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Grid Integration Challenges of Wind Energy: A Review

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ABSTRACT The strengthening of electric energy security and the reduction of greenhouse gas emissions have gained enormous momentum in previous decades. The integration of large-scale intermittent renewable energy resources (RER) like wind energy into the existing electricity grids has increased significantly in the last decade. However, this integration poses many operational and control challenges that hamper the reliable and stable operation of the grids. This article aims to review the reported challenges caused by the integration of wind energy and the proposed solutions methodologies. Among the various challenges, the generation uncertainty, power quality issues, angular and voltage stability, reactive power support, and fault ride-through capability are reviewed and discussed. Besides, socioeconomic, environmental, and electricity market challenges due to the grid integration of wind power are also investigated. Many of the solutions used and proposed to mitigate the impact of these challenges, such as energy storage systems, wind energy policy, and grid codes, are also reviewed and discussed. This paper will assist the enthusiastic readers in seeing the full picture of wind energy integration challenges. It also puts in the hands of policymakers all aspects of the challenges so that they can adopt sustainable policies that support and overcome the difficulties facing the integration of wind energy into electricity grids.

INDEX TERMS Angular stability, energy storage system, fault ride-through capability, frequency response, grid codes, reactive power support, voltage stability, wind intermittency.

I. INTRODUCTION

Wind power generation is continually evolving globally and has become an essential component in the operation of the grid in most of the countries that invested in this field heavily. The annual growth of the wind power generation worldwide increases its penetration into the power system and its contribution to the overall energy supply. Total installed wind generation capacity in 2018 was 599 GW globally, where the added capacity of that year was 53.9GW [1], [2]. By the end of 2019, the installed wind capacity is expected to reach 664.5 GW, with an additional capacity of 65.4 GW, an increase of 17.4% over 2018 [3]. Countries' policies and legislation for the transition to clean energy will contribute to more wind energy projects in the future. Fig. 1 shows the growth of wind energy over the last decade. Onshore wind farms are the most developed and globally used. In contrast, offshore wind farms are still in the cradle, and the reason for these differences between the two technologies is the technical difficulties and the cost. Fig. 2 shows the geographical share of the installed capacity of wind turbines around the world, where Asia tops the list, followed by Europe and North America and then the rest of the world.

Many efforts have been made to develop generic models of the four types used for the wind-generating system (type 1, type 2, type 3, and type 4) [4], [5].The International Electrotechnical Commission (IEC) is also developing standardized models of these types to be like their electrical power system counterparts. The generic models of the wind turbine system are shown in Fig. 8. For more details on the modeling and software develop them for analysis and stability studies purposes, the reader can refer to [6]–[14]. Components of each type are as follows

1) Type 1 and 2 System:
    - Induction generator (squirrel cage (type 1) and wound rotor (type 2))

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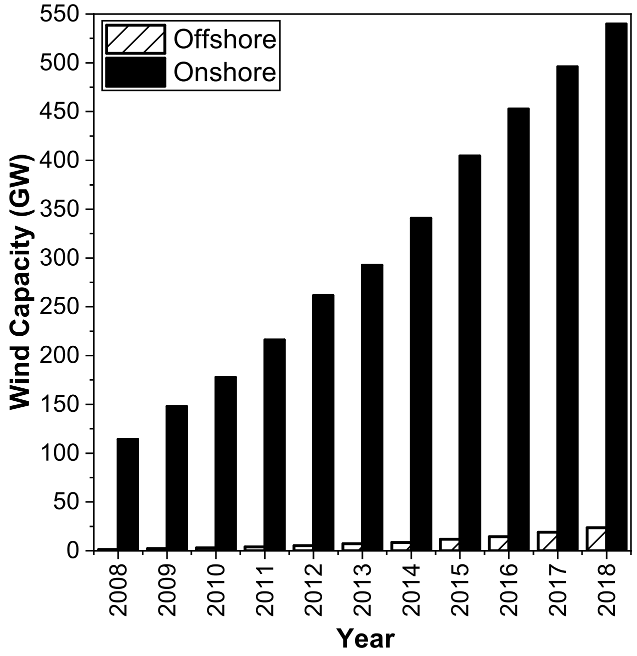


FIGURE 1. Wind installed capacity trend worldwide (IRENA).

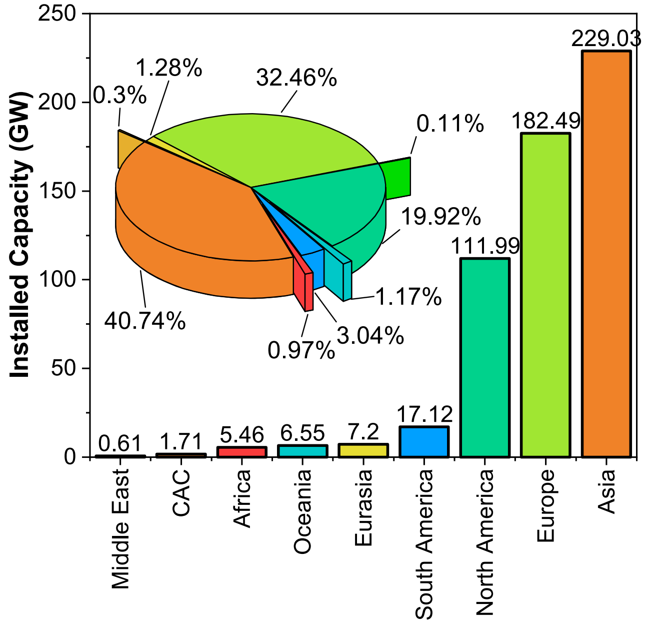


FIGURE 2. Regional installed wind capacity in 2018 (IRENA).

- Capacitors (Provide Reactive power to induction generator and to the grid (very limited))
- Gearbox to boost shaft speed (nearly 100 times)
- slip rings for type 2.
- control resistor for type 2.

2) Type 3 System:
   - induction generator (wound rotor), double-fed (DFIG).
   - Gearbox to boost shaft speed (nearly 100 times).

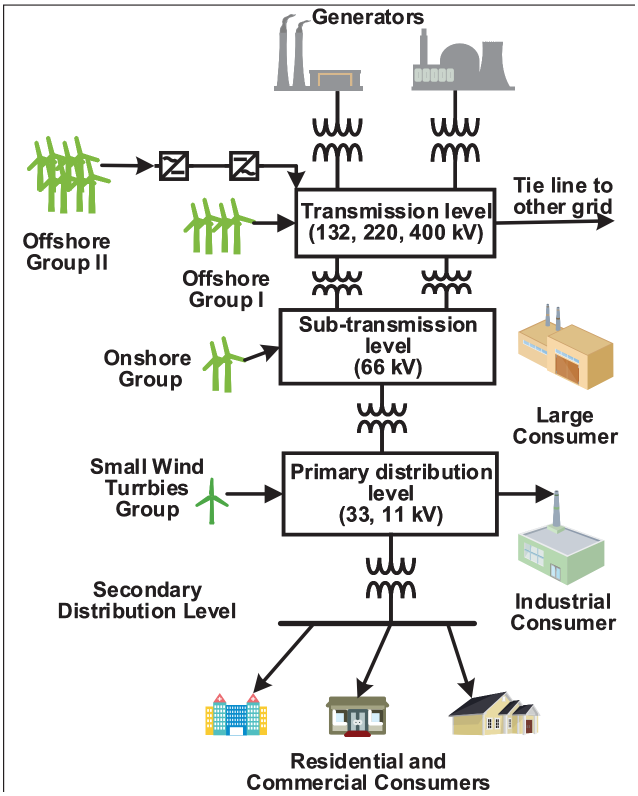


FIGURE 3. Power system grid with wind integration.

   - AC/DC-DC/AC converter (provide second supply to the wound rotor)
   - crowbar to protect rotor winding throughout the faults.

3) Type 4 System:
   - Generator (asynchronous, permanent magnet) or synchronous.
   - AC/DC generator side converter (covert AC (different frequency) to DC)
   - DC/AC grid side converter convert DC to AC (50 Hz / 60 Hz as needed).
   - Gearbox (eliminated in direct drive).

Fig. 3 shows the voltage levels to which wind turbines can be connected, depending on their size. Small turbines can be connected to the distribution network over a voltage of 0.4 kV to 33 kV if the group is large, we can move to a higher voltage level (66 kV) in the case of onshore farms, and finally, many offshore wind turbines connected to the voltage levels higher than 100 kV. Furthermore, in offshore wind turbines that are far from the transmission lines, it is preferable to use the HVDC to avoid losses and supply instability. This continuous growth and penetration must be matched by tools and information that help operators to manage the grid with resiliency and reliability. Many issues make the operators worried, including, but not limited to, power prediction, voltage/reactive power support, frequency stability, harmonics, power quality problems, small-signal stability, low voltage ride-through capability, protection, electricity market, and other challenges. Based on the mentioned notes, a handsome amount of researches and reviews have been emerged since the beginning of the integration of wind generation into the grid to address the challenges.

