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Article *in* IEEE Access · January 2022

DOI: 10.1109/ACCESS.2022.3174555

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3174555, IEEE Access

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2022.Doi Number

Grid Integration Challenges and Solution Strategies for Solar PV Systems: A Review

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The authors appreciate the research facility provided by the Deanship of Research Oversight and Coordination (DROC) and the Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS) at King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia.

ABSTRACT World leaders and scientists have been putting immense efforts to strengthen energy security and reducing greenhouse gas (GHG) emissions by meeting growing energy demand for the last couple of decades. Their efforts accelerate the need for large-scale renewable energy resources (RER) integration into existing electricity grids. The intermittent nature of the dominant RER, e.g., solar photovoltaic (PV) and wind systems, poses operational and technical challenges in their effective integration by hampering network reliability and stability. This article reviews and discusses the challenges reported due to the grid integration of solar PV systems and relevant proposed solutions. Among various technical challenges, it reviews the non-dispatch-ability, power quality, angular and voltage stability, reactive power support, and fault ride-through capability related to solar PV systems grid integration. Also, it addresses relevant socio-economic, environmental, and electricity market challenges. Finally, it highlights the proposed solution methodologies, including grid codes, advanced control strategies, energy storage systems, and renewable energy policies to combat the discussed challenges. The findings of this article assist the power system scholars and researchers in conducting further research in this field. Furthermore, it helps the decision-makers to choose the appropriate technologies to deal with the anticipated challenges associated with the grid integration of PV systems.

INDEX TERMS Angular and voltage stability; Energy policy; Energy storage systems; Greenhouse gas emissions; Grid code; Grid integration challenges; Intermittency; Review; Solar PV systems.

I. INTRODUCTION

Since the inception of the Kyoto Protocol in 1992, meeting the growing energy demand from safe, secure, and environment-friendly resources has become one of the top priorities for world leaders, researchers, and educators [1]–[6]. Hence, the countries started to substitute conventional fossil fuel-based energy sources with non-conventional and renewable energy resources to attain the mentioned goal and reduce GHG emissions. Besides, the RER can contribute to the world energy economy and strengthen energy security [7]–[12]. Therefore, the world has been observing a surging growth of RER-based energy production in recent years and is expecting to witness their continuous growth in the coming decades [13]–[18]. According to Renewable Energy Policy Network for the 21st Century (REN21) report, global generation capacity from the significant RER, e.g., solar PV and wind energy resources, has been increased to almost 95-fold and 8-fold, respectively, in 2020 compared to the capacity of 2007 [19]–[21]. FIGURE 1 presents the PV and wind power installation capacity growth over the last decade. As can be seen, the solar PV technology surpassed the wind technology in overall installation capacity in 2020. In addition, the technology becomes the most prominent one in terms of added installation capacity, as shown in FIGURE 2 (a). Percentage growth in added installation capacity of the major RER technologies is stacked in FIGURE 2 (b). It is evident from the presented data that solar PV stands for the lion's share of total RER growth for the last couple of years, followed by wind power, hydropower, and bio-power. Other RER technologies, including concentrated solar power (CSP), geothermal, and ocean power, are being added at a significantly slower rate [19]–[25]. The Asia Pacific region is leading the world, followed by the European and North American regions regarding total PV installation capacity until 2020, as presented in FIGURE 3 (a) [26]. Other regions have just started their installations in recent years.

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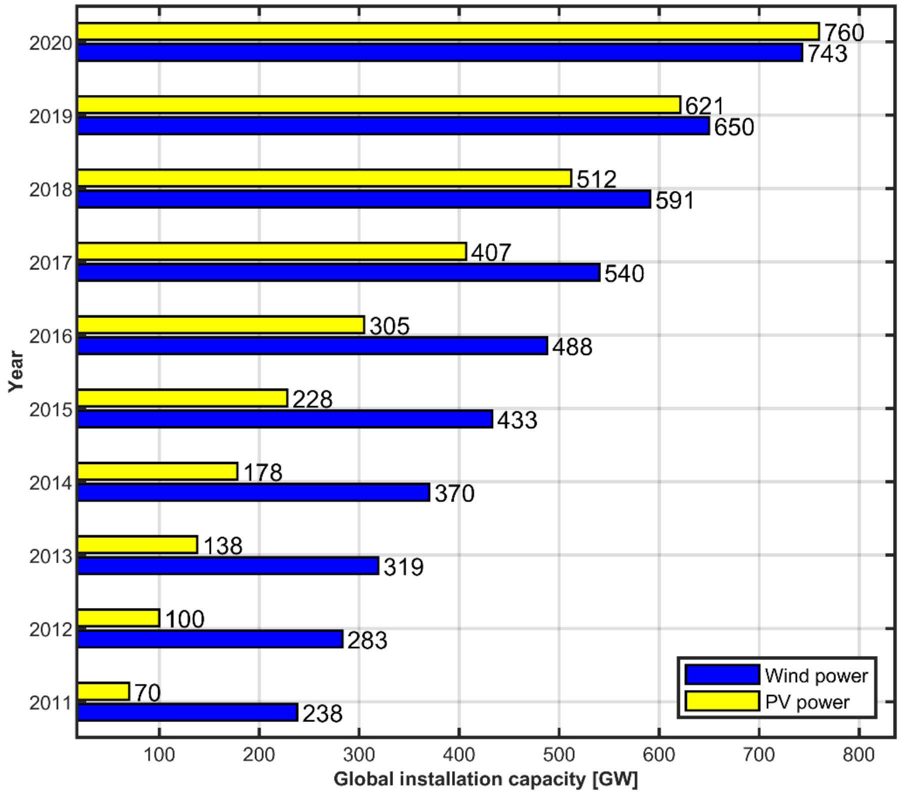
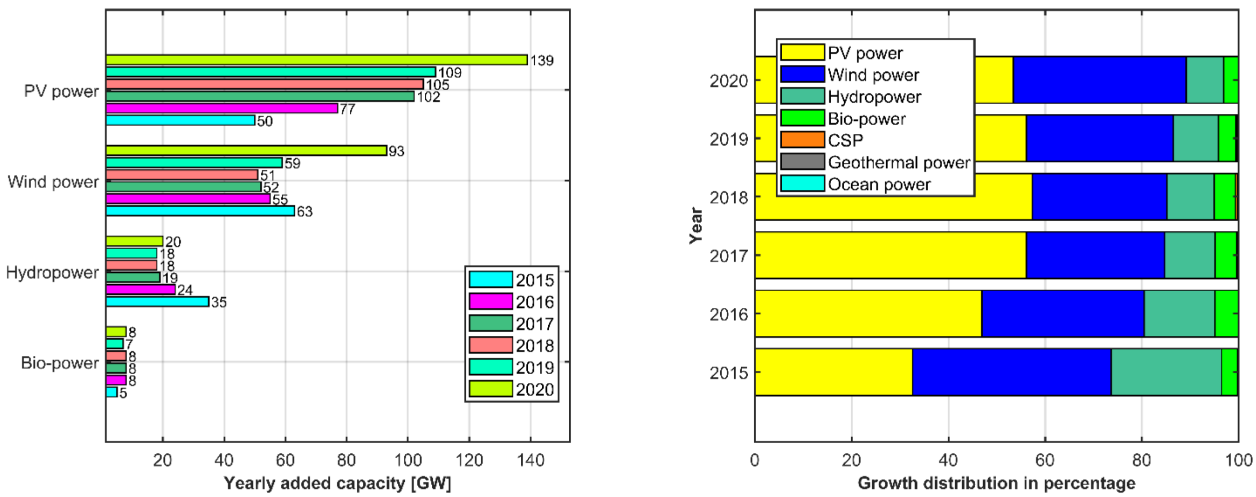


FIGURE 1. Global wind and PV installed power generation capacity from 2011 to 2020 [19]–[25].



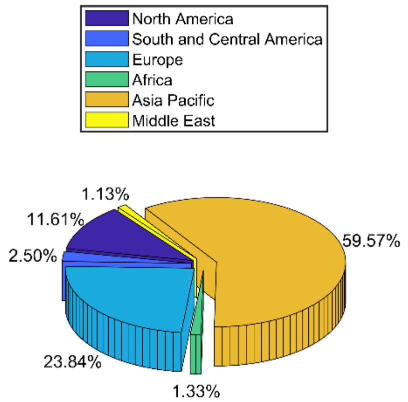
(a) Yearly added generation capacity of prominent RER

(b) Yearly RER growth distribution in percentage

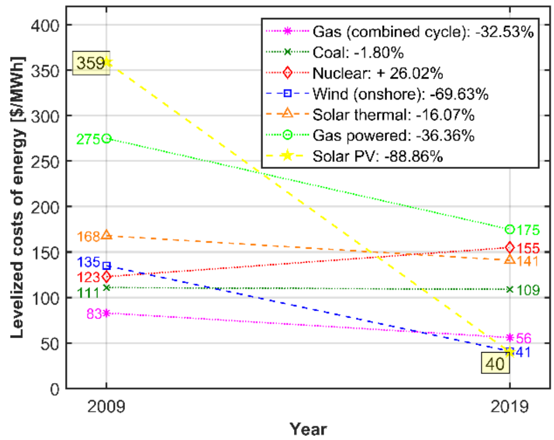
FIGURE 2. Yearly capacity addition and growth percentage of RER technology from 2015 to 2020 [19]–[25].

