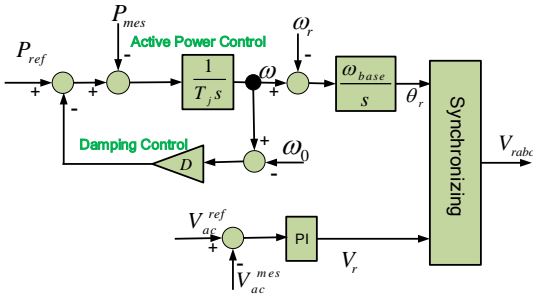


FIGURE 9. Synchroconverter control for DFIG based wind system for inertia support

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  $\omega$  via the virtual inertia. Phase angle i.e. the rotor voltage angle, for synchronization, is obtained by direct integration of slip frequency,  $\omega_{slip}$ .

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.

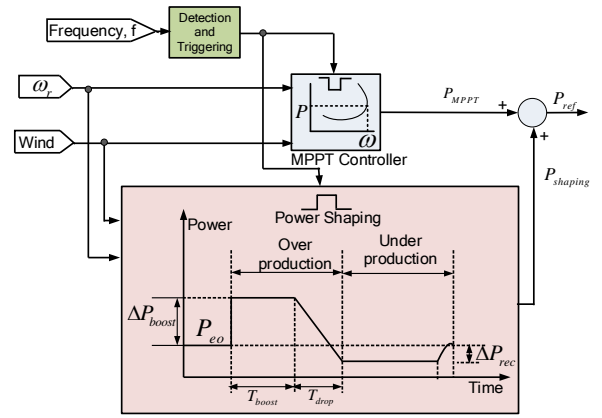


FIGURE 10. Fast power reserve technique for frequency support

### 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.

$$\Delta P_{droop} = K_{droop} \Delta f \quad (5)$$

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 ( $\Delta K_{droop}$ ) 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.

$$\Delta P = P_{low} - P_{high} = -\frac{\omega_{high} - \omega_{low}}{R} \quad (6)$$

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

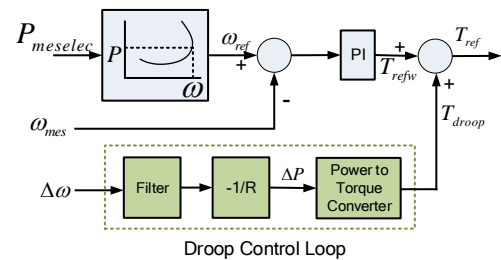


FIGURE 11. Droop control technique for wind system

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 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.

## 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.

### 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 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.

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

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

$$\Delta p_{freq}^{ref} = \Delta f / R_{pv} + 2H_{pv}\dot{f} \quad (8)$$

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

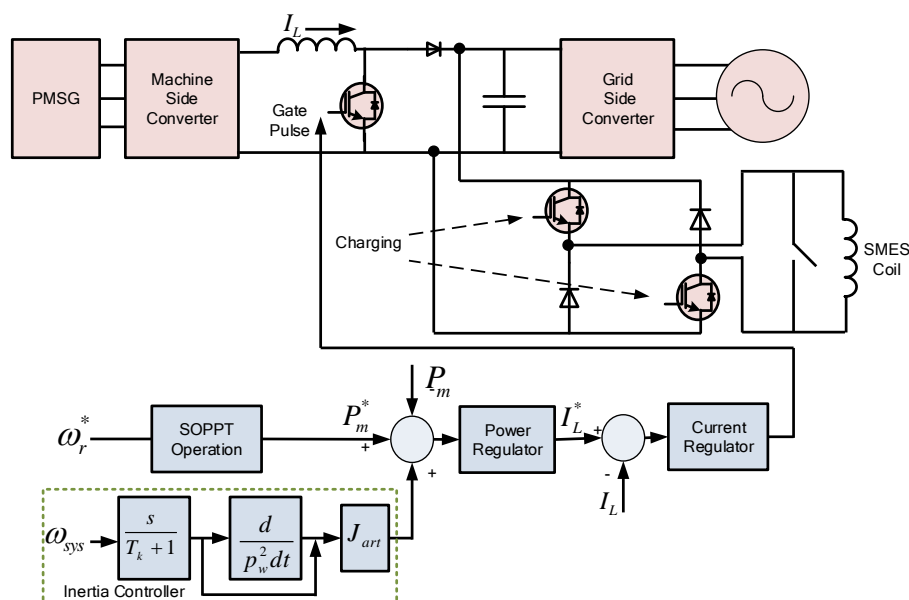
### 2) De-loading technique

The PV system can provide reserve and support system frequency by de-loading 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  $P_{max} - P_{deloaded}$ .

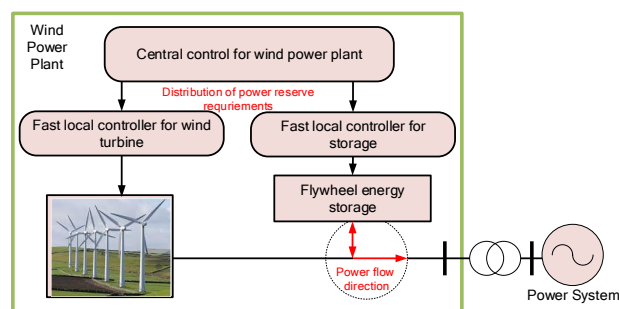
The de-loading technique as presented in [79] is shown in Figure 17. As shown, the PV output power depends on both  $V_{MPP}$  and system frequency deviation  $\Delta f$  which is given by the following equation.

$$V_{dc}^{ref} = V_{MPP} + V_{deloaded} - V_{dc}\Delta f \quad (9)$$

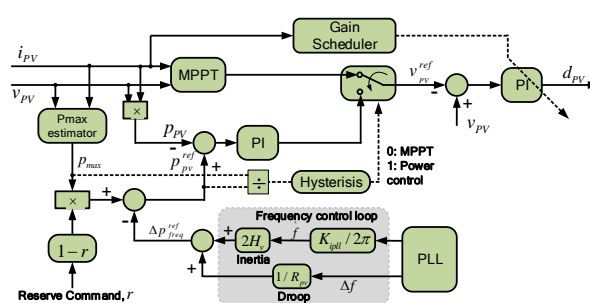
However, the controller presented in Figure 17 has non-uniform distribution of frequency regulation. This mainly happens for same amount of power release from the PV units



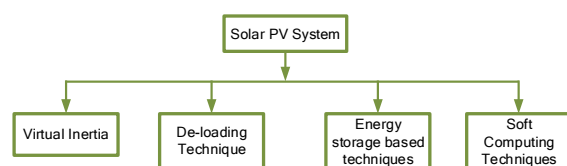
**FIGURE 12.** Energy storage based frequency support for PMSG wind system



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

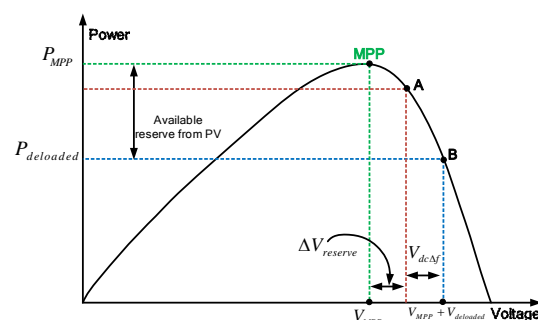


**FIGURE 15.** Primary frequency regulation and inertia emulation by PV



**FIGURE 14.** Frequency and inertia support by PV system

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



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

controller is given by the following equation.