However, most of the reviews published in the field of wind power integration into the electricity grids focused on one context of the effects of integration, such as discussing technical, economic, social, or environmental challenges. The motivation for writing this paper is to go through and summarize all the challenges encountered due to the integration of wind energy systems into the grids. Thus, the reader can see the full picture of this topic. It also puts in the hands of policymakers all aspects of the challenges so that they can adopt better and sustainable policies that support and overcome the difficulties facing the integration of wind power into the electric networks.

Although the challenges of integrating wind power have been discussed extensively in literature, the relationship between the penetration rate of wind power and these challenges, has not yet been clarified, and therefore, the quantitative rating of the penetration which considered as a trigger for protection failure, Voltage deterioration, or others, is indistinct in the bulk power system.

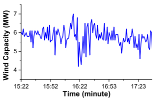
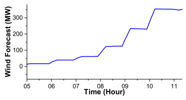
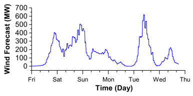
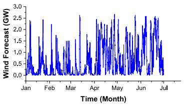
This paper reviews most of the critical challenges facing by the grids as a result of the integration of wind energy. Additionally, it discusses the available research to mitigate or address the impact of the integration. The technical challenges are discussed at the beginning of this article as one of the most influential one on the power system, followed by other challenges. Each challenge is discussed individually, focusing on the bulk integration of wind energy into the power system networks. Some solutions, including grids code, energy storage technologies, and other methodologies employed to mitigate the effects of the integration, are also included.

The rest of the paper structure is: Section II addresses wind power integration into the power grid challenges. In Section III, the solutions adopted by the legislators, regulatory bodies, and the contributions of researchers to alleviate the mentioned challenges are highlighted and discussed whereas Section IV presents the conclusions and future research directions in this field.

II. CHALLENGES OF WIND ENERGY INTEGRATION

Wind energy is one of the most important contributors to modern electric grids as a clean and environmentally friendly energy resource. The unique characteristics of the wind energy systems, including intermittent, turbine technology, and protection issues, bring new challenges for successful and economic integration to the grids [15]–[17]. This section addresses the impacts of wind energy integration on grids that must consider in order to maintain the stability and quality of the energy supplied to customers.

TABLE 1. The time horizon for the forecast.

Time scale	Sample	Usage
5 - 60 minutes		Regulation of real time dispatch decisions
1 - 6 hours ahead		Load following, next operating hour unit commitment
Day ahead		Economic dispatch, Unit commitment, and scheduling market trading
Seasonal/Long Term		Resource planning, contingency analysis

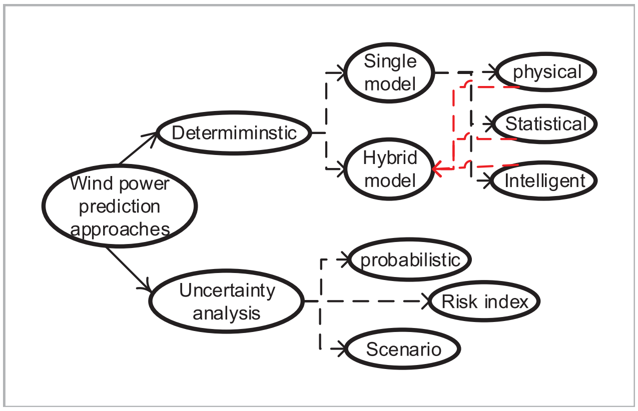


FIGURE 4. Wind prediction approaches.

A. OUTPUT POWER PREDICTION

Before the introduction of wind power in the grid, operators were interested in knowing the details of the generation that would help them in the process of units' commitment and the production cost of the unit in addition to spinning reserves. Increasing renewable energy share in the energy mix, especially wind turbines in many countries, has led operators to reconsider supply management in order to maintain grid flexibility and add efficiency to integrate the power supply from wind turbines and other intermittent energy sources [18]. In the case of high wind turbines integration, the prediction plays a significant role in reducing the cost of production as the lack of prediction requires the presence of spinning reserves in large quantities. Furthermore, unpredictable events of ramps can ruin the reliability of the grid. Finally, with wind turbines as a source of electricity, forecasting has become useful for network management [19]. However, there is no ideal strategy for the prediction of wind energy, as it is one of the most challenging meteorological items to be forecasted. Each methodology has its pros and cons, which may be reasonable in certain specific cases and inappropriate in different cases [20].

Depending on the operating need, the prediction divided into four periods (horizons), which are intra-hour (1-60min), short-term (1-6 hours), medium-term (day(s) ahead), and long-term (including week, season, year or more). Table 1 show these classifications and their most valuable uses.

The classification of forecasts based on the approaches used divided into two parts, deterministic forecasts and uncertainty analysis. The deterministic forecast includes four approaches: physical, statistical, intelligent, and hybrid. The uncertainty analysis divided into three, probability prediction, risk indices, and generation scenarios [21] (see Fig. 4).

The physical approach based on weather information (temperature, pressure, altitude, terrain, and others.) taken from various observation stations scattered in geographic areas modeled using dynamic equations (quasi-geostrophic theory, primitive equations, and others). The most famous predictive model called numerical weather prediction (NWP) [21]. One hindrance of this methodology is that it requires more calculation time, and is therefore inappropriate in short-term forecasting.

The statistical and intelligent approaches based on historical data, whether wind or generated power, resulting in a prediction of future power generation. As for the statistical approach, which is time series based, the science of statistics, probabilities, and stochastic represent the mathematical requirement. An example of the models used is the regression method and its various subset [22], [23], Kalman filter [24], and copula theory [25]. Archer *et al.* [26] presented wind power forecasting as a challenging issue for grid integration. The authors used the ARMA model to predict power. Huang *et al.* [27] developed a statistical model based on the mixed skewed distribution for the prediction of wind power on the transmission network of China. Naik *et al.* [28] developed a hybrid technique based on empirical mode decomposition with non-iterative kernel ridge regression for fast and efficient prediction of short-term wind speed/power using real-world data sets. Time series algorithms are robust and straightforward but are not capable of forecasting wind energy generation effectively as they are slow and linear in nature. Therefore, they are incapable of predicting the non-linear and non-stationary wind power fluctuations effectively [28].

Innovative improvement has prompted the development of savvy arrangements such as the use of artificial intelligence (and its subset such as machine learning and deep learning) in the prediction. The outcomes of forecasting using an intelligent approach proved a high degree of accuracy and consistency along with another advantage where it can deal with nonlinear time series [29] due to their adaptive nature and flexibility [30]. Chen and Folly investigated the performance of artificial neural networks (ANN) and adaptive neuro-fuzzy inference systems (ANFIS) in predicting short term wind power and concluded their superiority over time series autoregressive moving average (ARMA) technique [31].

The researchers modeled the stochastic behavior of the wind speed employing many approaches including the Weibull probability density function (PDF) [32]–[34], Rayleigh PDF [35], Monte Carlo method [36], time series analysis [37], statistical method [38], and artificial intelligence [39]. Then, in the next step, they calculated the power output of the wind farms from the wind speed associated power curves. The power curves are mathematical functions provided by the manufacturers to relate the wind speed with the output powers precisely [40]. Jordehi [41], reviewed possible techniques that dealt with the power systems uncertainties and found the Monte Carlo simulation (MCS) and scenario-based analysis (SBA) are simple and easy to be implemented over the point estimate and probabilistic methods. However, the MCS and SBA techniques are computationally expensive.

B. REACTIVE POWER/VOLTAGE SUPPORT

The machines used to generate electricity from wind energy are mostly induction generators, which by their very nature, consume reactive power (i.e., they require a reactive power source for excitation). So, they do not have the advantage of supporting the grid with reactive power like the synchronous machines [42]. Many research articles addressed ways to improve wind turbine in terms of providing reactive power support during the voltage collapse. Opila *et al.* [43] studied the ability of wind turbines to provide reactive power to the grid. According to the authors, the limits set for the value of voltages at the point of common coupling (PCC) are one of the factors that lead to reducing the amount of available reactive power. Mohseni [44] designed a control strategy to increase the reactive power support of the wind turbines connected to the AC grid through voltage source converters to adhere to the Danish grid code. The study suggested that wind turbine grid-side converter should be allowed to overload during the transient fault to avoid the increase of voltage values of the DC link connection above the permissible limit.

Xie *et al.* [45] and Liu *et al.* [46] proposed fault ride-through capability enhancement technique for the doubly-fed induction generator-based wind turbines to support both active and reactive powers. The proper design of wind turbines control systems is essential for optimal utilization of wind power plants by replacing the conventional generators. However, the ability of the wind power plants to produce or absorb reactive power depends on the strength of the grid and the length of the transmission lines [47] The study results reveal that wind turbines can provide reactive power support. Also, the coordination between the different reactive power sources associated with the wind turbine is essential to avoid instability problems. A wind turbine can contribute to the grid side flexibility by improving the voltage profile through the process of generating and absorbing reactive power [48]

Maintaining the voltage within the operational limit is always considered as one of the critical issues, especially when introducing new technology associated with the load or power generation. For instance, the fluctuation of wind power output causes voltage fluctuations and flickers that depend on the variation of wind speed and type of generation system [49]. Generators that dominate the wind turbine industry are divided into fixed-speed, variable-speed induction generators. The latter includes two categories: Variable speed doubly-fed induction generators and direct drive varying speed synchronous generators [50]. The fixed speed generators absorb reactive power that relies on the speed of the rotor [51]. This phenomenon is responsible for the creation of voltage fluctuation in electricity grids [52]. However, the deployment of the variable-speed wind turbines can smooth 75% of the voltage fluctuations produced by fixed-speed turbines [50], [53]. One of the main problems of this technology is its inability to meet the requirements of the network (grid codes) as it does not depend on the power electronics to connect with the network, which in turn are responsible for the control of reactive power and terminal voltage [54].