The modular nature and declining price of solar PV and wind energy technologies drive their comparatively faster growth over other RER [27]. In addition, technological advancement due to continuous investments in research plays a vital role in reducing the Levelized Costs of Energy (LCOE) and their integration into the electric grids. A comparison of LCOE for the prominent renewable and non-renewable electricity generation technologies from 2009 to 2019 is shown in FIGURE 3 (b) [28]. As can be seen, the LCOE for solar PV declined by almost 88.86% (359 \$/MWh in 2009 to 40 \$/MWh in 2019) in a decade, making it one of the cheapest electricity-generating technologies. In contrast, the LCOEs for the non-renewable resources were not reduced significantly; instead, the LCOE for the nuclear-based electricity production cost was increased by 26.02%. Besides, solar PV has also become competitive with other cheaper renewables, including hydropower and bio-power [29].

However, the intermittent nature of wind speed and solar irradiation due to climactic conditions can create a wide range of operational and protection challenges for electricity grids. Besides, the networks' power quality, reliability, and stability may also be hampered due to the bulk intermittent energy integration if timely appropriate measures are not taken [30]–[33]. Furthermore, load demand and RER power generation compatibility, transmission infrastructure and congestion, grid flexibility and resiliency, electricity market mechanism, and policies may lead to curtailment of installed RER. FIGURE 4 shows wind and solar PV power curtailment for the California Independent System Operator (CAISO) and China Electric Grid (CEG) from the year 2014 to 2020 [34]. According to Refs. [34]–[40], wind energy curtailment is much higher than PV energy curtailment in CEG, whereas PV energy curtailment in CAISO is more significant than wind energy curtailment. However, the RER curtailment in European countries like Germany, Spain, and Denmark is not that big as these countries consume RER-generated power locally. In contrast, China transmits the RER-generated power through a high voltage line too long distances [41]. In response, the power system researchers are coming forward and proposing advanced technologies and solution methodologies to combat the anticipated RER grid integration challenges, considering the mentioned notes.

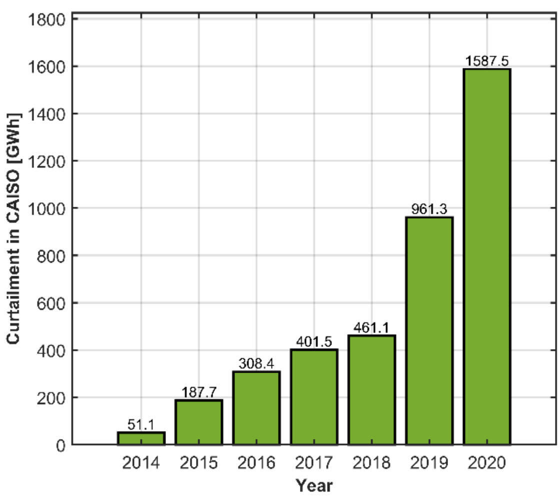


(a) Region-wise PV power installation share in percentage till 2020 [42].

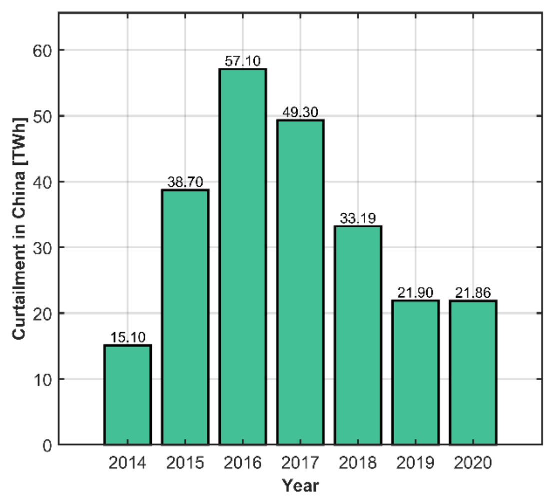


(b) Levelized costs of energy comparison from 2009 to 2019 [28].

FIGURE 3. Region-wise percentage PV share and technology-wise LOCE comparison.



(a) CAISO RER Curtailment (GWh) [34].



(b) CEG RER Curtailment (GWh) [35]–[40].

FIGURE 4. Wind and solar PV power curtailment for CAISO and CEG.

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To keep the decision-makers, research community, and newcomers in the field of renewable energy grid integration, a good number of review articles have been emerged in the renowned scientific outlets [43]–[58]. However, in most cases, those articles reviewed and discussed technical challenges and relevant solutions related to renewable energy grid integration only. In other cases, they addressed a specific challenge such as power prediction, fault ride-through capability, protection, power quality, and grid code requirements. A review consisting of the summary of techno-economic and socio-environmental grid integration challenges of PV systems with proper guidelines and solutions (grid codes, control strategies, and policies) can be found rarely. Recently, such a review on the wind energy grid integration challenges and available solutions was reported in [33], and there is no such summary article on the solar PV grid integration issues. Therefore, the prime motivation of this article is to summarize the reported challenges encountered due to the grid integration of the solar PV systems and available solution methodologies. The main contributions of this article are:

- It reviews and presents the grid integration challenges of solar PV systems. Among many challenges, the non-dispatch-ability, voltage, frequency, angular stability, power quality, reactive power support, fault ride-through capability, electricity market penetration, and socio-economic and environmental issues are addressed.
- It also sheds light on the proposed solutions, including grid codes, advanced control strategies, energy storage systems, and renewable energy policies to combat the discussed challenges and promote solar PV technologies.
- The findings of this article motivate the power system scholars and researchers to conduct further research and development in this field. It also helps the power system decision-makers choose the appropriate technologies in dealing with the discussed PV systems grid integration challenges.

The rest of the article is structured as follows: Section II addresses PV systems grid integration challenges. Section III highlights the solutions proposed and adopted by the researchers, legislators, and regulatory bodies to alleviate the mentioned challenges. Section IV discusses the conclusions and future research directions in PV systems grid integration. Finally, the references are appended at the end of the manuscript.

II. PV SYSTEMS GRID INTEGRATION CHALLENGES

Rigorous research in the enhancement of PV cell efficiency, reduction of PV panel cost, and maximum power extraction from the PV systems pave the way for the rapid growth of PV power generation [59]. Besides, these clean and environment-friendly power generation sources play vital roles in GHG emissions reduction by lessening the use of fossil fuels without compromising the required load demand. However, the variable generation property, along with other technical and protection-related issues, hinders the efficiency, reliability, and safety of the PV integration into the grid [54], [59]–[61]. This section addresses the grid integration challenges of the solar PV systems into the electric networks and the suggested mitigation techniques.

A. OUTPUT POWER PREDICTION

Significant operational uncertainties usually come from the demand side of the traditional electricity grids. However, the integration of RER throughout the networks changes the scenario and introduces uncertainty from both the demand and generation sides. For instance, the climatic factors affect the PV power generation by varying solar irradiation, as shown in the five parameter model of the solar PV cell [62]–[65]. The working current (I_{PV}) formula of the PV cell of FIGURE 5 can be represented as:

$$I_{PV} = I_{ph} - I_D - I_{sh} \tag{1}$$

$$I_{ph} = \left[I_{SC} + K_i\left(T - T_{ref}\right)\right]\frac{G}{G_{ref}} \tag{2}$$

$$I_D = I_0\left[exp\frac{q(V_{PV} + I_{PV}R_s)}{N_s AkT} - 1\right] \tag{3}$$

$$I_{sh} = \frac{V_{PV} + I_{PV}R_s}{R_{sh}} \tag{4}$$

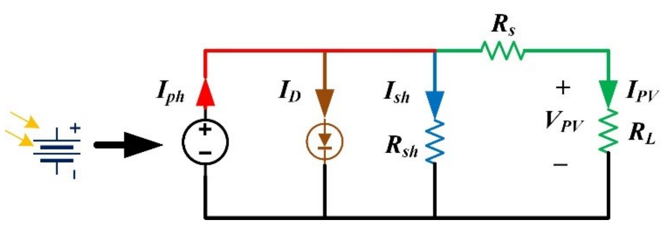

FIGURE 5. Equivalent circuit of five parameter PV cell model.

Where,
I_{ph} = photo generated current
I_D = diode current
I_{sh} = shunt branch current
I_{SC} = short circuit current
I_0= saturation current
K_i = temperature coefficient
T = actual PV cell temperature
T_{ref} = reference temperature (273 K)
G = actual solar irradiance
G_{ref} = reference solar irradiance (1000 w/m^2)
q = electron charge (1.6022×10^{-19} coulombs)
N_s= the number of PV cells connected in series.
A= ideality factor

k = Boltzmann constant (1.3807×10^{-23} JK^{-1})
V_{PV} = working voltage
R_s = series resistance of the PV cell
R_{sh} = shunt resistance of the PV cell.