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



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

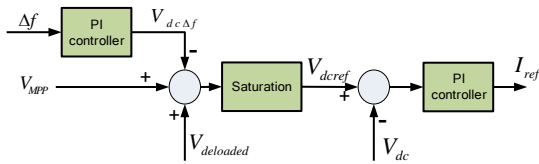


FIGURE 17. PV system deloading controller

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.

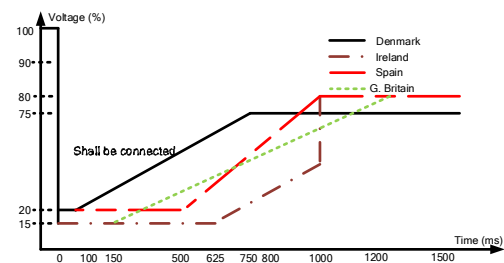


FIGURE 18. Grid code for different countries

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.

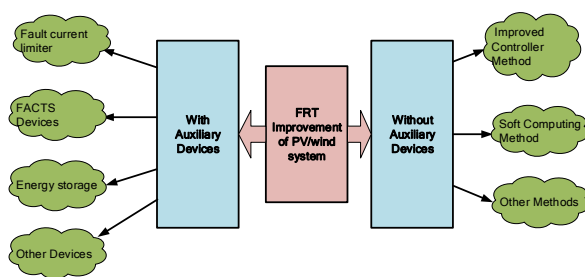


FIGURE 19. FRT improvement techniques of different renewable energy systems

As shown in Figure 19, different auxiliary devices, such as fault current limiter, 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 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, superconducting 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 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.

**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 Combined feed-forward and feed-back control Hybrid control	Reduced oscillation of DC link voltage and torque Improved transient performance Improvement of both low and high voltage ride through	Increased cost and complexity Dynamic voltage restorer (DVR) needed in grid side PI parameters are not optimized
PMSG [96], [102]–[106]	Fault reconfigurable parallel control	improved reliability 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	Not applicable for low inertia PMSG Additional pitch angle controller needed
	Combined vector and direct torque control	removal second-order active power fluctuation Fast transient and smooth steady-state performance	High cost due to use of two controllers
	Composite control structure	Reduction of rotor speed oscillation Reactive power support for grid voltage recovery	Crowbar circuit is mandatory Wind turbine must have 10% over speed capability
	Sugeno fuzzy logic controller Coordinated controller	Less stress on DC link capacitor Quick response, less overshoot, negligible steady-state error Full use of each unit of a hybrid wind farm Improved stability and adaptability No communication required among the wind farms	High power loss in gearbox 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	It needs additional controller for switching between normal mode and LVRT mode
	Comprehensive LVRT strategy	Low overshoot and fast tracking of reference signals 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	Initial assumption of PI parameter may deteriorate controller performance
	Synchronous frame method	Power oscillation is well damped 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	Complex control due to switching different operational modes
	Hybrid pitch angle controller	Active power loss is minimized Hybrid controller is superior over PI controller	High cost than PI due to extra controller
	Coordinated FRT control	Power and frequency oscillations are well damped Abnormal rise of DC link voltage is limited	Double frequency oscillations in reactive power during unsymmetrical fault
	Distributed compensation controller	Smoothing of injected reactive power during symmetrical fault 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 PV array DC link voltage has overshoot
	Reactive power injection method	PCC voltage profile is improved The controller has feasibility to implement in hardware in loop	
	Auto-tuned fuzzy PI approach	Less cost and simple design Minimization rotor over current	Switching is needed for grid side converter controller
	Modified controller	Voltage, power and torque fluctuation reduction Converter protection against over voltage Reactive power support during faults	Switching among different controllers takes long time