Additionally, the short circuit impedance at the point of connection between the wind turbine and the grid is another fundamental factor that contributes to the voltage fluctuations. For a more significant impedance, there will be a more considerable fluctuation in voltage and vice versa, as discussed in [55]. One of the characteristics that make the grid secure is to have a high fault current and a low deviation voltage, in other words, a small equivalent impedance. Proposed solutions in the case of integrating wind turbines to weak networks include the deployment of flexible AC transmission Systems (FACTS) devices and the modification of the plant's control systems [56]–[58].

In order to deal with the voltage fluctuations, a study revealed that the proportion of renewable energy in networks should not exceed 20% [59]. There are other studies and simulation analyses that indicate that penetration can be more. For instance, Feilat *et al.* [60], simulated the Jordan electric network and concluded that if the wind penetration level goes beyond 40%, the network face fluctuation. A study conducted on the Western Electricity Coordination Council (WECC) network in the USA showed that an annual penetration rate of 35% is technically feasible [56].

C. IMPACT OF THE FREQUENCY

The introduction of the wind-generated power to the electrical grid contributes to the reduction of the overall system inertia, and the effect is substantial for the smaller isolated systems [61], [62]. The control strategies of most of the wind power plants isolate the mechanical system from the electrical system in case of any disturbance that reduces the wind power plants contribute to the network inertia [63].

According to Morren *et al.* [64], the addition of an auxiliary controller to the wind turbine central control unit can change the torque set point to make it adaptable to the variation of grid frequency by taking advantage of the wind turbine mass during a disturbance. Using the same concept, Conroy and Watson [65] proposed a controller to control the output power of a permanent magnet synchronous generator (PMSG) based on grid frequency. Another control strategy was tested on a PMSG wind turbine during frequency oscillations in [66]. During a disturbance, the wind turbine can emulate a conventional generator and provide inertia support by exploiting the hidden kinetic energy of the wind turbine. The primary frequency control method was adopted in [67] in order to deal with the frequency fluctuation of electrical networks. Siemens company has developed a full-converter based wind turbine generator with the ability to regulate frequency up or down according to the state of the power system [68]. Other solutions like the use of energy storage systems, kinetic energy extraction, and load control can be implemented to solve the frequency degradation problem due to the high penetration of wind energy [69].

D. IMPACT OF THE HARMONICS/POWER QUALITY ISSUES

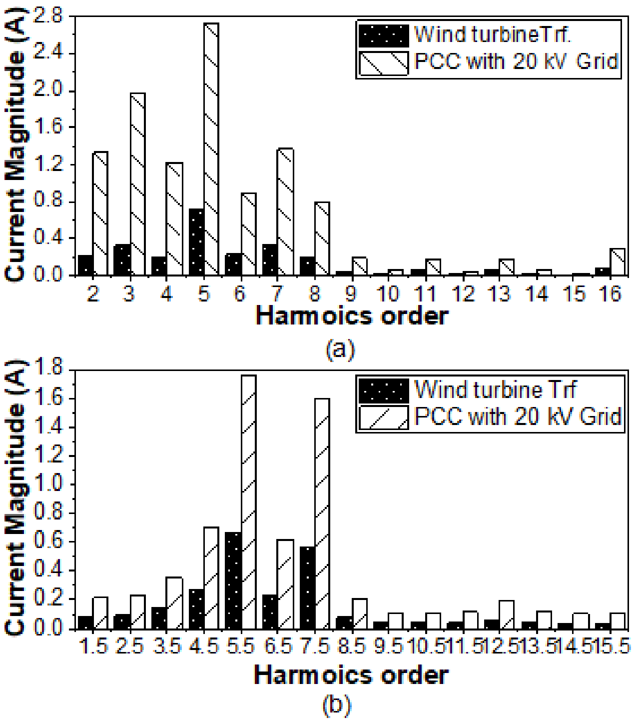
Wind turbines, like other conventional generators, must provide electricity of acceptable power quality (low harmonics emissions are one of these conditions) [70]. The integration of wind turbines into the grid will inject harmonics at different network levels.

To analyze harmonics and develop solutions to mitigate them, we need to know the elements that contribute to their emission. The elements that are the source of harmonics in the wind turbine system include cables used in the collector bus, turbine transformers, filters, capacitors, power factor correction devices, and power electronic converters [71]–[73]. Wind turbine harmonic models for types 1, 2, 3, and 4 are discussed in [74]–[76].

Several methods used to determine harmonics are discussed in [77], such as the harmonic power flow method, the distorted and non-distorted current method, the superposition method, the Harmonic state estimation method, and the IEC current and voltage phasor method.

The harmonics produced by a single turbine are somewhat small, while this rate increases for a wind farm at the point of common coupling (PCC), as shown in Fig. 5. In Fig. 5 (a), the values of the harmonic measured at the point of common coupling (PCC) increase by increasing the integration compared to the harmonic values measured for one turbine at the HV-side of the transformer. The value of the inter-harmonic shown in Fig. 5 (b) follows the same pattern of the harmonic indicated in Fig. 5 (a). The most common harmonics injected from wind turbines are (5^{th}, 7^{th}, 11^{th}, 13^{th}, and $17^{th)}$ [72], [78]. There is a detailed analysis of inter-harmonics and harmonics in [72].

Also, the contribution of wind turbines to the short-circuit capacity of the transmission system is minimal, making the transmission link weaker, resulting in increased levels of harmonics in the voltage. Several studies investigated the harmonic injection issues resulting from the integration of wind turbines to the grid. For instance, according to [79],



(a)

(b)

FIGURE 5. **Harmonics in wind farm consist of 6 wind turbines 2.5MW each connected to 20kV distribution network, Digsilent Powerfactory examples (DIgSILENT GmbH.) a) Harmonic at PCC and one wind turbine level. b) Inter harmonic at PCC and one wind turbine level.**

the integration of a PMSG wind power plant to a medium voltage network generated harmonics in the frequency range of 2 kHz to 150 kHz that can effectively lead towards malfunctioning of the power line communication.

Reis *et al.* [80] have established a control strategy to integrate the functions of filters into full-converter wind turbines to reduce current harmonics produced by each wind turbine. The developed strategy mitigated current harmonics by regulating the angle and amplitude of the inverter voltage, thus eliminating harmonics different from those of the bus bar inverter voltage. According to their discussion, the proposed strategy eliminated harmonics without the need for hardware modification. Vargas and Ramirez [81] proposed an extended harmonic domain model to study the frequencies of harmonics of mechanical and electrical transient states of wind turbine variables. Besides, the deployment of appropriate energy storage systems [82] and filter [83] can contribute to mitigating the harmonics introduced due to the integration of wind power plants.

To sum up, the development of converters requires further investigation to suppress the harmonics generated by wind farms integration to make reliable sources of power supply.

E. ANGULAR STABILITY/INTER-AREA OSCILLATION

The angular stability is the ability of the interconnected machines in the power system network to stay synchronized subjected to any disturbances [84]–[86]. Increased wind energy penetration in the grid improves small signal stability, Yang *et al.* [87]. In the short term, the reactive power of the wind turbine may create angular instability in the power system [88]. Gautam *et al.* [89] analyzed the effect of the steady increase of the number of integrated DFIG-based wind turbines on the stability (transient and small-signal) of a bulk power system. The results showed a significant change in the overall inertia of the power system concerning the amount of wind generation. The higher the contribution of the wind turbines to the grid, the lower is the inertia. In [90], the authors studied the effect of wind turbines on the transient behavior of the power system. The results revealed the superior performance of the DFIG type turbines over the squirrel-cage generator turbines. Besides, the integration of many wind turbines implicitly replacing the synchronous generators could destabilize the grid. In order to deal with the angular instability of the electric grids integrated with wind farms, the researchers need to investigate this topic more deeply.

F. GRID RELIABILITY AND RESILIENCY

The building blocks of network reliability can be summarized in 1) Frequency support by maintaining it stables within the electricity system by ensuring the balance between generation and demand and having a rapid response in cases of unbalance by reducing generation or demand. 2) Support the voltage by maintaining it within the operational limits of the grid in cases of routine or emergency operation to prevent the collapse of the system [91]. The conventional generation system provides these services as an essential part of its work, but the emergence of renewable sources such as wind turbines as a source of electricity has changed the dynamics of the grid [92]. In the next lines, reliability services that give the grid reliability in terms of frequency and voltage will be identified, as well as the wind turbine position of these services.