Hence, it is characterized by randomness, indirectness, and volatility that poses operational challenges for PV integration into the grid [66]. Therefore, accurate prediction of PV power has become an essential task for safe and stable power system operation. Prediction can focus on PV power or energy output or their rate of change. Prediction types also depend on the tools and information available from meteorological stations and PV system data. Liu et al. [67] developed a two-stage model for estimating the prediction periods among many endeavours. In the first stage, the genetic algorithm (GA) combined three artificial neural networks (ANN), namely the Elman, generalized regression, and extreme learning machine neural networks, to develop a weight-varying prediction model. The second stage determined the prediction intervals using a nonparametric kernel density estimation. The experiment results on a 15-kW grid-connected PV demonstrated superiority over usual short-term prediction methods. Elman neural networks, K-means, and Gray relational analysis were employed to develop another prediction model [67]. The study collected historical data to identify the days that were similar and predicted for similar days. The authors claimed improved accuracy of the proposed prediction model over its counterparts. In [68], the authors proposed a hybrid model for the prediction of short-term PV power in a real system combining wavelet transform, particle swarm optimization (PSO), and support vector machine (SVM). The PSO tuned the SVM parameters to achieve a higher forecasting accuracy. Kushwaha *et al.* [69] developed a time adaptive hybrid model assisted by discrete wavelet transform to forecast very short-term solar PV generation to facilitate the real-time balancing operation in an electricity market. The developed model enhanced overall social welfare by ensuring profits for energy suppliers and price-takers. Li *et al.* [66] proposed a hybrid improved multi-verse optimizer algorithm to optimize SVM parameters in predicting PV output for safe and stable power system operation. The stochastic behaviour of the solar irradiation was modelled using the beta probability density function (PDF) [70]–[73], Weibull PDF [74], and artificial intelligence [75]. Then, the output power of the PV plants from the solar irradiation was calculated. Machine learning approaches were also reported with superior PV power prediction capability [76]. Patel *et al.* [77] proposed a low-cost power predicting approach for a small-scale PV systems using various machine learning algorithms. A deep learning-based ensemble stacking scheme was reported for Solar PV energy generation prediction in the Netherlands [78]. A review of the machine-learning based PV energy prediction models in the Nordic context was reported in [79]. The authors suggested that the use of optimization algorithms, ensemble methods, and weather clustering can be used for performance enhancement. However, this area still needs further attention from the researchers to develop versatile PV power prediction models considering the weather condition, seasonal variation, and selection of appropriate features.

B. VOLTAGE STABILITY

To obtain a flat voltage profile with minor deviations, a constant source of power that is adaptable to the changes in the network is required. Unfortunately, solar PV plants do not possess the necessary characteristics, as the average hours (average peak sun-hours) under perfect conditions are from three to six hours [80]. Many studies investigated this issue and suggested solutions. Widén *et al.* [81] presented a stochastic methodology for simulating PV-system impacts on low-voltage distribution grids via detailed generation and demand models. The authors concluded that there would be an unacceptable voltage variability if the PV penetration level goes beyond a certain threshold. Gaunt *et al.* [82] analyzed the impact of a PV system on a residential distribution feeder. The adopted probabilistic approach showed that a certain percentage (*i.e.,* 25%) penetration of solar PV in low voltage feeders recommended by the South African grid code could lead to substantial voltage problems. Based on the study of Ref. [83], optimal level of PV hosting reduced the power loss in the system; however, with the increase of PV capacity beyond certain limit cause higher power loss and other issues. Ref. [84] proposed a continuation power flow algorithm to analyze the voltage stability of grid-connected PV. The study showed that the integration of PV generators at inappropriate locations could have serious consequences, leading to voltage instability. Wong *et al.* [85] studied the effect of PV integration on the electrical grid in terms of voltage. The study found that the absence of coordination while installing PV in a particular area may lead to voltage fluctuation. Besides, the volatile nature of power generation from the PV plants affects the transmission system voltage stability [86].

The authors of Ref. [87] reviewed the impact of renewable power sources at the distribution level on voltage control strategies. They concluded that intelligent grid applications such as demand-side integration and energy storage systems could alleviate voltage fluctuations with minimum network support. Lelis *et al.* [88] studied the overvoltage problems related to the increased PV penetration in the distribution system. The study used an iterative algorithm for power flow solutions in the radial grids. The results showed that the reactive power control mechanism could mitigate overvoltage problems. Shah *et al.* [89] investigated three factors: the PV generator, location, and penetration to transmission networks, as possible solutions to voltage instability issues. The authors concluded that the proper selection of the mentioned factors improves the system's overall voltage profile. In [90], the optimal penetration level of solar PV power into the Nigerian power system considering voltage stability was addressed. Ref. [91] proposed a three-layer voltage/var control strategy to enhance the voltage stability of the electric network considering large-scale PV penetration. The battery energy storage systems (BESS) were employed to compensate for the optimal active and reactive powers in a loaded power system to achieve voltage stability [92]. The theoretical explanation regarding the suitability of various flexible AC (alternating current) transmission systems (FACTS) devices considering a variation of the device parameters to the optimal voltage profile was investigated in [93]. However, the voltage stability analysis and enhancement are still the prime concerns of the decision-makers and researchers considering bulk penetration of PV power into the networks. Therefore, further studies are required to quantify the impact of solar PV penetration on the grids and come up with appropriate solutions.

C. FREQUENCY RESPONSE

The integration of PV systems into the grids increases the probability of an imbalance between generation and demand due to their intermittent nature. This load demand and generation mismatch may lead to frequency fluctuation in the networks that causes partial or total loss of electrical supply. Rahouma *et al.* [94] investigated the impact of increased PV share that accelerated the rate of change of frequency (ROCOF) and might lead to the system collapse during natural overloads. Qaid *et al.* [95] studied two IEEE benchmark transmission networks. They showed that more than 40% penetration of solar PV generation leads to the collapse of the systems during the worst contingency case due to the loss of inertia. The effect of the PV power plant outputs on frequency stability for the continental Europe synchronous zone during the solar eclipse of March 20, 2015, was studied in [96]. The study confirmed that there was a rapid generation decline during the eclipse. Furthermore, the gradient in output was twice as high as the peak load value, which might cause a significant disturbance in the grid frequency unless appropriate actions were taken ahead of time. Limsakul *et al.* [97] analyzed a two-area power system incorporated with automatic generation control to demonstrate the speed deviation of generators due to the PV output fluctuations. Yan *et al.* [98] investigated the impact of high PV and wind energy penetration on the modified South Australian electric grid on system frequency response. The authors showed that the low inertia and secondary PV tripping could create serious security threats to the network. Darussalam and Garniwa [99] investigated the frequency response of a 20 kV distribution grid due to the incorporation of PV generation following the Indonesian grid code. They suggested that more than 20% of PV generation integration leads to the collapse of the network. Madiba *et al.* [100] designed an optimal control strategy for a microgrid consisting of intermittent RER, conventional generation sources, and BESS to solve the frequency fluctuation issue. The authors used the economic dispatch technique by minimizing the fuel cost and maintaining the anticipated generation versus load balance to control the critical and non-critical load switching. In [94], the authors developed an algorithm to determine the appropriate amount of generation reserve for a PV plant based on the characteristics of the frequency behaviour to avoid severe damage or power outages. You *et al.* [101] investigated various tactics to improve frequency response without curtailing solar PV generation in the US Eastern Interconnection and Texas grid. The authors exploited available grid resources and explored energy storage systems (ESS) to enhance system frequency response even under bulk PV penetration. However, the penetration of intermittent RER will be higher in the future, leading to the decrease of the system inertia, and the impact analysis and control strategy for frequency response improvement will be crucial. Consequently, further investigation for their proper mitigation in this field is necessary.

D. REACTIVE POWER SUPPORT

PV power is produced in the form of a direct current (DC), and it does not have the merit of reactive power in itself, as this feature is a characteristic of the AC sources [102]. Hence, the importance of innovative technologies for providing reactive power is emerging to provide reactive power capability. A report on the reactive power capability in a North American grid [103] indicated that the variable generation plants such as wind and solar could contribute to the reactive power capability of the network. Yang *et al.* [104] investigated the strategies for injecting reactive power into the grid from PV power plants, including constant active current control, constant average active power control, thermally optimized reactive power control, and constant peak current control. The study recommended adopting these controls for future PV systems to provide reactive power support to the grid. In [105], the authors proposed another strategy to control the reactive power from PV power plants based on the theory of the two stationary phases. Molina-Garcia *et al.* [106] reported the centralized and decentralized strategies to determine the references for the reactive power in PV inverters integrated into the grid. Kabiri *et al.* [107] investigated the effect of five alternative methods on the voltage in the Australian distribution system for a reactive power control system of a PV inverter. In [108], the proposed reactive power compensation technique enhanced the system voltage profile, minimized voltage variation, and reduced total harmonic distortion of the PV power plant connected to the grid. Ref. [109] developed a distributed reactive power compensation scheme to enhance the voltage profile by reducing voltage imbalances in an unbalanced distribution grid. The voltage profile of a distribution grid was regulated

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using a combined solar PV and BESS in [110]. Jafarian *et al.* [111] developed a decentralized control scheme to control the active and reactive power of a PV system that enhanced system reliability and reduced the cost of the communication requirements. The efficient management of the reactive power in electricity grids improves network voltage profile, enhances system stability, and reduces power quality issues. The grid codes insist the power systems operators maintain a stable voltage level by managing the reactive power of the grids. Therefore, different control strategies for reactive power management and the deployment of FACTS and ESS devices for reactive power support require further attention for sustainable integration of the intermittent and low inertia RER.

E. IMPACT OF HARMONICS/POWER QUALITY

The power electronic converters employed to integrate PV into the grids introduce harmonics that can damage the equipment connected to the network and reduce their efficiency and lifetime. The characteristics of harmonics resulting from several PV systems integration into the grid were studied [112]–[115]. Sreedevi *et al.* [116] studied the effect of integrating the PV system in the Indian electricity grid and found harmonics. Torquato *et al.* [117] recorded high-frequency harmonics from the PV inverters installed in a Brazilian solar farm where the current distortion reached up to 2% of the fundamental frequency. Ref. [118] studied the harmonics generated due to PV power plant integration to the grid experimentally and developed a model to deal with the harmonics.