#### 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 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 con-

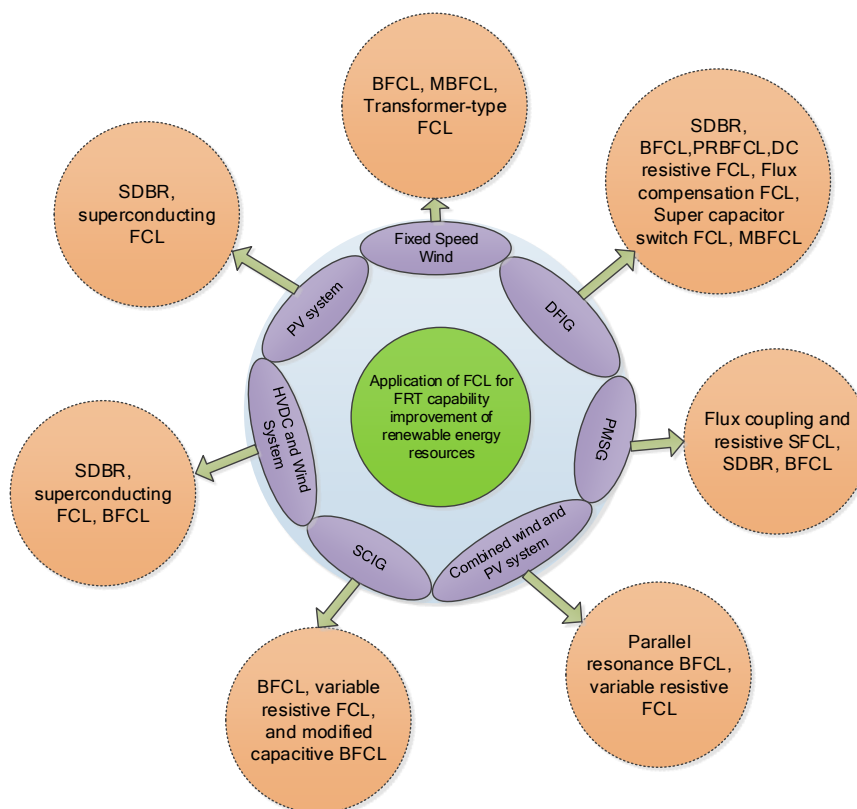


FIGURE 20. FRT improvement of renewable systems with FCLs

troller 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, super-

capacitor, 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



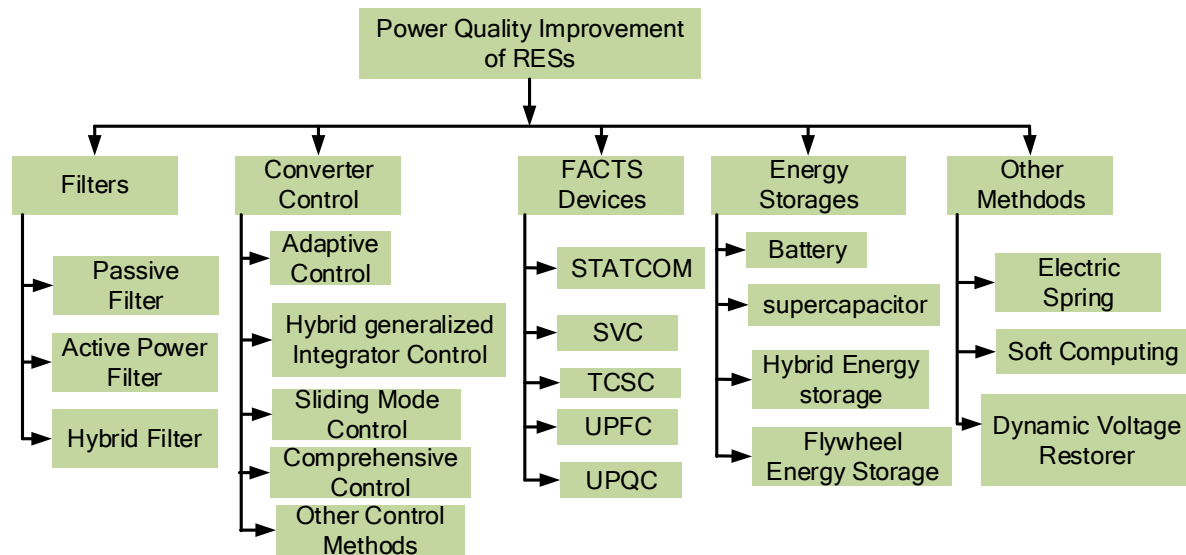


FIGURE 21. Power quality improvement techniques for RESs

TABLE 2. FACTS devices for power quality improvement

FACTS Devices	Contributions	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 deviation 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 mitigate 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

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 possibilistic 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 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

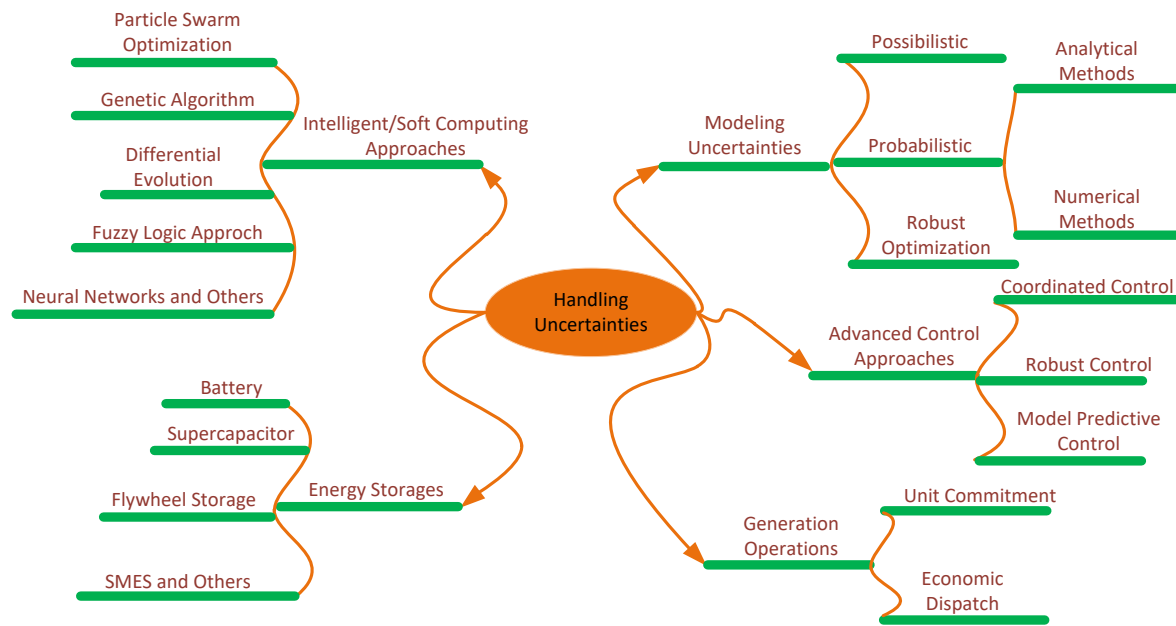


FIGURE 22. Pictorial elaboration of uncertainty mitigation methods

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 evo-

lution (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]. Afterwards, 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 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 con-

sidering 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.