1) VOLTAGE SUPPORT

a: REACTIVE POWER AND VOLTAGE REGULATION

The ability of the system to provide reactive power (leading or lagging) according to the need to maintain the grid voltage within the limits of operational permissible in cases of normal or contingency operations. Wind turbines can provide the network with this service through power electronics, which are part of the control circuit. This service is available whether the turbine is producing power or not [93].

b: LOW VOLTAGE RIDE THROUGH

The fault that occurs in a particular area of the grid may not be a risk in itself, but the loss of generating sources due to protection devices operating in the event of low voltage may lead to complete collapse, so generating sources are designed with a system to ride through the voltage drop for a certain period of time so that the protection devices can isolate the parts that are faulty and controllers rebalance the grid.

Wind turbines are designed with controllers that enable them to stay in the grid and ride through voltage drop during contingency events [94].

2) FREQUENCY SUPPORT

a: ARREST FREQUENCY DROP/ FAST FREQUENCY RESPONSE

In the event of an emergency (loss of a transmission line or primary generation source), the system frequency declines at a rate dependent on the inertia of the system. There are two ways to slow down the frequency at this stage and help to reach the nadir before the under-frequency relays pick up. The first process is by large inertial torque, which is characteristic of large conventional generators. The second technique is to inject a high amount of the active power in the grid and provide sufficient kinetic energy in what is known as fast frequency response (FFS). These days, wind turbines can provide this service through added controls [95].

b: PRIMARY FREQUENCY RESPONSE

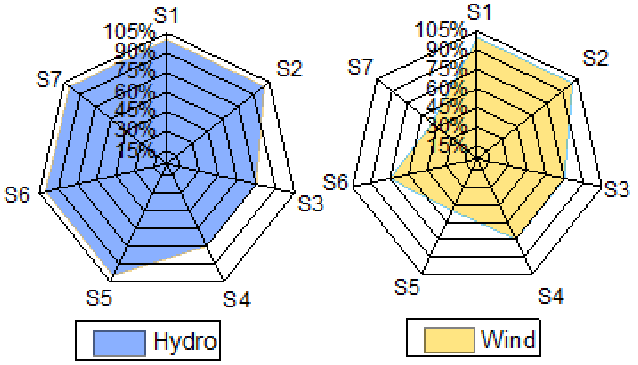
The governors perform this service by increasing the production to compensate for the loss or decrease in the case of overproduction, and it is an automatic response that occurs when the frequency deteriorates. Wind turbines can also participate in the primary frequency response in the presence of appropriate controls [96].

c: FREQUENCY REGULATION

This process is performed by generators responding to the feedback signal to adjust the frequency at normal operating value. This service is used during normal operation or recovery period following a contingency. Wind turbines can participate in this service provided that there is sufficient capacity at the moment of need (wind availability and the generated power is less than the maximum power of the turbine) [97].

3) FLEXIBILITY/ DISPATCH

Changes are a general feature of the electric power system, so flexible resources can counter these changes, whether anticipated or occurring randomly. Flexibility can include ramping in down and up directions, fast start time, fast shutdown time, minimum (down time /up time), and minimum stable generation level [98]. The design of these sources and the type of fuel used are influential elements of flexibility [99]. Wind turbines can contribute to this service in a downward direction if they are in production mode and with a quick response due to their use of power electronics in control. Also, if it is in a pre-curtailed mode, it can provide the service in an upward direction. Despite the above, the intermittent nature of the wind makes this service very costly when requested by wind turbines [100]. Efforts are being made to reduce the cost of utilizing this service through wind turbines [101], [102]. Fig. 6 is a summary of the wind turbine reliability and resiliency services. In Fig. 6, wind turbines compared with hydro power, which is the best provider of reliability and flexibility in the power system. We note that the wind turbine performs an excellent service concerning (voltage ride through and reactive power support) and is very good at slowing down the frequency, stabilize frequency and regulation. In the frequency recovery phase and flexibility, its performance is average and this due to the cost. For more information on this topic, the reader can view this article [103] by Milligan, which details the reliability and flexibility services and their source in the grid.



Disturbance ride through	S1
Reactive and voltage support	S2
Slow and arresting frequency	S3
Stabilize frequency	S4
Restore Frequency	S5
Frequency Regulation (AGC)	S6
Dispatchability/Flexibility	S7

FIGURE 6. **Wind performance in reliability/resiliency service verses hydro power [103].**

G. PROTECTION CHALLENGES

One of the most common types of power system failure is a short circuit. Therefore, protection devices are designed to represent the shield, which works to avoid loss of equipment or damage, either from the side of suppliers or consumers in the event of an electrical short circuit. In the future expansion of power grids, planners reassess these devices' settings by analyzing the short circuit test results.

Assessing the contribution of wind turbines to the short current of the transmission network is of great importance to know the impact of these plants and the stress they can cause to the elements of the network. The impact of wind turbines and their contribution to the short current depends on the type of wind turbines. Detailed models of wind turbines and their characteristics can be found in [104]–[107].

Wind turbines of type 1 and 2 have almost the same characteristics with a slight difference of type 2 represented by the additional resistance of the rotor, and thus the contribution of these two types to the short-circuit current is almost the same. The short-circuit current in type 1, 2, and 3 is the highest and occurs at the 3-phase fault, with a value ranging from 3 to 6 times the rated current. As for type 4, the short-circuit current found a value equal to (110% or more) of the rated current, and the reason for this is that its circuit is separated from the grid by a converter [105], [108], [109]. The rate of the short current at the point of common coupling (PCC) depends on the number and type of wind turbines connected in parallel.

The transmission networks face different protection challenges due to bulk penetration of the wind power including under/overreach issue of the relays due to change of fault impedance [110]. In response, many protection schemes have been proposed including adaptive logic program based scheme [111], adaptive distance relay setting scheme [112], support vector machine-based scheme [113], data-mining-based intelligent differential relaying [114], and wavelet and Fourier Transform based differential relaying [115]. The level of fault current, in addition to the selection and coordination of protective devices, are the main challenges of the microgrids incorporated with the wind [110]. Among many solutions adaptive overcurrent protection scheme [116], centralized communication with a localized backup scheme [117], fault distance estimation-based protection scheme [118], fuzzy inference system based scheme [119], microprocessor-based scheme [120], oscillation frequency and transient power-based scheme [121], parameter estimation approach [122], and voltage-current-time inverse-based scheme [123], are widely used protection schemes.

Besides, the selection of generator type for wind farms, *i.e.*, synchronous generator, induction generator, or converter interfaced generator, also plays a vital role in the design of the protection scheme of the electricity grids [124]. The synchronous generators have long-term high-current sustainability characteristics, and the inductive generators fault current decreases gradually. Conversely, the short circuit current of the converter-interfaced generators is limited to two or three times the rated current value of the generators.

For low voltage networks, the protection systems in the presence of renewable energy require special attention specifically in the distributed generators (DG) because it exposed to a new phenomenon of multi-directional power flow [125]. The traditional protection schemes (*i.e.*, overcurrent relays) used in the distribution networks fail to protect the networks when a large number of DG are integrated into the grids [126]–[128]. Directional Overcurrent Relay (DOR) can offer a promising solution by avoiding sympathetic tripping [129]. However, the bulk penetration of intermittent RER changes the fault level of the networks, and the DOR protection scheme cannot be able to protect the networks [130]. In addition to the mentioned challenges, other protection challenges, including blinding protection, false tripping, loss of coordination, islanding problems, and auto recloser problems for distribution networks with RER, have been reported in [110]. The authors also suggested new protection schemes for the distribution grids to face the mentioned challenges, including voltage-based protection, distance protection, harmonic restrained protection, adaptive relaying, use of fault current limiters, and restriction on wind and RER penetration.

To sum up, each protection scheme has its pros and cons, as discussed in [110]. Accordingly, there is still a need to develop comprehensive protection plans for the power system grids given every aspect of protection as well as to determine measurable ratios for the level of penetration of wind turbines in the grid at which the system operators need to review protection system.

H. LOW VOLTAGE RIDE-THROUGH (LVRT) CAPABILITY

The ability of wind turbine based power plants to stay connected to the grid during faults or voltage dips for a specified period is called Low Voltage Ride-Through (LVRT) capability [131]. Several innovative techniques have been reported in the literature to enhance the system ride-through capability, including a wide range of control strategies [82]. Among many control strategies, Liu *et al.* [132] proposed an integrated control strategy between a bi-directional buck-boost converter and a grid side converter to enhance the reliability of operation of a PMSG-based wind turbine. The adopted technique worked in normal operation mode and under a fault condition. The response of a wind turbine to a short circuit depends on the type of wind turbine. For instance, if the fault applied at the terminal of DFIG-based turbine, the short circuit current can reach up to five to six per unit (p.u.) of the rated rotor current that could damage the turbine [133], [134]. Zhu *et al.* [135] proposed a strategy to enhance the low voltage ride-through capability based on inductance-simulating control to coordinate and constraint both rotor voltage and rotor current. The equivalent rotor inductance is directly proportional to the rotor voltage and inversely proportional to the rotor current, which requires constraints to a trade off between the permissible values of the two elements. The results of experiments showed that the strategy could reduce and suppress the post-fault current within the acceptable range.