The IEEE published a standard to control the widespread harmonic problems [119]. Therefore, to adhere to the rules and ensure quality power supply to the customers by filtering out the introduced harmonics, deployment of appropriate filters is required that can be categorized as passive and active. The passive filters are based on a resistor, inductor, and capacitor, whereas the active filters use an active element such as a transistor in addition to the passive components [120]. Yong and Ramachandaramurthy [121] designed an LCL filter to alleviate the resulting harmonics of an inverter of a grid-tied PV system. The results showed that the filter employment reduced the total harmonic distortion (THD) level from 30% to 3.9%. In [122], the same authors designed and implemented a double-tuned filter to attenuate harmonics that met both individual and total harmonic distortion limits as per the standards. Prasad *et al.* [123] illustrated the passive harmonic filtering idea to enhance power quality by minimizing the current harmonics content in an electric grid incorporated with solar PV plants. The current control scheme was employed to suppress the harmonics in [124]. Another logic control with the hybrid active power filter was developed in [125] to solve the problems of power quality (oscillations and harmonics) issues. Xavier *et al.* [126] proposed a frequency adaptive harmonic current detection method in the presence of solar PV in the network. The authors also compensated for the detected harmonic using an adaptive proportional resonant controller to reduce the total harmonic distortion of the grid current. Li *et al.* [127] developed an active power filter principle to suppress harmonics using a boost converter and a dual-level four-leg inverter. Furthermore, Pereira *et al.*[128] presented a dynamic method to compensate for harmonic current introduced by the nonlinear loads using the power electronic converters employed for PV system integration as ancillary services. The authors also recommended that the system operator provide an incentive to the PV system owners who use inverters to improve power quality through harmonic compensation. However, the multifunctional PV inverters might adversely affect the overall system efficiency [129]. Therefore, advanced level investigation and analysis are required in this arena.

F. ANGULAR STABILITY

Incorporating solar PV into the grids might introduce several challenges for the system operators, including angular instability issues. Mitsugi and Yokoyama [130] analyzed and assessed the transient stability of a multi-machine electric system integrated with a large PV plant under a three-phase fault condition. The authors concluded that transient stability was dictated by the ratio of the constant impedance to constant power loads. The higher the rate, the more prominent the deterioration due to the repeated reconnection of the PV system. You *et al.* [131] studied the impact of large-scale PV penetration on an inter-area oscillation in the US Eastern Interconnection. The study found that the damping of the dominant oscillation mode decreases with the increase of PV penetration. Also, the variation of PV control strategies and parameters might create a new oscillation mode. Shah *et al.* [132] investigated the New England–New York test network for a different level of PV penetrations that revealed that large-scale infiltrations severely affect the inter-area mode of oscillations. Ref. [133] investigated the impact of bulk penetration of PV (rooftop and utility-scale) on the power system's small-signal stability. The eigenvalue analysis identified the locations of the critical modes with a frequency range of 0.01–2.0 Hz and a damping ratio of less than 10%. Hence, such integration reduces the damping of the dominant oscillation mode and introduces new oscillation mode.

Power system researchers exploited and explored many techniques and solutions in response to the mentioned issues. For instance, Ding *et al.* [134] enhanced the transient stability of a dynamic network by proposing a coordination method between the active and reactive power of a photovoltaic inverter system. In [132], the authors proposed a generator ranking-based operating point adjustment technique to minimize the angular separation and enhance the damping of the inter-area mode. Besides, the use of FACTS devices alone or in coordination with power system stabilizers (PSS) to strengthen the stability of conventional power systems are well established [135]–[138] that are being employed in PV integrated power systems as well. Selwa *et al.* [139] discussed the effect of the PV system on the transient stability of a multi-machine power system. They employed PSS and static synchronous compensator (STATCOM) to improve transient stability after being subjected to disturbances. In [140], the authors used the quasi-oppositional differential search algorithm (DSA) to tune the damper based on a static var compensator (SVC) and proportional-integral-derivative (PID) controller to improve the transient stability of a PV integrated power system. Movahedi *et al.* [141] coordinated the solar PV and wind farms' proportional-integral (PI) controllers with the PSS-based FACTS controllers of the synchronous generators to improve the overall stability of a multi-machine electric network. However, the solutions and techniques to deal with the angular stability issue are still early and require further study and investigations for technological maturity.

G. FAULT/LOW VOLTAGE RIDE-THROUGH CAPABILITY

Transformer-less PV inverters are widely adopted to attain higher efficiency for integrating the PV systems into the grid. The anti-islanding protection of the PV systems may suddenly disconnect them from the network, creating disturbances. Thus, the solar PV power systems should have fault ride-through (FRT) and low voltage ride-through (LVRT) features to provide the full range of services like the conventional power plants [142]. Also, FRT capability has become one of the most critical issues imposed by the grid codes to be fulfilled by the PV system owners.

Al-Shetwi *et al.* [143] proposed a comprehensive control strategy for a single-stage solar PV system to enhance LVRT capability based on new grid codes and Malaysian standards. The authors used the DC chopper brake controller and a current limiter to limit extreme alternating currents to absorb the excessive DC voltage. Adeel Sabir [144] proposed a novel LVRT capable energy management system for a grid-connected hybrid photovoltaic-fuel cell power source that was able to ride through during both symmetrical and asymmetrical voltage sags. Huka *et al.* [145] proposed a comprehensive LVRT control strategy for grid-connected solar PV plants under balanced and unbalanced faults. Afshari *et al.* [146] proposed another control strategy with the reference current generation method that used a new way to limit the current during low voltage situations. Shi *et al.* [147] proposed reducing the complexity of LVRT control by using a smooth switching in the virtual synchronization generator technology with proportional resonance by linking the PV source and the grid. In this smooth switching-based strategy, the voltage source mode is transformed into the current source mode to limit the output current and provide reactive power support during contingency cases. Worku and Abido [148] employed super-capacitor energy storage systems (SCESS) to enhance FRT capability and management of power in a grid-integrated PV system. The super-capacitor minimized short-term power fluctuation during regular operation, whereas it stored energy and improved FRT during fault at the grid side. To control LVRT capability, other techniques, including the use of the bypass principle and FACTS devices, were reported in [149]–[152]. To sum up, the FRT/LVRT control strategies for grid integration of solar PV systems are still an active research area, as all the mentioned strategies have their pros and cons in terms of grid code compliance, complexity, economic feasibility, and efficiency.

H. PROTECTION CHALLENGES

Like other power system components, the PV systems are also vulnerable to fault occurrences that significantly impede system reliability, efficiency, and safety. Hence, the conventional protection standards must be upgraded to safeguard PV systems from different kinds of faults [59]. However, the traditional protection devices sometimes fail to detect faults in the PV systems because of the lower magnitude of the fault currents, nonlinear PV characteristics, low irradiance condition, night-to-day transition, and presence of maximum power point (MPP) tracker and blocking diodes [153]–[157]. Besides, any fault in the DC side of the PV systems is usually unpredictable that can burn out the complete system even if the system is equipped with protection devices [158].

Considering the mentioned notes, Ref. [159] developed an automatic fault detection technique for grid integrated PV plants using a DC-AC power ratio. The method also used DC current-AC power ratio to locate the faults precisely. Another automated supervision, fault detection, and diagnosis scheme for grid-connected PV systems based on the comparison of simulated and measured yields was proposed in [160]. Garoudja *et al.* [161] proposed a model-based fault-detection scheme to detect shading on PV modules and DC side faults based on MPP coordinates. A precise and straightforward online fault detection algorithm using a multi-level decomposition wavelet transformation was proposed for a grid integrated PV system [162]. Dhimish *et al.* [163] proposed a parallel fault detection scheme for grid-connected PV systems to diagnose faults on both the DC and AC sides. The results indicated that the plan accurately detected and located different faults at the PV module, PV String, bypass diode, MPP tracking unit, and inverter unit. Appiah *et al.* [164] critically reviewed the detection and diagnosis techniques of four major PV array faults, namely the line-line-ground fault, ground fault, hotspot fault, and arc fault, along with recommendations for future research direction.

PV systems deployment changes the power flow of the distribution grids from unidirectional to multidirectional. Such changes challenge traditional protection schemes [165] and introduce variable short circuit current [166]. In response, Nkhasi and Saha [167] proposed an efficient adaptive protection system for distribution grids through necessary modifications of the traditional protection scheme with significant penetration of PV systems. Ref. [168] investigated the issue of the maximum current for overcurrent relays (OCR) in the presence of fluctuation associated with the PV system under a short-time three-phase-to-ground fault. The results showed that solar radiation and fault impedance variation significantly affected the current seen by the relays. Different protection strategies for distribution grids, including overcurrent, differential, distance, fault current compensation, and adaptive protection schemes, were reviewed and discussed [169]. However, their fault characteristics are also different due to the differences in structural configuration and control between distributed and centralized PV systems. Relative to these differences, Jia *et al.* [170] analyzed and calculated the fault current using simulated and field experimental data for an 850 MW PV power plant. Furthermore, the PV systems are vulnerable to direct or indirect atmospheric discharges due to their expanded surface and installation position in flat-open areas. Therefore, their lightning protection is of great importance for uninterrupted operation, avoidance of faults, and equipment damage [171]. Zaini *et al.* [172] offered a reference for installing surge protection devices for PV systems to minimize potential damage in the Malaysian environment as the country is prone to frequent lightning strikes.