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## 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, 2019.
- [2] A. D. IRENA, "Remap 2030: A renewable energy roadmap," 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," *Electric Power Systems Research*, vol. 130, pp. 89–102, 2016.
- [4] M. E. et al, "Renewables 2018: global status report," *Worldwatch*, 2018.
- [5] M. A. Hossain, H. R. Pota, M. J. Hossain, and F. Blaabjerg, "Evolution of microgrids with converter-interfaced generations: challenges and opportunities," *International Journal of Electrical Power & Energy Systems*, vol. 109, pp. 160–186, 2019.
- [6] M. A. Hossain, H. R. Pota, W. Issa, and M. J. Hossain, "Overview of ac microgrid controls with inverter-interfaced generations," *Energies*, vol. 10, no. 9, p. 1300, 2017.
- [7] Z.-j. Wang and Z.-z. Guo, "Uncertain models of renewable energy sources," *The Journal of Engineering*, vol. 2017, no. 13, pp. 849–853, 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," *Renewable and Sustainable Energy Reviews*, vol. 71, pp. 348–358, 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 *2016 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*. IEEE, 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 *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, 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," *International Journal of Electrical Power & Energy Systems*, vol. 86, pp. 104–119, 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 Generation, Transmission & Distribution*, vol. 12, no. 1, pp. 258–266, 2017.
- [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 Transactions on Power Systems*, vol. 31, no. 3, pp. 1671–1680, 2015.
- [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 Transactions on Smart Grid*, vol. 4, no. 2, pp. 1188–1196, 2012.
- [15] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: A review," *Renewable and sustainable energy reviews*, vol. 69, pp. 144–155, 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," *International Journal of Electrical Power & Energy Systems*, vol. 109, pp. 351–368, 2019.
- [17] S. A. Pourmousavi and M. H. Nehrir, "Real-time central demand response for primary frequency regulation in microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1988–1996, 2012.
- [18] A. Molina-Garcia, F. Bouffard, and D. S. Kirschen, "Decentralized demand-side contribution to primary frequency control," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 411–419, 2010.
- [19] T. S. Borsche, J. de Santiago, and G. Andersson, "Stochastic control of cooling appliances under disturbances for primary frequency reserves," *Sustainable Energy, Grids and Networks*, vol. 7, pp. 70–79, 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 Technology*, vol. 11, pp. 11–17, 2013.
- [21] B. N. Singh, B. Singh, A. Chandra, P. Rastgoufard, and K. Al-Haddad, "An improved control algorithm for active filters," *IEEE Transactions on Power Delivery*, vol. 22, no. 2, pp. 1009–1020, 2007.
- [22] L. Asiminoael, F. Blaabjerg, and S. Hansen, "Detection is key-harmonic detection methods for active power filter applications," *IEEE Industry Applications Magazine*, vol. 13, no. 4, pp. 22–33, 2007.
- [23] L. An, X. Qianming, M. Fujun, and C. Yandong, "Overview of power quality analysis and control technology for the smart grid," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 1, pp. 1–9, 2016.
- [24] E. Hossain, M. R. Tür, 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. 16 816–16 833, 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," *Applied Energy*, vol. 257, p. 114037, 2020.
- [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," *Journal of Cleaner Production*, p. 122117, 2020.
- [27] N. Kumar, P. Besuner, S. Lefton, D. Agan, and D. Hilleman, "Power plant cycling costs tech. rep," *National Renewable Energy Laboratory*, vol. 119, 2012.
- [28] T. S. Borsche, T. Liu, and D. J. Hill, "Effects of rotational inertia on power system damping and frequency transients," in *2015 54th IEEE conference on decision and control (CDC)*. IEEE, 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, 2019.
- [30] S. Yu, L. Zhang, H. H.-C. Iu, T. Fernando, and K. P. Wong, "A dse-based power system frequency restoration strategy for pv-integrated power systems considering solar irradiance variations," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 5, pp. 2511–2518, 2017.
- [31] A. S. Yunus, A. Abu-Siada, M. A. Masoum, M. F. El-Naggar, and J. X. Jin, "Enhancement of dfi lvr capability during extreme short-wind gust events using smes technology," *IEEE Access*, vol. 8, pp. 47 264–47 271, 2020.
- [32] J. Morren, S. W. De Haan, W. L. Kling, and J. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," *IEEE Transactions on power systems*, vol. 21, no. 1, pp. 433–434, 2006.
- [33] M. H. Fini and M. E. H. Golshan, "Frequency control using loads and generators capacity in power systems with a high penetration of renewables," *Electric Power Systems Research*, vol. 166, pp. 43–51, 2019.
- [34] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 7290–7297, 2014.
- [35] U. Tamrakar, D. Shrestha, M. Maharjan, B. P. Bhattarai, T. M. Hansen, and R. Tonkoski, "Virtual inertia: Current trends and future directions," *Applied Sciences*, vol. 7, no. 7, p. 654, 2017.
- [36] M. H. Fini and M. E. H. Golshan, "Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables," *Electric Power Systems Research*, vol. 154, pp. 13–22, 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. Ma and B. Chowdhury, "Working towards frequency regulation with wind plants: combined control approaches," *IET Renewable Power Generation*, vol. 4, no. 4, pp. 308–316, 2010.
- [39] A. Žertek, G. Verbič, and M. Pantoš, "Optimised control approach for frequency-control contribution of variable speed wind turbines," *IET Renewable power generation*, vol. 6, no. 1, pp. 17–23, 2012.
- [40] N. A. Janssens, G. Lambin, and N. Bragard, "Active power control strategies of dfi wind turbines," in *2007 IEEE Lausanne Power Tech*. IEEE, 2007, pp. 516–521.
- [41] G. Ramtharan, N. Jenkins, and J. Ekanayake, "Frequency support from doubly fed induction generator wind turbines," *IET Renewable Power Generation*, vol. 1, no. 1, pp. 3–9, 2007.
- [42] Z. Wu, W. Gao, J. Wang, and S. Gu, "A coordinated primary frequency regulation from permanent magnet synchronous wind turbine generation," in *2012 IEEE Power Electronics and Machines in Wind Applications*. IEEE, 2012, pp. 1–6.
- [43] C. Zhangjie, W. Xiaoru, and T. Jin, "Control strategy of large-scale dfi-based wind farm for power grid frequency regulation," in *Proceedings of the 31st Chinese Control Conference*. IEEE, 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 dfi-es system based on wind speed zone classification and fuzzy logic control," *International Journal of Electrical Power & Energy Systems*, vol. 107, pp. 363–378, 2019.
- [45] T. Kerdpichol, F. Rahman, Y. Mitani, K. Hongesombut, and S. Küfeoğlu, "Virtual inertia control-based model predictive control for microgrid frequency stabilization considering high renewable energy integration," *Sustainability*, vol. 9, no. 5, p. 773, 2017.
- [46] J. Morren, J. Pierik, and S. W. De Haan, "Inertial response of variable speed wind turbines," *Electric power systems research*, vol. 76, no. 11, pp. 980–987, 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 Transactions on Energy conversion*, vol. 19, no. 4, pp. 800–802, 2004.
- [48] L. Wu and D. G. Infield, "Towards an assessment of power system frequency support from wind plant—modeling aggregate inertial response," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2283–2291, 2013.
- [49] Z. Zhang, Y. Wang, H. Li, and X. Su, "Comparison of inertia control methods for dfi-based wind turbines," in *2013 IEEE ECCE Asia Dower*. IEEE, 2013, pp. 960–964.
- [50] F. M. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, "Control of dfi-based wind generation for power network support," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1958–1966, 2005.
- [51] Ö. Göksu, R. Teodorescu, P. Rodriguez, and L. Helle, "A review of the state of the art in control of variable-speed wind turbines," in *9th International Workshop on Large-Scale Integration of Wind Power into Power Systems, Aarhus, Denmark*, 2010.
- [52] D. Jovicic, L. Lamont, and L. Xu, "Vsc transmission model for analytical studies," in *2003 IEEE Power Engineering Society General Meeting (IEEE Cat. No. 03CH37491)*, vol. 3. IEEE, 2003, pp. 1737–1742.
- [53] T. Midsund, J. Suul, and T. Undeland, "Evaluation of current controller performance and stability for voltage source converters connected to a weak grid," in *The 2nd International Symposium on Power Electronics for Distributed Generation Systems*. IEEE, 2010, pp. 382–388.
- [54] Q.-C. Zhong and T. Hornik, *Control of power inverters in renewable energy and smart grid integration*. John Wiley & Sons, 2012, vol. 97.
- [55] S. Wang, J. Hu, and X. Yuan, "Virtual synchronous control for grid-connected dfi-based wind turbines," *IEEE Journal of Emerging and selected topics in power electronics*, vol. 3, no. 4, pp. 932–944, 2015.
- [56] N. R. Ullah, T. Thiringer, and D. Karlsson, "Temporary primary frequency control support by variable speed wind turbines—potential and applications," *IEEE Transactions on Power Systems*, 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," *Renewable Energy*, vol. 68, pp. 326–336, 2014.
- [58] S. El Itani, U. D. Annakkage, and G. Joos, "Short-term frequency support utilizing inertial response of dfi wind turbines," in *2011 IEEE Power and Energy Society General Meeting*. IEEE, 2011, pp. 1–8.
- [59] E. Jahan, M. R. Hazari, S. Mueen, A. Umamura, R. Takahashi, and J. Tamura, "Primary frequency regulation of the hybrid power system by deloaded pmsg-based offshore wind farm using centralised droop controller," *The Journal of Engineering*, 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 *2011 IEEE Power and Energy Society General Meeting*. IEEE, 2011, pp. 1–6.
- [61] R. Josephine and S. Suja, "Estimating pmsg wind turbines by inertia and droop control schemes with intelligent fuzzy controller in indian development," *Journal of Electrical Engineering and Technology*, vol. 9, no. 4, pp. 1196–1201, 2014.