Mohammadi *et al.* [136] have proposed an improved fault ride-through for a DFIG-based wind turbine under symmetrical and unsymmetrical faults. The strategy relied on the control of the rotor side and grid side converters to reduce the rotor and stator overcurrent and inject reactive power to the grid side to support voltage recovery, latter because of active compensation of the fault ride-through capability. Conversely, the passive compensator relied on connecting a rotor current limiter resistor in series with a rotor winding, thereby reducing the rotor and stator fault current. Furthermore, Naderi *et al.* [137], developed an optimum resistive type fault current limiter to achieve maximum fault ride-through capability with a constant-speed wind turbine. An effective control strategy for low voltage ride through for a PMSG-based variable speed grid-connected wind farm was proposed in [138], where a three-level neutral point clamped converter performed the power conversion. Alam *et al.* [139] developed a non-superconducting bridge-type fault current limiter (BFCL) to augment the fault ride-through capability of a DFIG wind power system and showed that the control strategy outperformed over the series dynamic braking resistor based strategy.

I. PLANNING CHALLENGES

In addition to the discussed operational and protection challenges, large-scale integration of wind energy imposes complexities into power system planning as well [140]–[143]. Traditional but widely adopted power system planning and simulation modeling tools are employed to design optimal generation portfolios throughout the planning horizon where the cost minimization is the objective function in most of the cases [140]. Such modeling approaches do not consider renewable energy-related uncertainties and proposed solution aspects in their planning stages [144]. However, due to the limited dispatchability of wind energy system, dispatchable power plant provides a quick generation supplement during low wind speed, energy storage system smooths the fluctuation, transmission grid balances generation and demand, and demand-side management controls non-critical loads to strengthen the system elasticity [145]–[149]. Therefore, planning tools need to be upgraded to achieve the economy and technicality of the wind power, considering the practical constraints and available flexible solutions.

In response, researchers are putting their efforts to cope up with the challenges of traditional power system planning tools due to the bulk integration of wind power. For instance, Zhou *et al.* [145] quantified the impact of wind generation and flexibility requirements by exploring an integrated energy assessment model and evaluating the role of wind energy in the power sector of China. Rong *et al.* [150] developed a coordinated dispatching method to achieve the highest economic benefit from hybrid systems by consuming extra wind power in the heat storage system. An advanced methodology to reduce error magnitude in the generation expansion planning model considering the integration of wind power and the role of energy storage technology was presented in [151]. Roos & Bolkesjø [149] investigated the demand flexibility on the load profile and electricity markets of the German electric system. Wierzbowski *et al.* [152] presented an energy mix optimization model intending to balance daily load demand under the short-term operation of wind considering reserve requirement. Hungerford *et al.* [153] considered residential hot water systems as a flexible load to accommodate a high penetration of wind in the Australian Electricity Market. Dagoumas and Koltsaklis [154] classified and summarized a good number of power system planning models considering the integration of wind power. They discovered that all models have their pros and cons. Therefore, further investigation and development in power system planning models/tools under bulk integration of intermittent RER (i.e. wind) considering more constraints and benefits including generation flexibility, demand-side management, and role of energy storage system are still needed.

J. TRANSMISSION, COMMUNICATION, AND SECURITY CHALLENGES

In general, the wind power plants built far away from the traditional load centers that create stress on transmission infrastructure and made the power access point to the grid weaker [155], [156]. The stress on transmission infrastructure or transmission congestion is the widely known reason for the curtailment of wind power generation amongst other reasons, including excessive supply during low load periods, electricity market mechanism and policy, grid flexibility and resiliency, and interconnection issues [157]–[160]. The curtailment due to transmission congestion often leads to the operation of expensive generators instead of cheap wind power generation. Building a long-distance transmission corridor requires a longer time than construction of wind power plants. Thus, it hinders the transmission of available energy to the load centers. In response to the mentioned notes, the National Renewable Energy Laboratory (NREL) proposed a wind curtailment reduction process by the ongoing expansion of transmission infrastructure [161]. However, further research on the reinforcement of transmission infrastructure is necessary for the useful inclusion of wind energy into the energy generation mix by avoiding curtailment.

In order to ensure uninterrupted and secure power supply to the customers, the communication and security aspects are very crucial for the smart grids. The information o n the wind farms located far away from the load cent ers should be transmitted to the control center through internet protocol for monitoring and excellent scheduling in real-time. However, the existing wind farm monitoring and control systems are vulnerable to external attacks, and the Stuxnet and Ukraine power outages due to malicious attacks made the power system decision-makers worried about data security of the wind power plants [162], [163]. For instance, Zhang *et al.* [164], developed an evaluation technique of the power system reliability considering the trips of wind farm due to various cyber-attacks that indicated a reduction of the overall system reliability. In response to the mentioned issue, Lai *et al.* [163], proposed an active security defense strategy combining the whitelist and security situation assessment assisted in eliminating security concerns of data networking and enhanced the integrity of the cyber security defense for the wind power plants. However, the authors believe that the energy system and cybersecurity experts should undertake several research initiatives on the subject through joint research.

K. ELECTRICITY MARKET CHALLENGES

The wind power requires higher installment cost that needs several years for a return on investment. Active participation of wind power producers in the wholesale market can help them to overcome their higher investment costs as well as increase their profits. However, the electricity markets are very complex by nature where the electricity as a commodity needs to be traded instantaneously. Therefore, the power generation uncertainties of these resources create impediments in their participation in electricity markets, main ly in the short-term market, as the uncertainties lead towards the inefficient operation of traditional power plants to balance the generation and demand. Also, the wind power producers are a bit resistant to participate in bidding in the day-ahead market, as they have no guarantee of their exact production. Even they can offer a lower production than the output expected, which can lead to lower revenues because the plant can operate at below maximum power point (MPP). Besides, the peak of wind power generation and the peak of load demand may not occur at the same instance that may lead to operational challenges in load centers. Moreover, the lack of appropriate market framework and smart incentive packages hamper renewable energy trading [155]. Identifying emerging electricity market challenges and discussing several bidding strategies reported in the literature can effectively help in dealing with such challenges. Li and Park [165], proposed an advanced wind power bidding strategy in the short term electricity market incorporating required market information for a set of real data collected from a wind farm of the PJM market. Aquila *et al.* [166], analyzed the feasibility of investment in wind power plants to identify their major uncertainty parameters and risks in the Brazilian electricity market employing value at risk technique. The proposed approach verified the higher probability of economic feasibility for such projects. Besides, a novel approach proposed in for quantifying the influence of variable generation sources on future energy systems that showed with the increase of renewable energy penetration, the electricity price was reduced [167].

L. SOCIO-ECONOMIC AND ENVIRONMENTAL CHALLENGES

The environmental impact of wind energy is trivial compared to the environmental footprint of conventional energy sources [168]. In comparison to coal and oil, wind energy uses no fuel and releases no greenhouse gases. The energy consumed in the produce and transport of products used in the building of the wind power project is equivalent to the clean energy generated by the turbine within a few months [168]. Onshore wind turbines are being viewed as affecting the scenery. Their turbine, path, transmission, and substation network can lead to *a concrete jungle* [169]. They generally require more property and more distributed than other power plants, and this would entail developing wind farms more massive than the cities itself to supply most cities and towns by wind solely. These usually also have to be constructed in both natural and rural regions, contributing to rapid industrialization and the loss of biodiversity [169]–[172]. A study by the Scottish Mountaineering Council found that wind farms in areas designated for natural scenery and scenic views have a detrimental impact on tourism [173].

Nevertheless, it is still possible to use the area between the turbines for farming [174]. There are also records of increased mortality of birds and bats in wind turbines as other synthetic structures occur. Based on specific conditions, the severity of the environmental impact might or might not be substantial [175]–[177]. According to study Loss *et al.* [178] collisions with onshore wind turbines killed somewhere 140,438 to 234,012 birds, whereas oil mines slayed between 500,000 and 750,000 birds. Nature Canada's study reported that 13,060 birds were killed per year by wind turbine blades, while the petroleum industry caused 18,661 bird deaths [179]. There is no record of accidents at offshore wind turbines. Offshore wind turbines introduce additional objects on the seabed that may damage the benthic fauna and flora by blocking sunshine into the seawater, change the neighborhood fish distribution, and affect overall biodiversity [180], [181]. In particular, marine mammals, including porpoises and seals, react to the construction of offshore wind power plants [182].

Several scientific studies with peer- reviewed on wind farm noise were conducted and found that wind farms infra-sound is not a threat to public health and there is no empirical evidence of "Wind Turbine Syndrome" triggering vibroacoustic conditions [183], [184]. The law sets out criteria for distance to residences and noise limits. In compliance with the Statutory Order on Wind Turbines for Danish [185], wind turbines must comply with sound limits. The boundaries set between 39 and 44 dB (wind speeds of 8 m/s) and 37 to 42 (wind speeds of 6 m/s), and for lower frequency, the limit is 20dB. No hearing damage is typically caused by noises between (0-60) dB levels [186].