This section discussed various faults, including the physical, environmental, and electrical failures, along with different protection schemes and remedial actions. Protection of grid-connected PV systems is one of the least explored areas globally compared to other PV systems, including MPPT and array reconfiguration techniques. A detailed analysis of the available protection schemes considering their accuracy, integration complexity, cost, and computational effectiveness is also not readily available. Moreover, the high-impedance faults limit the fault current values that are not detectable or comparable to load current values. Finally, the protection standards of grid-connected PV systems also require the attention of scholars for their up-gradation, as most of them offer appropriate protection facilities [173].

I. TRANSMISSION, COMMUNICATION, AND SECURITY CHALLENGES

Large solar PV projects are usually located in deserts, mountainous areas, or places far from the city center that require billions of dollars to create new transmission lines, which is a significant financial challenge for investors [174]. Their locations also require remote monitoring and control solutions for efficient and reliable operation and integration into the grids. The high concentrations of rooftop PV systems in the distribution grids result in network congestions [175]. The mentioned challenges may lead to malfunctioning and unwanted curtailment of the PV generation. In response to congestion issues, Sreejith *et al.* [176] explained various series of compensated FACTS devices to enhance the power transfer capability of the transmission lines considering RER integration. In [177], the authors transformed the PV inverter into a STATCOM that improved the power transfer capability of the network. The authors also employed the PV-STATCOM to enhance power system stability under contingency cases. In response to the communication challenges, Zedak *et al.* [178] suggested using the internet of things (IoT) to store temperature, voltage, current, and other relevant information from the solar field that facilitate system monitoring and faults diagnosis, event forecasting, and preventive maintenance. Real-time monitoring and management of the PV system utilizing IoT hardware, software, and communication protocol were presented in [179]. In [180], the authors proposed a low-cost wireless solution based on long-range technology for communication with remote PV power systems that required minimum power consumption and maintenance. Sarabia *et al.*[181] illustrated another wireless and real-time PV plant monitoring system where the Arduino devices were in charge of data acquisition through Bluetooth communication protocol. Shahid *et al.* [182] investigated the communication technologies, standards, and protocols used in RER monitoring and management. According to the authors, the area faces several challenges, including data reliability, the time required for information exchange, the application protocol layer, and the standards and policies. Ref. [183] illustrated the impact of cyberattacks on power losses on data coordination between RER plants and system operators. Teymouri *et al.* [184] studied the cyberattack in the electric grid with PV units having reactive power capability that drove the network integrated RER to a precarious state by jeopardizing system stability.

In response to the security issues, a sliding mode-based observer was proposed to detect and estimate the attacks where the captured information was utilized to compensate for the corrupted data [185]. Lore *et al.* [186] proposed a novel data anomalies detection algorithm for many attacks on a solar farm using machine learning techniques. Furthermore, in [187], the authors employed a centralized control scheme to detect the cyberattacks in distribution systems integrated with several PV systems. Finally, Qi *et al.* [188] proposed a holistic attack-resilient framework to protect the grid-integrated RER and overall grid infrastructure from malicious cyberattacks without hampering the grid stability, resiliency, and reliability. However, considering the importance and criticality of the transmission, communication, and security challenges, the power system researchers should explore and investigate further methodologies for future grids' safe and secure operation.

J. ELECTRICITY MARKET CHALLENGES

In electricity markets, electricity as a commodity needs to be traded instantaneously. However, the power generation uncertainties of the RER create impediments to their

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effective participation in electricity markets, particularly in short-term markets. Besides, the withdrawal of government incentives over time pushes the PV systems to compete with well-established low price fossil fuel-based generation technologies. Moreover, the lack of appropriate market frameworks and innovative incentive packages impede RER trading in the electricity market [189]. In response to the mentioned challenges, two bidding strategies (worst-case scenario and average profile strategy) considering the uncertainties of PV power generation were proposed in [190]. The authors proposed an aggregator, budget-based analysis approach to mitigate potential risks. Saranya and Swarup [191] modelled the PV plant as a price taker in the day-ahead electricity market, considering electricity prices and PV generation uncertainties. An aggregation platform comprising both renewable and non-renewable energy resources can be regarded as the tool for an aggregator to participate in the electricity market with increasing resiliency [192]. Gomes *et al.* [193] addressed a stochastic wind, PV, and thermal commitment to enhancing the bidding process of an aggregator in the day-ahead electricity market of the Iberian Peninsula. The case study revealed the benefits of aggregation in making more revenue and profit over the disaggregated system. An optimal bidding strategy for a PV-wind system integrated with ESS devices, as illustrated in [194]. Reported results confirmed the superiority of the coordinated approach over the non-coordinated system in terms of overall profit. In [195], the authors addressed the challenges of PV integration into the electricity market. They proposed a solution for the optimal scheduling of PV systems using ESS to participate in daily and intraday markets. However, not all ESS technologies are feasible for RER integration into the grid. Beltran *et al.*[196] analyzed the ageing experienced by six different types of batteries used in a large-scale PV plant that participated in the electricity market to generate controlled energy and minimize deviation to avoid penalties. The authors concluded that the lithium-ion batteries performed well over other battery types in coordination with the sodium-sulfur batteries. Ref. [197] studied the Australian electricity market considering substantial PV penetration into the market, and concluded that effective penetration of PV required subsidies and mechanisms to support ESS technologies. Haghdadi *et al.* [198] reported that the grid integrated PV systems reduced and delayed the peak demand time in the Australian electricity market. However, regular incentives, supporting the capital costs, and long-term flat rate trading contracts with the PV owners may lead towards an unstable and inefficient energy market model by abolishing the competition [199]. Zwaenepoel *et al.* [200] investigated the risks and challenges of the electricity market of Belgium, considering the direct participation of the PV owners in the market through the abolishment of fixed-rate trading. The authors concluded that the move could be positive but might face multiple challenges. Therefore, the policies, regulatory frameworks, incentives, bidding strategies, and control mechanisms require further investigation and modification for the PV system's effective participation in the electricity market. Furthermore, the coordination amongst different players, including the owners of renewable and non-renewable energy resources, energy storage technologies, and load aggregators, can be improved through further research and investigation. Finally, the market reform is critical to enabling a clean energy transition by making the RER cost-effective. Significant reduction of the RER curtailment can be considered as one the major indicators of the success of power market reformation. For instance, solar curtailment fell to 2% in China in 2020, from a high of 11% in 2015 [40].

K. ENVIRONMENTAL AND SOCIO-ECONOMIC CHALLENGES

PV system is a source of clean energy, and the industry creates millions of jobs over the years and stimulates the overall economy [23]. Nevertheless, it has negative impacts on the environment. It requires large project areas, a bulk amount of treated water during the manufacturing, and normal cleaning processes involving hazardous materials for manufacturing the solar cells [201]. These hazardous materials of the PV modules under regular operation do not pose any risk to human health or the environment. Still, broken or abandoned modules may create an extreme situation for the environment [202]. Tammaro *et al.* [203] presented the leachable metal emissions from different PV panels and their environmental effects. The authors experimentally showed that most of the panels released hazardous substances that could have severe consequences for human health. The waste from the PV industries might reach 1.7–8.0 and 60.0-78.0 million tons by 2030 and 2050, respectively, which is likely to achieve the same order of global electronic waste [204]. If these wastes are not managed appropriately, the toxic substances released from the PV system components will contaminate the air, water, and soil.

The landfill is one of the most popular and cost-effective waste management techniques adopted for PV systems. However, severe environmental pollution due to the exposure of PV components to the environment is the main drawback of this technique [205]. Incineration is the second option for PV waste management, like other electronic waste management. It does not require separating PV waste from other industrial waste, but it abolishes the chances of recovering raw materials or reusing the PV panels. The third choice is reusing the PV module by repairing them, which reduces their efficiency by 1.0-2.0 percent [206]. Deng *et al.* [204] compared the economic viability of different PV waste management techniques: landfill, glass, mechanical, and thermal. They found the landfill technique the cheapest option but not sustainable, whereas glass recycling is economically viable but not implemented widely.

Conversely, thermal recycling involves more expenses than mechanical recycling, and to make both of them economically viable further research and development are required. Apart from the environmental issues, citizen perception in diverting their behaviour toward new resources is another barrier to PV adoption throughout the world. According to Padmanathan *et al.* [207], to change the view of the different citizen groups in India towards the use and importance of the RER, the institutions and organizations can play a vital role through awareness programs. Besides, lucrative policies like the feed-in-tariff, net metering, incentive initiative, and installation service encourage rural areas for PV adoption [208]. In [209], the authors addressed the role of higher educational institutions in Ireland to accelerate sustainable energy development by developing a new method that adopted the concept of quantitative analysis and social analysis to adopt PV systems. Nurunnabi *et al.* [210] generated the lowest possible adverse socio-economic and environmental impacts of the RER, including grid-tied PV systems, by guaranteeing a certain degree of monetary benefits that will encourage people to PV system adoption. Parkins *et al.* [211] found that rooftop PV was a helpful technique for Canadians to adopt renewable energy through incentive initiatives, including subsidies, community education, and social networks. To overcome the mentioned environmental and socio-economic challenges, much attention, research, and investment are required shortly.