- [62] M. Y. Worku, M. Abido, and R. Iravani, "Power fluctuation minimization in grid connected photovoltaic using supercapacitor energy storage system," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 1, p. 013501, 2016.
- [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 Transactions on Industry Applications*, vol. 51, no. 4, pp. 2732–2742, 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 *2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*. IEEE, 2017, pp. 1–5.
- [65] S. Zhang, Y. Mishra, and M. Shahidepour, "Fuzzy-logic based frequency controller for wind farms augmented with energy storage systems," *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1595–1603, 2015.
- [66] M. Khalid and A. V. Savkin, "An optimal operation of wind energy storage system for frequency control based on model predictive control," *Renewable energy*, vol. 48, pp. 127–132, 2012.
- [67] H. Zhao, Q. Wu, S. Hu, H. Xu, and C. N. Rasmussen, "Review of energy storage system for wind power integration support," *Applied energy*, vol. 137, pp. 545–553, 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 Transactions on industry applications*, vol. 49, no. 4, pp. 1649–1657, 2013.
- [69] N. Mendis, K. 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 Transactions on Industry Applications*, vol. 50, no. 3, pp. 2258–2268, 2013.
- [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 Transactions on Applied Superconductivity*, vol. 29, no. 2, pp. 1–6, 2018.
- [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," *International Journal of Electrical Power & Energy Systems*, vol. 68, pp. 313–326, 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," *Renewable Energy*, vol. 74, pp. 555–567, 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 Transactions on smart grid*, vol. 3, no. 2, pp. 850–857, 2012.
- [74] N. Kakimoto, S. Takayama, H. Satoh, and K. Nakamura, "Power modulation of photovoltaic generator for frequency control of power system," *IEEE Transactions on Energy Conversion*, vol. 24, no. 4, pp. 943–949, 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 Transactions on Sustainable Energy*, vol. 4, no. 4, pp. 985–993, 2013.
- [76] P. Zarina, S. Mishra, and P. Sekhar, "Exploring frequency control capability of a pv system in a hybrid pv-rotating machine-without storage system," *International Journal of Electrical Power & Energy Systems*, vol. 60, pp. 258–267, 2014.
- [77] H. Alatrash, A. Mensah, E. Mark, G. Haddad, and J. Enslin, "Generator emulation controls for photovoltaic inverters," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 996–1011, 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," *Electric Power Systems Research*, vol. 127, pp. 186–196, 2015.
- [79] P. Zarina and S. Mishra, "Power oscillation reduction contribution by pv in deloaded mode," in *2016 IEEE 6th International Conference on Power Systems (ICPS)*. IEEE, 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," *The Journal of Engineering*, vol. 2019, no. 16, pp. 3383–3387, 2019.
- [81] S. Showers and A. Raji, "Frequency regulation of grid connected solar pv system using battery storage system," in *2019 International Conference on the Domestic Use of Energy (DUE)*. IEEE, 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 *IEEE EUROCON 2019-18th International Conference on Smart Technologies*. IEEE, 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 *2016 IEEE Power and Energy Society General Meeting (PESGM)*. IEEE, 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," *Applied Soft Computing*, vol. 85, p. 105823, 2019.
- [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 Transactions on Energy Conversion*, vol. 26, no. 2, pp. 559–571, 2010.
- [86] B. Sakeen, N. K. Bachache, and S. Wang, "Frequency control of pv-diesel hybrid power system using optimal fuzzy logic controller," in *2013 IEEE 11th International Conference on Dependable, Autonomic and Secure Computing*. IEEE, 2013, pp. 174–178.
- [87] R. H. Lasseter, Z. Chen, and D. Pattabiraman, "Grid-forming inverters: A critical asset for the power grid," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 2, pp. 925–935, 2019.
- [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 *2018 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 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 *2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe)*. IEEE, 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 Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 4, pp. 849–858, 2014.
- [91] L. A. F. Ruano, F. Iov, J. A. M. Reos, A. Hansen, and F. Blaabjerg, "Induction generator model in phase coordinates for fault ride-through capability studies of wind turbines," in *2007 European Conference on Power Electronics and Applications, EPE*. EPE Association, 2007.
- [92] M. S. Alam, M. A. Y. Abido, A. E.-D. 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, 2019.
- [93] E. Munkhchuluun, L. Meegahapola, and A. Vahidnia, "Long-term voltage stability with large-scale solar-photovoltaic (pv) generation," *International Journal of Electrical Power & Energy Systems*, vol. 117, p. 105663, 2020.
- [94] M. S. El Moursi, W. Xiao, and J. L. Kirtley Jr, "Fault ride through capability for grid interfacing large scale pv power plants," *IET Generation, Transmission & Distribution*, vol. 7, no. 9, pp. 1027–1036, 2013.
- [95] M. Mohseni, M. A. Masoum, and S. M. Islam, "Low and high voltage ride-through of dfig wind turbines using hybrid current controlled converters," *Electric Power Systems Research*, vol. 81, no. 7, pp. 1456–1465, 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," *Engineering Applications of Artificial Intelligence*, vol. 87, p. 103328, 2020.
- [97] E. Z. Bighash, S. M. Sadeghzadeh, E. Ebrahimzadeh, and F. Blaabjerg, "Improving performance of lvr capability in single-phase grid-tied pv inverters by a model-predictive controller," *International Journal of Electrical Power & Energy Systems*, vol. 98, pp. 176–188, 2018.
- [98] M. J. Morshed and A. Fekih, "A new fault ride-through control for dfig-based wind energy systems," *Electric Power Systems Research*, vol. 146, pp. 258–269, 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 transactions*, vol. 53, no. 3, pp. 827–833, 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 conversion and management*, vol. 78, pp. 88–95, 2014.