The low-frequency noise produced by wind turbines contributes to stress and headaches [187]. The air authorities in Germany imposed restrictions on the heights of the onshore wind power plants as they create visual disruption [188]. In addition, the interference of the wind power plant equipment with the radar or television hampers their signal strengths [189]. These effects may lead to the reduction of the land price in the neighborhood of the wind power plants [188]. The construction of wind power plants and transmission corridors may disturb the local ecosystem that may require a longer time for recovery [181].

In response to the mentioned issues, the wind turbine manufacturers are putting efforts in redesigning the wind turbines to reduce the noise levels and enhance their aesthetic views. Therefore, public acceptance of wind power plants are gaining momentum with time, and they show a positive attitude if the wind turbine structures look nice, impressive, and produce less noise [177], [189]. However, there is still a need for further investigations on turbine size and social acceptance, landscape appreciation, appropriate inclusion of local inhabitants in the planning process, and other environmental factors. Furthermore, prevention and protection measures must be taken to lessen avian mortality and marine biodiversity with a thorough and comprehensive investigation.

III. SOLUTIONS ADOPTED TO MITIGATE INTEGRATION EFFECTS

To resolve the challenges mentioned in association with the integration of wind energy to the grid, accurate modeling, simulation and evaluation techniques are needed to investigate power systems and develop adaptation strategies. There are hard ways to solve problems by over-sizing everything, and the result is a costly, inefficient power system. The other way is through soft paths to solve problems by more control & optimal operation and a cheaper, more efficiently operating power system) [190]. Scholars follow the soft paths for reliable integration of wind power into the grid that make them observable and controllable through the achievements of better flexibility, stability, and resiliency. Many proposed solution techniques have already been discussed in the respective sections. This section focuses on a few selected but very crucial techniques for the effective grid-integration of RER.

A. GRID CODES

The technical specifications of the electricity grid for safe, secure, reliable, and economical operation is commonly known as grid code. Any grid code is designed by the authorities responsible for monitoring the integrity and operation of the power system. Its contents can vary from country to country based on the requirements of the participants, especially, the transmission companies. It dictates the integration of any power generation, including renewable energy generation. All Wind energy producers should adhere to the available grid codes that include network frequency and voltage variation requirements, fault right through, reactive power, and power factor regulation capabilities. Samples of grid codes for frequency tolerance, transmission voltages range and reactive power requirement for wind generators in some countries are given in the Appendix A, Table 5, Table 7, and Table 6, respectively. Grid codes in a vast majority of countries gave close attention to the fault ride-through capability of the wind turbine. For instance, Federal Energy Regulatory Commission (FERC) stipulated that the wind power plants must have the ability to stay connected for 625 milliseconds or 10 cycles during a three-phase fault on the HV side of the substation transformer [191]. Fig. 7 provides a comparison of two country standards (China and the United States) for wind turbine survival to stay connected when a three-phase fault occurs in the transmission system. The Chinese standard requires wind turbines to work continuously for 625 milliseconds when the voltage drops to 20% of its nominal value, as well as during the process of recovery to 90% of its nominal value within 2 seconds. Concerning active power, in this case, the standard requires that it be recovered at least 10% per second after the fault clearance [192]. For the U.S. standard adopted by the Electric Reliability Council of Texas (ERCOT), wind turbines are required to remain in service for 150 milliseconds when the voltage drops to zero due to a transmission network faults, as well as during the process of restoring the voltage to 90% of its nominal value in 1.75 seconds. The reader can refer to [193]–[201] for more details on the operational constraints of both renewable and non-renewable power plants. However, the shift towards sustainable energy requires a significant updating of the current grid codes through stability analysis of the electricity grids.

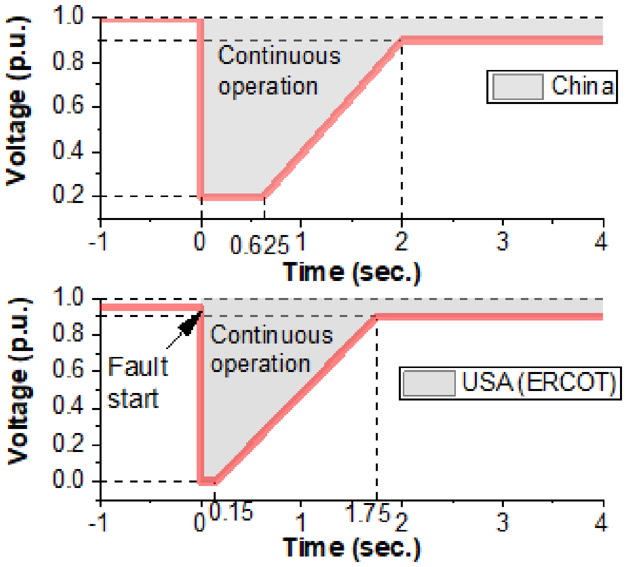


FIGURE 7. Voltage profiles stipulated by the grid codes during a three-phase fault [202].

TABLE 2. Monitoring and control strategies for wind turbines.

Types [reference]	Techniques
Torque Control (MPPT) [204]–[206]	Optimal Torque Control (OTC) Tip Speed Ratio (TSR) Hill Climb Search (HCS) Sliding Mode Control (SMC) Power Signal Feedback (PSF)
Pitch Angle Control [207]–[210]	Collective pitch control Individual Pitch Control
Grid integration Control [69], [211]	Frequency Regulations Reactive Power Control

B. ADVANCED MONITORING AND CONTROL STRATEGIES

The purpose of wind turbine control systems is to ensure that the turbine operates within the permissible limits due to wind speed fluctuations, and also to obtain the maximum possible power from the wind [203]. Also, the control devices enable the participation of wind turbines to support the grid in the event of a failure, which led to the deterioration of voltage or frequency. Table 2 below shows the types of control and techniques used in wind turbines.

C. ENERGY STORAGE SYSTEMS

Renewable energy resources suffer from the lack of dispatching ability that can be easily handled by the deployment of the Energy Storage System (ESS) [212]. Besides, ESS is one of the crucial technologies to enhance grid flexibility, resiliency, and reliability. This technology also can help to integrate RER into the grid effectively and to reduce the peak load demand and electricity price in the competitive electricity market. Most of the deployed EES in large-scale are based on pumped hydroelectric ESS (PHESS) and compressed air ESS (CAESS). The total volume of these two ESS technologies is equivalent to only 3% of the total global