III. SOLUTIONS FOR GRID INTEGRATION PROBLEMS

Grid integration challenges of the PV systems can be dealt with following two different paths (hard and soft) [212]. The hard paths oversize everything while addressing the challenges that are expensive, inefficient, and sometimes impractical. Conversely, the soft tracks deal with the difficulties in pragmatic ways that are less expensive and more efficient and reliable. The scholars and researchers follow the soft paths for integrating RER into the grid by achieving better flexibility, stability, reliability, and resiliency. This article has already discussed many proposed solution methodologies in the respective sections. This section focuses on a few more selected vital solution techniques, including the grid codes, advanced control strategies, energy storage systems, and renewable energy policies for the effective grid integration of the solar PV systems.

A. GRID CODES

Electricity grids have technical specifications for safe, secure, reliable, and economical operation, known as grid codes. They are the authorities responsible for monitoring the integrity and operation of the design of the electric networks. Grid codes' contents vary from country to country based on participants' requirements. These codes dictate the integration of power generation, including renewable energy generation, into the national grids to ensure grid stability and security. Therefore, the energy producers should adhere to the available grid codes, including network frequency and voltage variation requirements, fault ride-through, reactive power, and power factor regulation capabilities. For instance, TABLE I and TABLE II summarize a few selected grid codes' frequency and voltage variations requirements. As can be seen from TABLE I, if the frequency of any grid-connected PV systems goes beyond the specified limits, the plant should be immediately disconnected. Otherwise, the PV system owner should continue operating the system or stay connected for a pre-approved duration before disconnecting the network.

TABLE I
FREQUENCY TOLERANCE RANGE IN GRID CODES

Grid Code (Network Frequency)	Frequency range (Hz)	Duration Requirements
Australia (50 Hz) [56]	> 52.0	2 seconds of operation
	47.5 – 52.0	Continuous operation
	< 47.5	2 seconds of operation
Canada – Alberta (60 Hz) [213]	>61.7	0 seconds of operation
	61.6 – 61.7	30 seconds of operation
	60.6 – 61.6	3 minutes of operation
	59.4 – 60.6	Continuous operation
	58.4 – 59.4	3 minutes of operation
	57.8 – 58.4	30 seconds of operation
	57.3 – 57.8	7.5 seconds of operation
	57.0 – 57.3	45 cycles of operation
	< 57.0	Immediate disconnection
China (50 Hz) [56]	> 52.0	Immediate disconnection
	50.2 – 52.0	2 minutes of operation
	49.5 – 50.2	Continuous operation
	48.0 – 49.5	10 minutes of operation
	< 48.0	Depend on the inverter
Denmark (50 Hz) [214]	50.2 – 52.0	15 minutes of operation
	49.5 – 50.2	Continuous operation
	49.0 – 49.5	5 hours of operation
	48.0 – 49.0	30 minutes of operation
	47.5 – 48.0	3 minutes of operation
	47.0 – 47.5	20 seconds of operation
Germany (50 Hz) [215]	50.5 – 51.5	30 minutes or less of operation
	49.0 – 50.5	Continuous operation
	48.5 – 49.0	30 minutes or less of operation
	48.0 – 48.5	20 minutes or less of operation
	47.5 – 48.0	10 minutes or less of operation
Ireland (50 Hz) [216]	50.5 – 52.0	60 minutes or less of operation
	49.5 – 50.5	Continuous operation
	47.5 – 49.5	60 minutes or less of operation
	47.0 – 47.5	20 seconds of operation
Japan (50 Hz) [56]	> 51.5	Immediate disconnection
	47.5 – 51.5	Continuous operation
	< 47.5	Immediate disconnection

Japan (60 Hz) [56]	> 61.8	Immediate disconnection
	58.0 – 61.8	Continuous operation
	< 58.0	Immediate disconnection
Romania (50 Hz) [56]	> 52.0	Immediate disconnection
	47.5 – 52.0	Continuous operation
	< 47.5	Immediate disconnection
Saudi Arabia (60 Hz) [217]	> 62.5	Immediate disconnection
	61.6 – 62.5	30 seconds of operation
	60.6 – 61.5	30 minutes of operation
	58.8 – 60.5	Continuous operation
	57.5 – 58.7	30 minutes of operation
	57.0 – 57.4	30 seconds of operation
	< 57.0	Immediate disconnection
South Africa (50 Hz) [56]	> 52.0	4 seconds of operation
	51.0 – 52.0	60 seconds of operation
	49.0 – 51.0	Continuous operation
	48.0 – 49.0	60 seconds of operation
	47.0 – 48.0	10 seconds of operation
	< 47.0	0.2 seconds of operation
Spain (50 Hz) [56]	> 51.5	Immediate disconnection
	47.5 – 51.5	Continuous operation
	48.0 – 47.5	3 seconds of operation
	< 47.5	Immediate disconnection
UK (50 Hz) [218]	51.5 – 52.0	15 minutes of operation.
	51.0 – 51.5	90 minutes of operation.
	49.0 – 51.0	Continuous operation.
	47.5 – 49.0	90 minutes of operation.
	47.0 – 47.5	20 seconds of operation.
USA—North American Electric Reliability Corporation (60 Hz) [56]	> 61.5	0.16 seconds of operation
	61.0 – 61.5	300 seconds of operation
	58.5 – 61.0	Continuous operation
	57.0 – 58.5	300 seconds of operation
	< 57.0	0.16 seconds of operation

TABLE II
VOLTAGE TOLERANCE RANGE IN GRID CODES

Grid Code (Network Frequency)	Nominal Voltage (kV)	Normal Operating Range (kV)
Canada - Ontario [213]	115	113 – 127
	230	220 – 250
	500	490 – 550
Denmark (50 Hz) [214]	400	320 – 420
	220	Not mentioned - 245
	150	135 – 170
	132	119 – 145
	60	54 – 72
	50	45 – 60
Germany (50 Hz) [215]	380	350 – 420
	220	193 – 245
	110	96 – 123
India (50 Hz) [219]	400	360 – 420
	220	200 – 245
	132	120 – 145
Malaysia (50 Hz) [56]	500	500 ± 5%
	< 275	< 275 ± 10%
Saudi Arabia (60 Hz) [217]	380	380 ± 5%
	230	230 ± 5%
	132	132 ± 5%
	115	115 ± 5%
	110	110 ± 5%
UK (50 Hz) [220]	400	400 ± 5%
	275	275 ± 10%
	132	132 ± 10%
	< 132	132 ± 6%
Japan, South Africa, Italy, and China [56]	Nominal voltage	Nominal voltage ± 10%
Singapore (50 Hz) [221]	Nominal voltage	Nominal voltage ± 3%

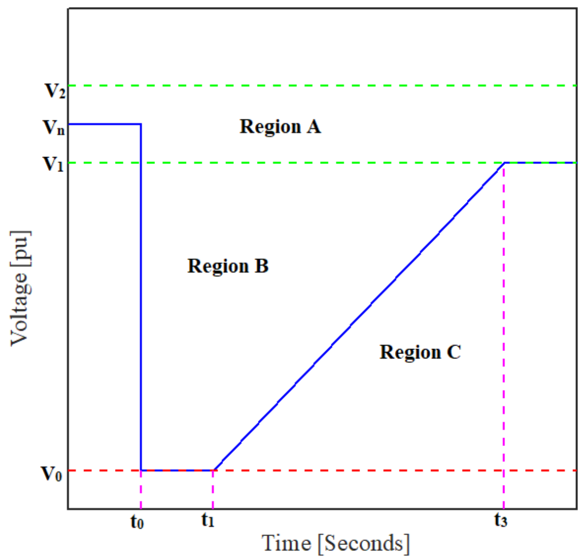

FIGURE 6. Voltage-vs-time graph by the grid codes during a three-phase fault [56].

Besides, the grid codes provide full attention to the fault ride-through (FRT) capability of the grid integrated RER considering the importance. In general, FIGURE 6 illustrates the LVRT requirements of the grid codes with a voltage-vs-time graph where the voltage is presented in per unit (pu). The figure regions decide whether the PV systems remain connected to the grid or abandon their operation. The PV systems continue their operation in region A if the voltage of the point of common coupling (PCC) is above a specific voltage (V_1). If their voltage is in region B due to any disturbance, the PV systems should withstand the voltage dip and remain connected for some time (t_1-t_0). If the systems start to recover, they should remain connected for another period (t_2-t_1). The PV systems must continue operation if they recover the voltage (V_1) within the specified time. Otherwise, the PV systems must abandon their operation by disconnecting from the grid. However, the scales of the graph vary from country to country. For instance, V_0 is zero percent of the nominal voltage in Australia, Germany, Italy,

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South Africa, and Malaysia. V_0 is fifteen percent of the nominal voltage in the USA and Romania, whereas 20 percent of the nominal voltage is in Japan and Spain. Likewise, other parameters (V_1, V_2, t_0, t_1, and t_2) also vary from country to country [46].