- [101] R. A. J. Amalorpavaraj, P. Kaliannan, S. Padmanaban, U. Subramaniam, and V. K. Ramachandaramurthy, "Improved fault ride through capability in dfbg 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 Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 604–614, 2018.
- [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 Transactions on Sustainable Energy*, vol. 8, no. 1, pp. 3–12, 2016.
- [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 Transactions on Energy Conversion*, vol. 34, no. 3, pp. 1287–1295, 2019.
- [105] P. Xing, L. Fu, G. Wang, Y. Wang, and Y. Zhang, "A composite control method of low-voltage ride through for pmsg-based wind turbine generator system," *IET Generation, Transmission & Distribution*, vol. 12, no. 1, pp. 117–125, 2017.
- [106] J. Yao, J. Pei, D. Xu, R. Liu, X. Wang, C. Wang, and Y. Li, "Coordinated control of a hybrid wind farm with dfbg-based and pmsg-based wind power generation systems under asymmetrical grid faults," *Renewable Energy*, vol. 127, pp. 613–629, 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," *Solar Energy*, vol. 159, pp. 665–681, 2018.
- [108] G. B. Huka, W. Li, P. Chao, and S. Peng, "A comprehensive lvr strategy of two-stage photovoltaic systems under balanced and unbalanced faults," *International Journal of Electrical Power & Energy Systems*, vol. 103, pp. 288–301, 2018.
- [109] A. Mojallal and S. Lotfifard, "Enhancement of grid connected pv arrays fault ride through and post fault recovery performance," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 546–555, 2017.
- [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. 124 196–124 206, 2019.
- [111] Y. Wang and B. Ren, "Fault ride-through enhancement for grid-tied pv systems with robust control," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 3, pp. 2302–2312, 2017.
- [112] H. M. Hasanien, "An adaptive control strategy for low voltage ride through capability enhancement of grid-connected photovoltaic power plants," *IEEE Transactions on power systems*, vol. 31, no. 4, pp. 3230–3237, 2015.
- [113] H. Wen and M. Fazeli, "A new control strategy for low-voltage ride-through of three-phase grid-connected pv systems," *The Journal of Engineering*, vol. 2019, no. 18, pp. 4900–4905, 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," *Electric Power Systems Research*, vol. 136, pp. 163–172, 2016.
- [115] K. Naik and C. Gupta, "Improved fluctuation behavior of scig based wind energy system using hybrid pitch angle controller," in *2016 IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics Engineering (UPCON)*. IEEE, 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 *2016 Second International Conference on Computational Intelligence & Communication Technology (CICIT)*. IEEE, 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 Transactions on Power Electronics*, vol. 30, no. 3, pp. 1704–1713, 2014.
- [118] Y. He, M. Wang, and Z. Xu, "Coordinative low-voltage-ride-through control for the wind-photovoltaic hybrid generation system," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2019.
- [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 *2015 IEEE international autumn meeting on power, electronics and computing (ROPEC)*. IEEE, 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 Transactions on Sustainable Energy*, 2019.
- [121] O. Noureldean and A. M. Ibrahim, "Low-voltage ride-through capability enhancement of a grid-connected photovoltaic/wind hybrid power system," in *2017 Nineteenth International Middle East Power Systems Conference (MEPCON)*. IEEE, 2017, pp. 786–795.
- [122] M. S. Alam, M. A. Y. Abido, and I. El-Amin, "Fault current limiters in power systems: A comprehensive review," *Energies*, vol. 11, no. 5, p. 1025, 2018.
- [123] M. S. Alam, M. Abido, and Z. Al-Hamouz, "Model predictive control approach for bridge-type fault current limiter in vsc-hvdc system," *Arabian Journal for Science and Engineering*, vol. 44, no. 3, pp. 2079–2089, 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. 34 431–34 438, 2018.
- [125] C. Huang, X. Y. Xiao, Z. Zheng, and Y. Wang, "Cooperative control of sfcl and smes for protecting pmsg-based wtg s under grid faults," *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 2, pp. 1–6, 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," *Solar Energy*, vol. 180, pp. 340–350, 2019.
- [127] H. Heydari-Doostabad, M. R. Khalghani, and M. H. Khooban, "A novel control system design to improve lvr capability of fixed speed wind turbines using statcom in presence of voltage fault," *International Journal of Electrical Power & Energy Systems*, vol. 77, pp. 280–286, 2016.
- [128] A. Ayyaz and M. Özdemir, "A combined usage of sdbr and svc to improve the transient stability performance of a pv/wind generation system," in *2016 National Conference on Electrical, Electronics and Biomedical Engineering (ELECO)*. IEEE, 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 *Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010*. IEEE, 2010, pp. T12–13.
- [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 Transactions on Power Delivery*, vol. 30, no. 3, pp. 1128–1136, 2014.
- [131] M. Y. Worku and M. A. Abido, "Grid-connected pv array with super-capacitor energy storage system for fault ride through," in *2015 IEEE International Conference on Industrial Technology (ICIT)*. IEEE, 2015, pp. 2901–2906.
- [132] J. NERC and W. S. Report, "900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report," Tech. Rep., 02 2018.
- [133] ERCOT, "Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid," Tech. Rep., Available at: <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 Transactions on Industry Applications*, vol. 54, no. 4, pp. 3100–3111, 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," *International Journal of Power Electronics*, 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," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 475–488, 2013.
- [137] M. M. Elkholy, M. El-Hameed, and A. El-Fergany, "Harmonic analysis of hybrid renewable microgrids comprising optimal design of passive filters and uncertainties," *Electric Power Systems Research*, vol. 163, pp. 491–501, 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 *2014 International Renewable and Sustainable Energy Conference (IRSEC)*. IEEE, 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," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 635–655, 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 Systems Research*, vol. 177, p. 105957, 2019.