TABLE 3. **Comparison of energy storage systems.**

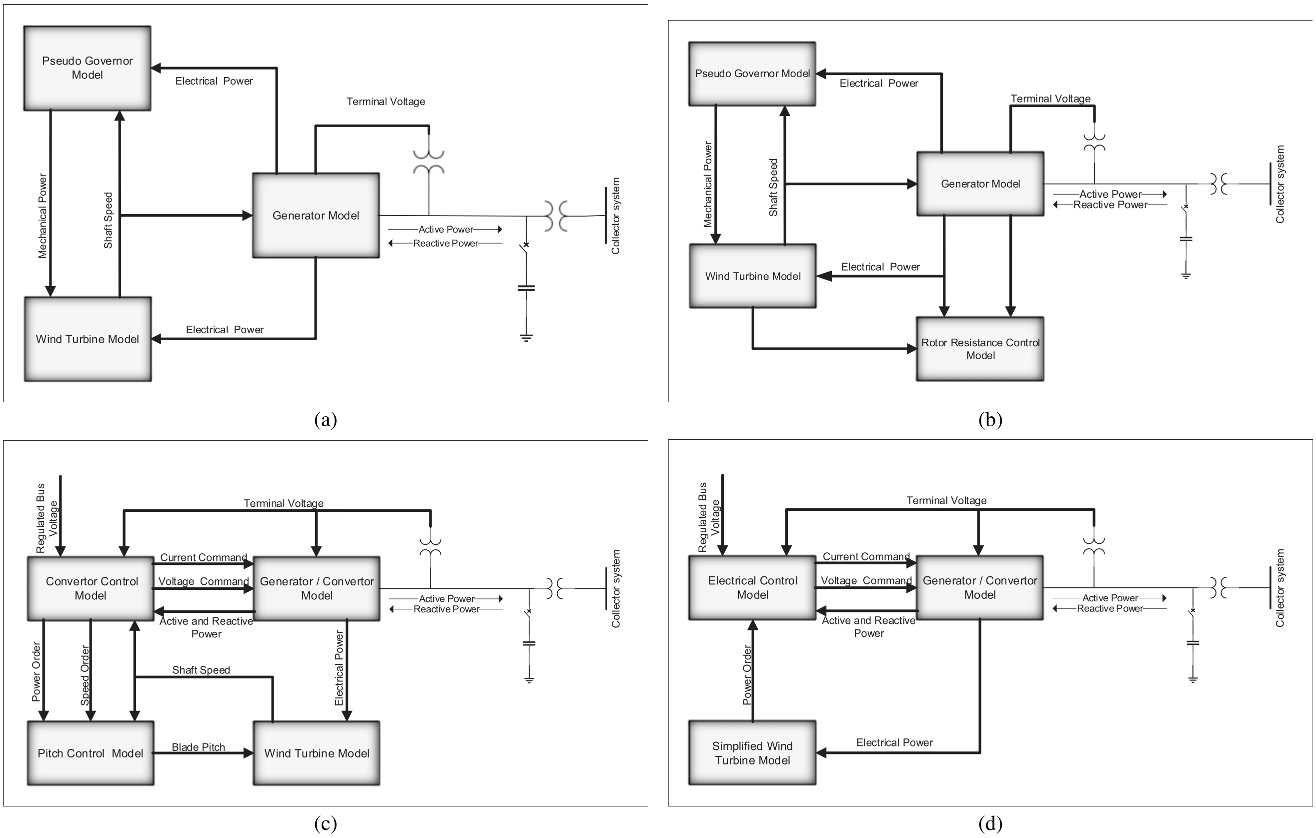
Technology	Normal Batteries	Flow Batteries	Super Capacitors	Flywheel	Compressed Air	Pumped-Hydro
Power density (W/kg)/(kW/m^3)	75 - 340 / 75-10x10^3	50 - 160 /1 - 270	0.1 - 10 / (4-12) x 10^4	(4-16 / 50) x 10^2	NA / 0.2 - 0.6	NA / 0.1 - 0.2
Energy density (Wh/kg)/ (kWh/m^3)	30 - 250 /75 - 620	60 - 80 /20 - 35	0.1 - 15 / 10 - 20	5 - 130 / 20 - 80	30 - 60 / 12	0.5 - 1.5 / 0.2 - 2
Operating temperature	-40 - 350	0 - 50	-40 - 85	20 - 40	Ambient	Ambient
Discharge time	s- 3 h	s - 10 h	ms - 1 h	15 s - 15 min	h-days	h-days
Charging time	min - 16 h	min - 4 h	s-min	<15 min	min - h	min - h
Response time	ms-s	<1ms	ms	ms-s	1-15 min	s - min
Lifetime (Year/cycle)	3-20 /(1-4) x10^3	5-20/(2-13) x10^3	>20 / 5 x10^5	>20 /10^7	20-40/no limit	50 -100/ >500
Maturity	mature &	Demo/early Comm.	*Comm.	mature	Demo/early comm.	mature

TABLE 4. **Wind energy policies in selected countries.**

Country	Installed capacity [216]	Year of Activation	Policy status	Policy Type
China	221GW	2001-2018	In force & Superseded	Regulatory Instruments ; Information provision; Codes and standards; Feed-in tariffs/premiums; Tax relief; Direct investment; [217]–[221]
United States	96.4GW	1994-2010	In force & Superseded	Codes and standards; Technology development; Grants and subsidies; Obligation schemes; Public Voluntary Schemes; Renewable Portfolio Standard [222]–[227]
Germany	59.3GW	1989-2012	In force	Feed-in tariffs/premiums; Grants and subsidies; Strategic planning [228]–[230].
India	35GW	2000-2018	In force & Superseded	Grants and subsidies; Green certificates; Feed-in tariffs/premiums; Loans; Strategic planning; Tax relief [231]–[235].
Spain	23GW	2007-2016	In force & Superseded	Regulatory Instruments; Feed-in tariffs/premiums; Codes and standards [236]–[238]
United Kingdom	20.7GW	2002-2014	In force	Feed-in tariffs/premiums; Regulatory Instruments; Codes and standards [239]–[242]
France	15.3GW	2006-2016	In force	Strategic planning; Feed-in tariffs /premiums [243], [244]
Brazil	14.5GW	2002-2016	In force	Tax relief; Regulatory Instruments [245]–[247].
Canada	12.8GW	1974-2016	In force & Superseded	Feed-in tariffs/premiums; Grants and subsidies [248]–[251].
Italy	10.1GW	–	Superseded	Strategic planning; Taxes; Codes and standards [228]

generation capacity [213]. Recently, battery ESS (BESS) received widespread attention due to the reduction of their costs and higher conversion efficiency [214]. Among other ESS technologies, flywheel ESS (FESS) is the electro-mechanical storage system, the super-capacitor ESS (SESS) is the electrostatic storage system, and the superconducting magnetic ESS (SMESS) is the direct energy storage system. The BESS creates power control challenges in the electricity grid, as its dynamic response is slow due to low power density. In contrast, the SESS and FESS can supply a high power demand that decreases their lifespan [215].

As discussed, each ESS has its pros and cons; essential differences amongst the widely employed ESS are presented in [252]–[254] (see Table 3). As can be seen, none of the existing storage technologies is capable of meeting both energy and power density simultaneously due to their physical limitations. Therefore, it is necessary to enrich the transient and steady-state performance of the storage system in energy management by hybridizing the available ESS that is suitable for both high energy and power applications [215]. For wind turbines to be available to system operators to dispatch as needed, production forecast data must be available for the following day or hours ahead. However, relative to the unpredictable wind nature, it is difficult to commit to a firm wind-power production, and as an effective solution to stabilize the capacity, energy storage systems can be an option to relieve the randomness associated with the error in wind power predictions. Energy storage systems can refine turbine output and control the rate of the ramp, MW/MIN, making the source of wind somewhat reliable in scheduling.



(a) (b) (c) (d)

FIGURE 8. Wind turbines generic models: (a) Type 1. (b) Type 2. (c) Type 3. (4) Type 4.

TABLE 5. Transmission voltage tolerance range for some countries.

Grid Code (Nominal frequency)	Nominal Voltage	Normal Operating Range	
Canada - Ontario [195]	115 kV	113 kV – 127 kV	
	230 kV	220 kV – 250 kV	
	500 kV	490 kV – 550 kV	
Denmark (50 Hz) [196]	400 kV	320 kV – 420 kV	
	220 kV	Not specified - 245 kV	
	150 kV	135 kV – 170 kV	
	132 kV	119 kV – 145 kV	
	60 kV	54 kV – 72 kV	
	50 kV	45 kV – 60 kV	
Germany (50 Hz) [197]	380 kV	350 kV – 420 kV	
	220 kV	193 kV – 245 kV	
	110 kV	96 kV – 123 kV	
UK (50 Hz) [201]	400 kV	400 kV ± 5%	
	275 kV	275 kV ± 10%	
	132 kV	132 kV ± 10%	
	110 kV	110 kV ± 5%	
Saudi Arabia (60 Hz) [266]	115 kV	115 kV ± 5%	± 10% for 30 min.
	132 kV	132 kV ± 5%	
	230 kV	230 kV ± 5%	
	380 kV	380 kV ± 5%	

TABLE 6. Reactive power requirements in grid codes for wind generators.

Grid Code (Network Frequency)	Reactive requirement location	Reactive requirement range (p.u. of rated output)	Equivalent full load power factor (lag – lead)
Australia [267]	PCC	0.395 (automatic)	Not specified
Canada-Ontario [267]	PCC	-0.33 – 0.33	Not specified
Denmark [196]	PCC	-0.33 – 0.33	0.90 – 0.95
ENTSO-E* [267]	PCC	-0.50 – 0.65	0.838–0.894
Canada-Alberta [267]	LVT	Not specified	0.90 – 0.95
Canada-Quebec [267]	PCC	Not specified	0.95
Germany [268]	PCC	-0.228– 0.48	0.90 – 0.97
		-0.33 – 0.41	0.95 – 0.925
		-0.41 – 0.33	0.925 – 0.95
Ireland [269]	LVT	-0.33 – 0.33	0.95
Spain [270]	PCC	-0.30 – 0.30	Not specified
UK (50 Hz) [201]	PCC	-0.33 – 0.33	0.95 – 0.95
USA-Texas [267]	PCC	Not specified	0.95 – 0.95
Saudi Arabia [266]	PCC	-0.33 – 0.33	0.85 -0.95

The size of the optimal storage system is the challenge faced by researchers and system operators, which requires a careful understanding of the wind power forecasting errors. Optimum storage size assessment makes this solution economic versus peers. Usually, the distribution of forecast errors is assumed to be a normal distribution, but this does not represent the appropriate distribution in all cases, as indicated in [255], [256].