Like LVRT, many grid codes have stipulated the high voltage ride-through (HVRT) requirements. For instance, in 20 percent voltage swell, Germany and South Africa allow PV systems operation for 0.10 seconds and o.15 seconds, respectively. Spain and Australia allow PV systems operation for 0.25 seconds and 0.06 seconds, respectively, while there is a voltage swell of 30 percent. However, China and Romania did not define anything in their grid codes regarding voltage swell [56]. Furthermore, modern grid codes impose conditions for the PV systems to contribute to grid stability during and after disturbances by controlling their reactive power [222] and injecting reactive current [146]. In Germany, China, Italy, and South Africa, the PV systems should provide reactive power support within the power factor (PF) range of 0.95 under-excited (inductive) to 0.95 overexcited (capacitive). In Spain and the USA, the PF range for the PV systems should be from 0.85 inductive to 0.85 capacitive, whereas Japan and Romanian grid codes did not mention anything on PF [56]. As discussed, there is no specific technical and economic justification for varying penetration levels of PV systems and their technical specifications into the grids due to the variability of the grid codes. Such variations impose extra expenditures and lead to the inefficient design of the PV systems. Therefore, the European Renewable Energy Council advised European system operators to update their grid codes consistently. Such consistency and harmonization of the grid codes for PV integration require significant up-gradation to reduce associated manufacturing expenditures and enhance overall system efficiency. Different technical standards offered by IEEE 1547, IEEE 929, IEEE 519, NFPA 70, UL 1741, and IEC TC 82 should be followed for up-gradation of the grid codes for PV integration [223].

B. ADVANCED CONTROL STRATEGIES

Integrating intermittent RER into grids introduces many challenges, as discussed in Section 2 [224]. Researchers investigated many conventional and advanced technologies to combat the challenges in response. This paper has already discussed many of them in the respective sections. This section summarizes a few more critical and advanced technologies. For instance, Ref. [225]–[227] reviewed the power fluctuation smoothing techniques of the grid integrated PV systems. Many advanced technologies, including geographical dispersion [228], principal component analysis [229], fuzzy wavelet filtering [230], ramp-rate control [231], GA-based feedback control [232], wavelet transform based ANN [233], Elman neural network [234], and deep neural network [235] were illustrated for PV output power smoothing. Two different control strategies with and without ESS received full attention to providing primary frequency response by the power electronic converter interfaced PV systems [236]. Frequency control strategies for the grid-connected PV systems without ESS are known as the de-loading technique and were proposed in [237]–[240]. Ref. [241]–[243] presented frequency control strategies for the grid-tied PV systems with ESS. Other strategies such as active power control [244], fuzzy logic control [245], and adaptive neuro-fuzzy inference system (ANFIS) [246] were also explored for frequency deviation mitigation. Scholars and scientists proposed different voltage control strategies to combat the grid-connected PV systems' overvoltage and voltage flicker issues. The proposed approaches can be ramified as decentralized and centralized voltage control techniques [247]. Sansawatt *et al.* [248] presented a decentralized control strategy for overvoltage and thermal issues in an electric grid. In contrast, Pukhrem *et al.* [249] combined reactive power control and active power curtailment strategies to stabilize the voltage profile by increasing the PV penetration level for a rooftop PV system. Other centralized and decentralized strategies, including volt-watt and volt-var [250], multi-agent [251], fuzzy control [252], reactive power control [253], and active power curtailment [254] techniques were also illustrated in literature for voltage regulation. The researcher also deployed ESS [255], tap changing transformers [256], and FACTS devices [257] for enhancement of the system voltage profile.

Likewise, many advanced control strategies were proposed in the literature for optimal reactive power dispatch as it significantly affects many grid parameters. Such strategies can be classified as graphical, analytical, numerical, heuristic, and dynamic planning methods [258]. Among many approaches, Ansari *et al.* [259] presented a Holonic architecture-based reactive power control strategy that minimized the active power losses and enhanced network fault tolerance level by exploiting available reactive power resources. A PI controller was illustrated to control the reactive power capability in [260]. Other strategies include adaptive droop control [261], index-based reactive power control [262], prosumer-owned control [263], fuzzy-based reactive power control [264], and system of system-based control [258] was also investigated for grid integrated PV systems. Furthermore, Al-Shetwi [46] reviewed control approaches employed to enhance grid-integrated PV systems' FRT capability. These strategies can be ramified into two as external devices (braking resistors [265], current limiters [266], ESS [267], and FACTS [268]) and improved controller-based (flyback inverter [269], adaptive DC-link voltage control [270], single and two-stage inverter [271], model predictive control [272], fuzzy logic control [273], and hybrid control [274]) strategies. However, most of the mentioned control strategies are still in their early stages and require further investigation to develop effective, intelligent, and robust control techniques.

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C. ENERGY STORAGE SYSTEMS

As discussed earlier, the RER suffers from the lack of dispatch ability that imposes operational challenges to the electric grid and can be resolved through the deployment of the energy storage systems (ESS) [275]–[279]. This technology also helps to integrate intermittent RER into the network and reduces peak load demand and electricity prices in competitive markets. Most of the deployed large-scale ESS is based on pumped hydroelectric ESS (PHESS) and compressed air ESS (CAESS). However, the total volume of these two technologies is equivalent to 3% of the entire global electricity generation capacity only [280]. Battery ESS (BESS) received widespread attention due to its cost reduction and enhanced conversion efficiency in recent years [281]–[283]. Other technologies like flywheel ESS (FESS) are the electro-mechanical storage system, the super-capacitor ESS (SCESS) is the electrostatic storage system, and the superconducting magnetic ESS (SMESS) is the direct storage system has also received excellent attention. Another ESS, namely the hydrogen fuel cell ESS (FCESS), is suitable for emission-free electricity generation and is applied in the electric power system [291].

TABLE III
COMPARISON OF ENERGY STORAGE SYSTEMS [284]–[290]

Storage technology	PHESS	CAESS	FESS	BESS		SMESS	SCESS	FCESS
				Lithium-ion	Lead-acid			
Power range (MW)	100-5000	5-300	0-0.25	0-0.1	0-40	0.1-10	0-0.30	0-50
Energy range (kWh)	2×10^5-5×10^6	2×10^5-10×10^5	25-5000	250-25000	10^2–10^5	0.1-100	0.001-5	< 200,000
Energy density (Wh/kg)	0.5-1.5	30-60	5-80	120-230	30-50	0.5-5	0.05-15	500-3000
Power density (W/kg)	-	-	700-12000	150-2000	75-300	500-2000	10-10^6	> 500 (W/L)
Efficiency (%)	65-87	80-89	85-95	75-97	63-90	95-98	84-97	20-66
Pick uptime	2 – 5 minutes	1-2 minutes	Seconds	Milliseconds	Milliseconds	Milliseconds	Milliseconds	Seconds
Discharge time	Hours-days	Hours-days	Seconds-minutes	Minutes-hours	Seconds-hours	Milliseconds-seconds	Milliseconds-minutes	Seconds-days
Storage period	Hours - months	Hours - months	Seconds-minutes	Minutes-days	Minutes-days	Minutes-hours	Seconds-hours	Hours-months
Lifetime (years)	40-60	20-60	15-	5-15	5-15	20+	10-30	5-15
Environmental impact	High	High	No	Very low	Medium	low	low	low
Advantages	-Matured technology. -low cost and flexibility.	-Matured technology. -low investment.	-fast response. -No environmental impact.	- Long life cycle. -Lightweight.	-Matured technology. -Cheap and recyclable.	-Faster response. -High power density.	- High power density -Faster response.	- Long-time storage. -No emission.
Disadvantages	-Geographic location and environmental condition oriented. -Long construction time.	-Only large-scale storage systems are economically viable. -Long construction time.	-Mechanical components affect their stability and efficiency. -Short time storage.	-Higher initial cost. -Less recyclability.	-Requires regular checks and external venting.	-Higher capital cost. -Not matured technology.	-Limited storage capacity. -High initial cost.	-Lower roundtrip efficiency. -Higher capital cost

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3174555, IEEE Access

Besides, a new chemical ESS is the power-to-gas (P2G) that produces combustible gases (hydrogen and methane) from water and carbon-di-oxide utilizing excessive electricity generation or RER [292]. However, the BESS creates power control challenges during grid integration due to the slow dynamic response. Conversely, the SCESS and FESS can supply a high power demand that decreases their lifespan [293]–[295]. Therefore, each ESS has its pros and cons; differences among the widely employed ESS are presented in TABLE III [284]–[290]. None of the existing ESS can simultaneously meet energy and power density due to their physical limitations. Therefore, it is necessary to enrich ESS transient and steady-state performance by hybridizing them suitable for high energy and power applications [293]–[295]. Worku *et al.* [296] minimized grid-tied PV power fluctuation caused by the changes in temperature and irradiation using SCESS. The authors integrated the SCESS with the system through a bi-directional buck-boost converter. Prajapati and Mahajan [297] minimized the planning and transmission congestion cost by optimizing the EES size, considering the RER's intermittency. Ref. [298] investigated the impact of BESS on power system stability with high-level penetration of inverter-based distributed generators, especially PV systems. The results showed that proper coordination of the ESS charging and discharging enhanced the network's transient stability. A joint control strategy was illustrated for a PV-based DC grid integrated with a HESS consisting of BESS and SCESS [299]. Ref. [300] employed hybrid ESS consisting of a capacitor bank, fuel cell, electrolyzer, and hydrogen storage to ensure reliable and quality power supply during a large-scale natural disaster and minimize the fluctuation of solar power generation. Zhang *et al.*[301] combined the hydrogen system and SMES to compensate for the output power fluctuation of a solar power generator. Furthermore, a hybrid ESS structure can enhance the life span of different ESS (*i.e.,* battery and fuel cell) by smoothing their power profile. Gee *et al.*[302] improved battery life span by 19% by employing HESS consisting of a battery and super-capacitor where the SCESS severed the high-frequency demand. Moreover, Ref. [239] analyzed the economic performance of HESS in shifting the peak demand and controlling the frequency. According to the analysis, the HESS offers better economic efficiency over the single-type BESS. Despite huge potential and capabilities, the ESS industries face financial challenges as the technology is nascent, with few proven cost recovery cases [303]. The investors are hesitant due to the vulnerability and risk of the investments. Also, the electricity grid leaders partially recognize the technology to effectively integrate intermittent RER into the grid and provide other ancillary services. Therefore, further research on technological maturity is required to convince investors. Besides the financial issues, providing appropriate dynamics to various types of loads, including unbalanced, nonlinear, and pulse loads employing ESS, also needs further investigation. Furthermore, the collaborative design of distributed HESS and local controllers also required the attention of the researchers for the successful integration of PV systems into the grid.