- [141] J. W. Kolar, T. Friedli, J. Rodriguez, and P. W. Wheeler, "Review of three-phase pwm ac-ac converter topologies," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 11, pp. 4988–5006, 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 *The 2010 International Power Electronics Conference-ECCE ASIA-*. IEEE, 2010, pp. 317–322.
- [143] S. Litran and P. Salmeron, "Analysis and design of different control strategies of hybrid active power filter based on the state model," *IET Power Electronics*, vol. 5, no. 8, pp. 1341–1350, 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, 2018.
- [145] L. Qian, D. A. Cartes, and H. Li, "An improved adaptive detection method for power quality improvement," *IEEE Transactions on Industry Applications*, vol. 44, no. 2, pp. 525–533, 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 Transactions on Industry Applications*, vol. 53, no. 5, pp. 4149–4161, 2017.
- [147] F. Chishti, S. Murshid, and B. Singh, "Weak grid inertia wegs with hybrid generalized integrator for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 2, pp. 1113–1123, 2019.
- [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. 76 596–76 605, 2018.
- [149] F. Chishti, S. Murshid, and B. Singh, "Lmmn-based adaptive control for power quality improvement of grid inertia wind-pv system," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 9, pp. 4900–4912, 2019.
- [150] A. S. Bubshait, A. Mortezaei, M. G. Simoes, and T. D. C. Busarello, "Power quality enhancement for a grid connected wind turbine energy system," *IEEE Transactions on Industry Applications*, vol. 53, no. 3, pp. 2495–2505, 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 *2018 IEEE Canadian Conference on Electrical & Computer Engineering (CCECE)*. IEEE, 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*, 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," *Renewable and sustainable energy reviews*, vol. 82, pp. 502–514, 2018.
- [154] A. A. Abdelsalam and A. M. Sharaf, "A novel facts compensation scheme for power quality improvement in wind smart grid," in *2012 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*. IEEE, 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," *International Journal of Engineering Research and Applications*, 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 *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM-2012)*. IEEE, 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 *2015 International Conference on Energy Systems and Applications*. IEEE, pp. 329–332.
- [158] E. Jamil, S. Hameed, B. Jamil et al., "Power quality improvement of distribution system with photovoltaic and permanent magnet synchronous generator based renewable energy farm using static synchronous compensator," *Sustainable Energy Technologies and Assessments*, vol. 35, pp. 98–116, 2019.
- [159] K. S. Thampatty, "Design of mrac based tsc for damping sub-synchronous oscillations in scig based wind farm," in *TENCON 2019-2019 IEEE Region 10 Conference (TENCON)*. IEEE, 2019, pp. 1846–1852.
- [160] H. Kuang, L. Zheng, S. Li, and X. Ding, "Voltage stability improvement of wind power grid-connected system using tscs-statcom control," *IET Renewable Power Generation*, vol. 13, no. 2, pp. 215–219, 2018.
- [161] A. Savić and Ž. Đurišić, "Optimal sizing and location of svc devices for improvement of voltage profile in distribution network with dispersed photovoltaic and wind power plants," *Applied energy*, vol. 134, pp. 114–124, 2014.
- [162] T. Tayebifar, M. Shaker, and M. Aghababae, "Performance comparison of statcom versus svc to improve reactive power control in wind power based dfig under short circuit fault," in *2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER)*. IEEE, 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 *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*. IEEE, 2016, pp. 173–176.
- [164] A. Bhargava, S. Verma et al., "Power quality enhancement using unified power flow controller in grid connected hybrid pv/wind system," in *2019 International Conference on Communication and Electronics Systems (ICCES)*. IEEE, 2019, pp. 2064–2069.
- [165] A. Kalair, N. Abas, A. Kalair, Z. Saleem, and N. Khan, "Review of harmonic analysis, modeling and mitigation techniques," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1152–1187, 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 *2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]*. IEEE, 2015, pp. 1–7.
- [167] M. Chaudhary, P. Tapre, and C. Veeresh, "Enhancement of power quality using upqc in hybrid wind/diesel system with energy storage," in *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*. IEEE, 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," *International Journal of Control, Automation and Systems*, vol. 16, no. 6, pp. 2644–2655, 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 Transactions on power electronics*, vol. 26, no. 12, pp. 3545–3559, 2011.
- [170] V. Behraves, 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," *Solar Energy*, vol. 182, pp. 80–95, 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 *4th International Conference on Power Engineering, Energy and Electrical Drives*. IEEE, 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 *2010 International Conference on Electrical Machines and Systems*. IEEE, 2010, pp. 437–441.
- [173] M. Y. Worku and M. Abido, "Fault ride-through and power smoothing control of pmsg-based wind generation using supercapacitor energy storage system," *Arabian Journal for Science and Engineering*, vol. 44, no. 3, pp. 2067–2078, 2019.
- [174] M. Ding and J. Wu, "A novel control strategy of hybrid energy storage system for wind power smoothing," *Electric Power Components and Systems*, vol. 45, no. 12, pp. 1265–1274, 2017.
- [175] H. Seo, A. Kim, M. Park, and I. Yu, "Power quality enhancement of renewable energy source power network using smes system," *Physica C: Superconductivity and its Applications*, vol. 471, no. 21–22, pp. 1409–1412, 2011.
- [176] P. Mukherjee and V. Rao, "Effective location of smes for power fluctuation mitigation of grid connected doubly fed induction generator," *Journal of Energy Storage*, vol. 29, p. 101369, 2020.
- [177] J. Soni and S. K. Panda, "Electric spring for voltage and power stability and power factor correction," *IEEE Transactions on Industry Applications*, vol. 53, no. 4, pp. 3871–3879, 2017.
- [178] A. Benali, M. Khia, 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. 68 634–68 648, 2018.