TABLE 7. **Frequency tolerance range in grid codes.**

Grid code (Nominal Frequency)	Frequency range	Operation duration requirements
Australia (50 Hz) [271]	>52.0 Hz	2 seconds of operation
	47.5 Hz – 52.0 Hz	Continuous operation
	<47.5 Hz	2 seconds of operation
Canada – Alberta (60 Hz) [195]	>61.7 Hz	0 seconds of operation
	61.6 Hz – 61.7 Hz	30 seconds of operation
	60.6 Hz – 61.6 Hz	3 minutes of operation
	59.4 Hz – 60.6 Hz	Continuous operation
	58.4 Hz – 59.4 Hz	3 minutes of operation
	57.8 Hz – 58.4 Hz	30 seconds of operation
	57.3 Hz – 57.8 Hz	7.5 seconds of operation
	57.0 Hz – 57.3 Hz	45 cycles of operation
	<57.0 Hz	0 seconds of operation
China (50 Hz) [272]	>52.0 Hz	Immediate disconnection
	50.2 Hz – 52.0 Hz	2 minutes of operation
	49.5 Hz – 50.2 Hz	Continuous operation
	48.0 Hz – 49.5 Hz	10 minutes of operation
	<48.0 Hz	Depend on the inverter
Denmark (50 Hz) [196]	50.2 Hz – 52.0 Hz	15 minutes of operation
	49.5 Hz – 50.2 Hz	Continuous operation
	49.0 Hz – 49.5 Hz	5 hours of operation
	48.0 Hz – 49.0 Hz	30 minutes of operation
	47.5 Hz – 48.0 Hz	3 minutes of operation
	47.0 Hz – 47.5 Hz	20 seconds of operation
Germany (50 Hz) [197]	50.5 Hz – 51.5 Hz	30 minutes or less of operation
	49.0 Hz – 50.5 Hz	Continuous operation
	48.5 Hz – 49.0 Hz	30 minutes or less of operation
	48.0 Hz – 48.5 Hz	20 minutes or less of operation
	47.5 Hz – 48.0 Hz	10 minutes or less of operation
Japan (50 Hz) [272]	>51.5 Hz	Immediate disconnection
	47.5 Hz – 51.5 Hz	Continuous operation
	<47.5 Hz	Immediate disconnection
South Africa (50 Hz) [272]	>52	4 seconds of operation
	51.0 Hz – 52.0 Hz	60 seconds of operation
	49.0 Hz – 51.0 Hz	Continuous operation
	48.0 Hz – 49.0 Hz	60 seconds of operation
	47.0 Hz – 48.0 Hz	10 seconds of operation
	<47.0 Hz	0.2 seconds of operation
Spain (50 Hz) [272]	>51.5 Hz	Immediate disconnection
	47.5 Hz – 51.5 Hz	Continuous operation
	48.0 Hz – 47.5 Hz	3 seconds of operation
	<47.5 Hz	Immediate disconnection
UK (50 Hz) [201]	51.5 Hz – 52.0 Hz	15 minutes of operation
	51.0 Hz – 51.5 Hz	90 minutes of operation
	49.0 Hz – 51.0 Hz	Continuous operation
	47.5 Hz – 49.0 Hz	90 minutes of operation
	47.0 Hz – 47.5 Hz	20 seconds of operation
USA—NERC (60 Hz) [272]	>61.5 Hz	0.16 seconds of operation
	61.0 Hz – 61.5 Hz	300 seconds of operation
	58.5 Hz – 61.0 Hz	Continuous operation
	57.0 Hz – 58.5 Hz	300 seconds of operation
	<57.0 Hz	0.16 seconds of operation
Saudi Arabia (60 Hz) [266]	57 – 57.4 Hz	30 seconds of operation
	57.5 – 58.7 Hz	30 minutes of operation
	58.8 – 60.5 Hz	Continuous
	60.6 – 61.5 Hz	30 minutes of operation
	61.6 – 62.5 Hz	30 seconds of operation

Usually, the error signal in prediction is modeled as a noise signal added to the productive capacity using one of the following three methods: Markov model or timeline model (for example, ARMA model) and the Joint Probability Distribution model [257]. H. Pierre and others have used the simple regression model to understand the random behavior of the errors of daily forecasts. They found that the correlation coefficient (between two consecutive hours) always ranges between 80-90%. With the help of Monte Carlo simulation and the value of the correlation, they calculated the capacity required for storage [258]. The results also showed that when ignoring the correlation, the required capacity estimates are insufficient.

Shi *et al.* [259] proposed a hybrid power storage system (battery and super-capacitor) to get the optimal size of storage and improve the scheduling of unpredictable wind power in the short term. Authors used real-time model prediction-multi-objective cross-entropy energy management algorithms combined with Hilbert Huang's transform to extract energy production properties and regulate the state of charge. The results showed that fluctuations in the production firm were reduced, and the cost of the storage system reduced.

Gan *et al.* [260] summarized the optimal capacity for renewable energy mixture (wind & solar) and storage systems to overcome fluctuations for scheduling purposes. The models, methods, and programs used for optimization are addressed according to the energy storage modes of renewable energy systems.

The energy storage systems, including electric vehicles integrated with renewable energy generators, play a vital role in smoothing their power output. The pretty faster response can also reduce the reliance on fast ramping but expensive traditional generators. Besides, these energy storage systems are capable of providing frequency regulation, voltage profile improvement, power quality correction, and demand response, including peak load shaving, load shifting, and energy management [261]–[264].

D. RENEWABLE ENERGY POLICIES

The contribution of wind energy to the total product of electric energy has become a fact that cannot be missed. Many countries share wind energy in their production exceeding 20% [265]. All this has encouraged several countries to enact laws and policies that help the growth of this industry while at the same time supporting the economic, social, and environmental aspects of these countries. The following Table 4 gives an overview of the most prominent policies of the 10 most energy-producing countries from the wind.

IV. CONCLUSION

This article reviewed and discussed challenges of wind energy integration into the electricity grids and shed lights on the available solution methodologies. Among discussed challenges, it focused on wind energy intermittency, reactive power support, voltage and frequency stability, power quality issues, fault ride-through capability, protection, cyber security, electricity market, planning, socio-economic, and environmental challenges. Besides, this article reviewed available solution methodologies including grid codes, energy storage systems, and wind energy policy to combat with the challenges. Therefore, the policymakers will find this article as a guideline in developing their future strategies and the enthusiastic researcher will find their future research directions. Now-a-days, many of the discussed challenges have been overcome by the wind turbines manufacturers to reduce network problems and even to help in solving other relevant issues. Additionally, it is expected that many other

TABLE 8. Comparison wind turbines types and their comply with integration requirements.

	WTG Type 1	WTG Type 2	WTG Type 3	WTG Type 4	Comments
Rotor Speed Range (slip)	(1 % at most)	(around 10%)	(around 30%)	(0 to rated speed)	The grid isolation for type 4 give it a privilege for a flexible range. Type 1, 2, and 3 have limited speed
Power rating	max 2 MW	max 2 MW	6 MW or more	6 MW or more	Type 4 has more range than Type 3
Reactive power capability	external support	external support	inherent capability	inherent capability	The voltage source converters in type 3 and 4 give them wide range capability
Low (or zero) voltage ride through	Poor	Poor	Acceptable	Excellent	Type 4 capable of expanded to ZVRT. Type3 typically enters the "crowbar" during fast changes in voltage. LVRT ability needs to be backed up with Type 1 and 2.
Dynamic Voltage Regulation	No	No	good	Excellent	Type 3 has machine time constants, the reactive ability is minimal. Type 1 and 2 do not have voltage support ability. Type 4 has STATCOM-like regulation capabilities.
Frequency Response	Ok	Ok	Ok	Excellent	Type4 has a quick and accurate converter response.
Negative Sequence Withstand	Ok	Ok	Ok	Excellent	Type 4 usually allows the removal of negative sequence currents in their totality. Type 3 negative sequence currents suppression is limited due to rotor voltage availability
Cost and maintenance	cheap	cheap	moderate	expensive	Type3 require some maintenance for the slip rings and brushes. Type4 require minor continuous maintenance

innovative solution methodologies will emerge in a very short period due to technological advancement and extensive ongoing research. However, there are still concerns regarding the integration of wind energy to the electricity grids including wind energy intermittency, resiliency, and reliability issues.

Development of large-scale energy storage system infrastructure, enhancement of their life span, their endurance for harsh weather conditions, and their cost reduction are considered as one of the most critical concerns for the energy storage companies and manufacturers. Thus, researchers should pay more attention on this area and find solutions regarding storage capacity and how to prolong the storage period. The energy storage systems with the required specifications may solve several issues related to grid integration of wind energy systems including their dispatchability and reliability. Besides, the employment of new probabilistic uncertainty methods/studies is recommended to improve prediction accuracy and to reduce the computational burden while developing prediction models in the future. Therefore, the researcher should also discover the link between the wind energy generation uncertainties with the demand side management to ensure reliable integration of wind energy systems into the grids. Moreover, as a future extension of this work, reviewing and investigating the similar challenges and their impact on the distribution grids will be very useful. Also, addressing the detailed solutions proposed to meet these challenges could be considered as the extension of this work.

APPENDIXES

APPENDIX A

GRID CODES IN SOME COUNTRIES

This appendix contains three tables on the requirements of integrating wind turbines at the the transmission system level in terms of frequency, voltage and reactive power in some countries

APPENDIX B

GENERIC MODEL OF FOUR TYPES WIND TURBINE

Since there are no standard models yet, when additional information is available, the general wind turbine generator models will be modified and/or replaced with more modern when additional information is available, generic wind turbine generator models (see fig. 8) will be modified and/or replaced with more up-to-date models.

Table 8 summarizes the compliance of existing wind turbine types to grid integration requirements.

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