D. RENEWABLE ENERGY POLICIES

Solar PV can mitigate global energy demand and climate change issues among many RER by ensuring energy security. Mass deployment of solar PV systems and their integration into the electricity grids require favourable and supportive policies. The growth of solar PV systems is usually supported by different policies worldwide, including the feed-in-tariffs (FiT), feed-in-premium (FiP), investment tax credit (ITC), renewable portfolio standards (RPS), net energy metering (NEM), quota systems (QS), green certificates, capital subsidy, low-interest bank loans, national renewable energy targets, and reverse auctions [304]–[306]. A FiT is a long-term contract between renewable energy producers and the government, governed by the generation cost of each technology and considered one of the most successful policies in promoting RER [307]. Besides, tenders or competitive auctions are the fastest ways for RER promotion. Moreover, NEM is another successful policy in promoting RER technology and their grid integration; it gives producers credits or payments on the produced and exported energy. It can be implemented in combination with other policies (FiT or competitive auctions) to achieve a greater spread of renewable energy integration into the grid. Among many countries, Germany adopted different policies over the years to facilitate sustainable energy development, promote RER power generation, reduce energy cost, and protect the environmental effects [304]. The FiT policy introduced by the country helped to increase its solar energy generation from 61 GWh in 2000 to 48,641 GWh in 2020 [308]. According to the plan, 90% of the output of 10 kW to 1.0 MW plants should be for the national grid where the price varies from 17.94 €cent/kWh to 24.43 €cent/kWh based on the types and size of the PV systems. The remaining 10% of the generation can be consumed on-site, sold in wholesale, and spot markets at a lower rate (approximately 3–5€ cents/kWh) [304].

Besides, the developments of the PV systems (small or large) are also supported by the bank. However, the country updated its FiT policy several times since its inception by modifying/reducing the tariff as the overall investment cost of the PV systems was reduced significantly [304], [309]. In France, the building-integrated PV systems of sizes less than 9 kW, from 9 kW to 36 kW, and from 36 kW to 100 kW receive FiT rates of 24.6 €cent/kWh, 13.3 €cent/kWh, and 12.6 €cent/kWh, respectively as of July 2016. More massive than 100 kW building-integrated PV systems and ground-mounted plants should go through tendering [310]. In Belgium, green power generation is promoted through green certificates, energy subsidies, investment assistance, and NEM [306]. UK supports the PV systems by combining QS and FiT schemes. Any PV system within 50 kW to 5 MW

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should choose either the QS or the FiT [306]. In the USA, the Modified Accelerated Cost Recovery System (MACRS), Local Solar Permitting (LSP), and ITC are the essential policies for the rapid growth of solar PV systems. MACRS provides better market certainties for the investors, whereas the LSP helps the solar energy developers. Conversely, the ITC reduces the tax liabilities for individuals and businesses to encourage investment in solar energy technologies. Also, third-party financing and NEM support the growth of solar PV systems [304]. The country has different policies state-wise [306]. The Brazilian government introduced the NEM policy in 2012 and revised it in 2015. The prosumers receive energy credit for exporting net excess energy into the grid that can be compensated for over five years. PV systems up to 5 MW (micro and mini plants) are eligible for energy sharing through the NEM scheme [306].

China adopted the FiT policy to support PV installation and integration into the grid in 2013 and amended it several times. Initially, the country set the benchmark FiT rates at RMB 0.90/kWh, RMB 0.95/kWh, and RMB 1.00/kWh with a guarantee period of 20-year according to the solar power resources and construction costs for three different resources zones nationwide. The standard subsidy rate was RMB 0.42/kWh [311]. However, through multiple amendments, the FiT rates were changed to RMB 0.40/kWh, RMB 0.45/kWh, and RMB 0.55/kWh for the centralized ground-mounted plants in different resource zones. The amendments set FiT rates for the poverty alleviation projects as RMB 0.65/kWh, RMB 0.75/kWh, and RMB 0.86/kWh for three different zones [312]. As an early promoter of solar PV systems, Japan provided investment and financing aid by introducing RPS in 2003 and replacing it with FiT in 2012. In 2016, the country adopted a FiT rate of 31 ¥/kWh for PV systems less than 10 kW with a guarantee of 10-year, whereas the FiT price of 24 ¥/kWh was for the systems higher than 10 kW with a warranty of 20-year [306]. In Australia, Victoria state implemented FiT in 2009 to support PV systems up to 5 kW by providing 0.60 $/kWh for the energy export into the grid [313]. A minimum tariff was set to 0.05 $/kWh in 2016 through several modifications and upgrades. The state introduced a time-varying FiT policy by setting an off-peak rate of 0.099 $/kWh, a shoulder rate of 0.116 $/kWh, and a peak rate of 0.146 $/kWh from July 2019 for any system is less than 100 kW [314]. This time-varying tariff encourages the prosumers to export energy during peak hours, increasing system generation capacity and helping demand-side management. As can be noticed, most countries went through successive regulatory changes to cope with the impacts of the PV system integration into the grids. The resource availability and investment costs are also the driving force for such regulatory changes. Therefore, the regulatory authorities should follow up with all associated factors to develop appropriate policies to promote grid integration of PV systems.

IV. CONCLUSIONS

Meeting the growing energy demand from safe, secure, and environment-friendly resources by substituting conventional fossil fuel-based energy resources and reducing GHG emissions is one of the top priorities of the planet earth. Therefore, the solar PV markets are experiencing astronomical growth worldwide due to their reduced price, higher comparative efficiency, government incentives, and technological advancement. However, solar PV integration into the grid is not smooth; instead poses many operational, technical, and economic challenges. This paper reviewed such grid integration challenges of PV systems along with available solution technologies. The reviewed significant challenges are the accurate output power prediction, voltage, frequency, angular stabilities, injection of harmonics, and system fault ride-through capability. Other reviewed challenges include the up gradation of the protection schemes of the traditional power systems, transmission congestion management, penetration into the electricity markets, and socio-economic and environmental issues due to the incorporation of PV systems into the grids. Finally, this article discussed available methodologies investigated and explored by the researchers and scientists to combat the reviewed challenges.

This article discussed grid codes for the effective integration of the PV systems into the grid, among many solution strategies. It also discussed different advanced control strategies explored and tested for PV integration and efficient PV power prediction techniques. Besides, this paper sheds light on the deployment of energy storage technologies to effectively mitigate many technical and operational challenges associated with grid integration of solar PV systems. Energy policies of selected countries with various weather conditions were also discussed that promoted the exponential growth of the PV systems. Moreover, this article identified research gaps in the discussed challenges in the respective sections. The findings of this article provide meaningful information for power system researchers and decision-makers (regulators, planners, operators, and reliability coordinators) on how to combat challenges and develop innovative ideas related to grid integration of PV systems.

NOMENCLATURE

AC: Alternating current
ANFIS: Adaptive neuro-fuzzy inference system
ANN: Artificial neural network
BESS: Battery energy storage systems
CAESS: Compressed air energy storage systems
CAISO: California Independent System Operator
CEG: China Electric Grid
CSP: Concentrated solar power
DC: Direct current
DSA: Differential search algorithm
ESS: Energy storage systems
FACTS: Flexible AC transmission systems
FCESS: Fuel cell energy storage systems
FESS: Flywheel energy storage systems

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FiP: Feed-in-premium
FiT: Feed-in-tariffs
FRT: Fault ride-through
GA: Genetic algorithm
GHG: Greenhouse gases
GW: Gigawatts
HVRT: High voltage ride-through
IoT: Internet of things
IEEE: Institute of Electrical and Electronics Engineers
ITC: Investment tax credit
LSP: Local solar permitting
LVRT: Low voltage ride-through
MACRS: Modified accelerated cost recovery system
MPP: Maximum power point
NEM: Net energy metering
OCR: Overcurrent relays
P2G: Power-to-gas
PDF: Probability density function
PCC: Point of common coupling
PF: Power factor
PHESS: Pumped hydroelectric energy storage systems
PI: Proportional-integral
PID: Proportional-integral-derivative
PSO: Particle swarm optimization
PSS: Power system stabilizers
PV: Photovoltaic
QS: Quota systems
REN21: Renewable Energy Policy Network for the 21st Century
RER: Renewable energy resources
ROCOF: Rate of change of frequency
RPS: Renewable portfolio standards
SCESS: Super-capacitor energy storage systems
SMESS: Superconducting magnetic energy storage systems
STATCOM: Static synchronous compensator
SVC: Static var compensator
SVM: Support vector machine
THD: Total harmonic distortion

ACKNOWLEDGMENT

The authors appreciate the research facility provided by the Deanship of Research Oversight and Coordination (DROC) and the Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS) at King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia.

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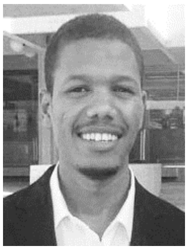

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