- [179] A. Latif, S. 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," *Applied Energy*, vol. 266, p. 114858, 2020.
- [180] A. M. Amjad and Z. Salam, "A review of soft computing methods for harmonics elimination pwm for inverters in renewable energy conversion systems," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 141–153, 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, 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 *NEIS 2017; Conference on Sustainable Energy Supply and Energy Storage Systems*. VDE, 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 *2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*. IEEE, 2019, pp. 2127–2132.
- [184] F. Shahnazian, J. Adabi, E. Pouresmaeil, and J. P. Catalão, "Interfacing modular multilevel converters for grid integration of renewable energy sources," *Electric Power Systems Research*, vol. 160, pp. 439–449, 2018.
- [185] A. Antonio-Ferreira, C. Collados-Rodríguez, and O. Gomis-Bellmunt, "Modulation techniques applied to medium voltage modular multilevel converters for renewable energy integration: A review," *Electric Power Systems Research*, vol. 155, pp. 21–39, 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 Transactions on Power Systems*, vol. 33, no. 3, pp. 2984–2994, 2017.
- [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," *Simulation Modelling Practice and Theory*, vol. 72, pp. 51–68, 2017.
- [188] H. R. Baghaee, M. Morsalim, 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 Renewable Power Generation*, vol. 11, no. 6, pp. 867–877, 2017.
- [189] A. Zakaria, F. B. Ismail, M. H. Lipu, and M. Hannan, "Uncertainty models for stochastic optimization in renewable energy applications," *Renewable Energy*, vol. 145, pp. 1543–1571, 2020.
- [190] J. Gottschall and J. Peinke, "How to improve the estimation of power curves for wind turbines," *Environmental Research Letters*, vol. 3, no. 1, p. 015005, 2008.
- [191] T. Jin and Z. Tian, "Uncertainty analysis for wind energy production with dynamic power curves," in *2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems*. IEEE, 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," *Applied Energy*, vol. 239, pp. 1356–1370, 2019.
- [193] X. Shang, Z. Li, J. Zheng, and Q. Wu, "Equivalent modeling of active distribution network considering the spatial uncertainty of renewable energy resources," *International Journal of Electrical Power & Energy Systems*, vol. 112, pp. 83–91, 2019.
- [194] F. Verástegui, Á. Lorca, D. E. Olivares, M. Negrete-Pincetic, and P. Gazmuri, "An adaptive robust optimization model for power systems planning with operational uncertainty," *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4606–4616, 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*, 2019.
- [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 Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 797–807, 2015.
- [197] A. Monticelli, "Electric power system state estimation," *Proceedings of the IEEE*, vol. 88, no. 2, pp. 262–282, 2000.
- [198] J. Ostrowski, M. F. Anjos, and A. Vannelli, "Tight mixed integer linear programming formulations for the unit commitment problem," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 39–46, 2011.
- [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, 2016.
- [200] J. Devlin, K. Li, P. Higgins, and A. Foley, "The importance of gas infrastructure in power systems with high wind power penetrations," *Applied Energy*, vol. 167, pp. 294–304, 2016.
- [201] F. Fallahi and P. Maghouli, "Integrated unit commitment and natural gas network operational planning under renewable generation uncertainty," *International Journal of Electrical Power & Energy Systems*, vol. 117, p. 105647, 2020.
- [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," *Renewable Energy*, vol. 118, pp. 909–917, 2018.
- [203] H. Quan, D. Srinivasan, A. M. Khamadkone, and A. Khosravi, "A computational framework for uncertainty integration in stochastic unit commitment with intermittent renewable energy sources," *Applied Energy*, vol. 152, pp. 71–82, 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, p. 116203, 2019.
- [205] A. Ahmadi, A. E. 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 Transactions on Industrial Informatics*, vol. 16, no. 5, pp. 3064–3075, 2019.
- [206] R. Jiang, J. Wang, and Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 800–810, 2011.
- [207] C. Zhao and Y. Guan, "Data-driven stochastic unit commitment for integrating wind generation," *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 2587–2596, 2015.
- [208] C. C. Carøe, A. Ruszczyński, and R. Schultz, "Unit commitment under uncertainty via two-stage stochastic programming," 1997.
- [209] J. Hetzer, C. Y. David, and K. Bhattacharai, "An economic dispatch model incorporating wind power," *IEEE Transactions on Energy Conversion*, vol. 23, no. 2, pp. 603–611, 2008.
- [210] X. Liu and W. Xu, "Economic load dispatch constrained by wind power availability: A here-and-now approach," *IEEE Transactions on Sustainable Energy*, vol. 1, no. 1, pp. 2–9, 2010.
- [211] J. Lujano-Rojas, G. Osório, and J. Catalão, "New probabilistic method for solving economic dispatch and unit commitment problems incorporating uncertainty due to renewable energy integration," *International Journal of Electrical Power & Energy Systems*, vol. 78, pp. 61–71, 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," *Electric Power Systems Research*, vol. 158, pp. 240–249, 2018.
- [213] J. Lavaei and S. H. Low, "Zero duality gap in optimal power flow problem," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 92–107, 2011.
- [214] M. Wang-Hansen, R. Josefsen, and H. Mehmedovic, "Frequency controlling wind power modeling of control strategies," *IEEE transactions on sustainable energy*, vol. 4, no. 4, pp. 954–959, 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," *Renewable Energy*, vol. 128, pp. 108–124, 2018.
- [216] X. Lyu, J. Zhao, Y. Jia, Z. Xu, and K. P. Wong, "Coordinated control strategies of pmsg-based wind turbine for smoothing power fluctuations," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 391–401, 2018.
- [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. 51 201–51 210, 2019.
- [218] Q. Jiang and H. Wang, "Two-time-scale coordination control for a battery energy storage system to mitigate wind power fluctuations," *IEEE Transactions on Energy Conversion*, vol. 28, no. 1, pp. 52–61, 2012.
- [219] X. Chen, W. Cao, Q. Zhang, S. Hu, and J. Zhang, "Artificial intelligence-aided model predictive control for a grid-tied wind-

- hydrogen-fuel cell system," *IEEE Access*, vol. 7, pp. 51 301–51 310, 2020.
- [220] X. Liu, P. Paritosh, N. M. Awalganekar, I. Bilionis, and P. Karava, "Model predictive control under forecast uncertainty for optimal operation of buildings with integrated solar systems," *Solar energy*, vol. 171, pp. 953–970, 2018.
- [221] M. Mahmud, M. Hossain, H. Pota, and N. Roy, "Robust nonlinear controller design for three-phase grid-connected photovoltaic systems under structured uncertainties," *IEEE transactions on power delivery*, vol. 29, no. 3, pp. 1221–1230, 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," *Sustainable cities and society*, vol. 32, pp. 627–637, 2017.
- [223] K. Gholami and E. Dehnavi, "A modified particle swarm optimization algorithm for scheduling renewable generation in a micro-grid under load uncertainty," *Applied Soft Computing*, vol. 78, pp. 496–514, 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 Transactions on Sustainable Computing*, 2019.
- [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," *Applied Soft Computing*, vol. 76, pp. 445–458, 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," *Applied Soft Computing*, vol. 88, p. 105979, 2020.
- [227] S. Hakimi, S. M. Tafreshi et al., "Smart virtual energy storage control strategy to cope with uncertainties and increase renewable energy penetration," *Journal of Energy Storage*, vol. 6, pp. 80–94, 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," *International journal of hydrogen energy*, vol. 35, no. 3, pp. 872–891, 2010.
- [229] A. Nikoobakht, J. Aghaei, M. Shafie-Khah, and J. P. Catalão, "Assessing increased flexibility of energy storage and demand response to accommodate a high penetration of renewable energy sources," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 659–669, 2018.
- [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 Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 685–696, 2015.
- [231] U. Akram, R. Shah, and N. Mithulananthan, "Hybrid energy storage system for frequency regulation in microgrids with source and load uncertainties," *IET Generation, Transmission & Distribution*, vol. 13, no. 22, pp. 5048–5057, 2019.
- [232] E. Oh and S.-Y. Son, "Theoretical energy storage system sizing method and performance analysis for wind power forecast uncertainty management," *Renewable Energy*, 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," *International Journal of Electrical Power & Energy Systems*, vol. 55, pp. 100–107, 2014.
- [234] P. Yang and A. Nehorai, "Joint optimization of hybrid energy storage and generation capacity with renewable energy," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1566–1574, 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," *Renewable Energy*, vol. 116, pp. 786–794, 2018.



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