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A Review on Grid Integration Challenges of WindEnergy Systems

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ABSTRACT

In recent decades, the strengthening of electric energy security and the reduction of greenhouse gas emissions acquired great traction. The integration of large-scale intermittent renewable energy resources (RER) such as wind energy into existing electrical systems has risen dramatically in recent years. In the last few years, however, this integration creates several operational and control issues that impede the process. Grid functioning must be reliable and stable. This article will look at the problems that have been documented as a result of the recommended solutions techniques and the integration of wind energy Among the many difficulties, Generation uncertainty, power quality difficulties, angular and voltage stability, and reactive power support are all factors to consider. The ability to ride through faults is examined and explored. Aside from that, there are financial, environmental, and political factors to consider.

Keywords-- PV System, Voltage Stability, Grid Interconnection

I. INTRODUCTION

Wind power generation is constantly evolving globally, and in most nations that have extensively invested in this field, it has become a key component in grid operation. Wind power generation is increasing its penetration into the power system and contributing to the global energy supply on an annual basis.

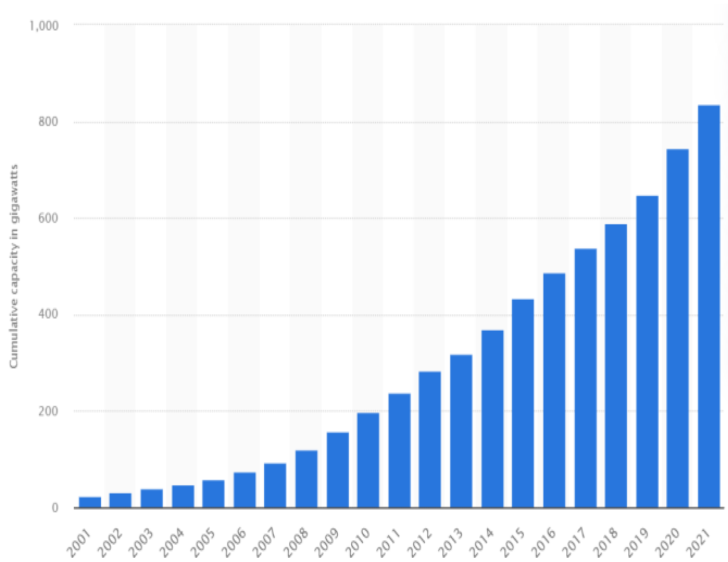

Figure 1: Total installed wind power capacity

In 2021, the total installed wind power capacity was 837 GW globally, with an increased capacity of 63.9 GW [1], [2]. By the end of 2022, installed wind capacity is forecast to reach more than 900 GW, up 10 percent from 2021 [3], with an extra capacity of 65.4 GW. More wind energy projects will be built in the future as a result of countries' policies and legislation for the transition to renewable energy. The rise of wind energy over the last two decades is depicted in Figure 1. The most developed and widely utilized wind farms are onshore. Offshore wind farms, on the other hand, are still in their infancy, and the discrepancies between the two technologies are due to technical challenges and costs.

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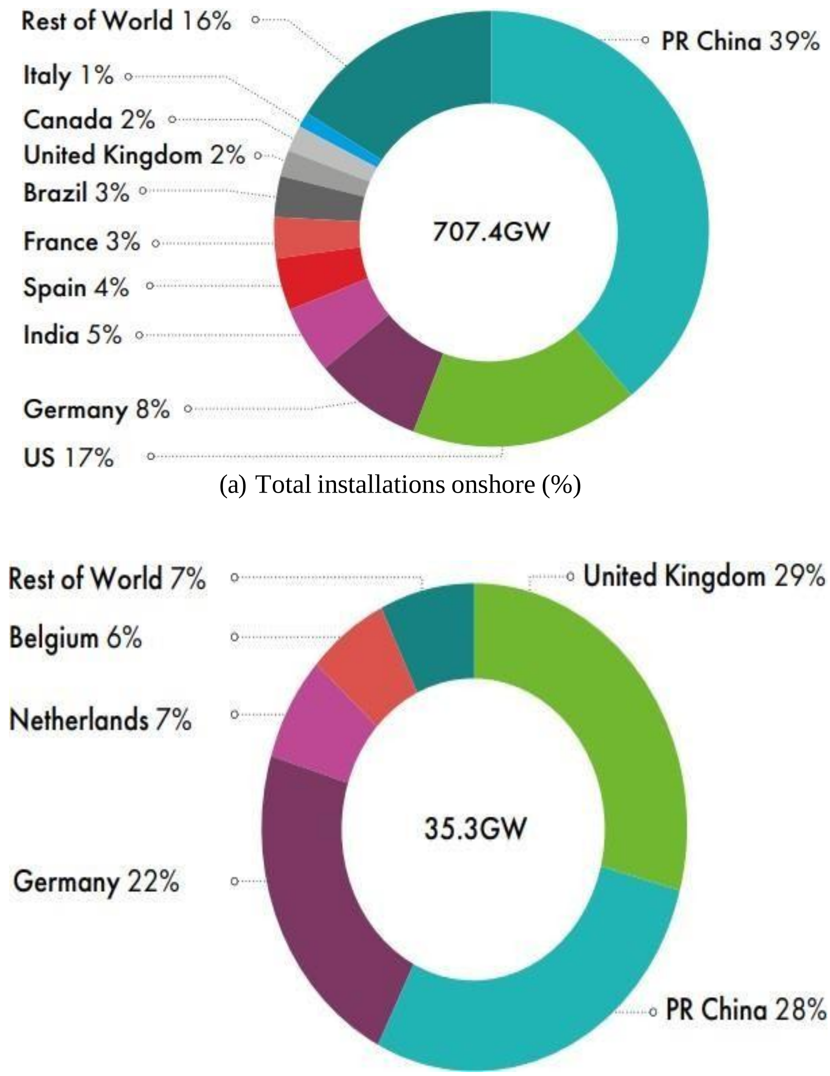

(a) Total installations onshore (%)

(b) Total installations offshore (%)

Figure 2: Regional on / offshore installed wind capacity

Figure 2 depicts the global distribution of wind turbine installed capacity, with Asia leading the way, followed byEurope and North America, and finally the rest of the world. According to GWEC Global wind report 2021, there are new additional installations of 86.9 GW and 6.1 GW in the recent year for onshore and offshore respectively.

These wind systems need to be integrated with the existing transmission networks to serve the load demands of consumers.

Depending on their size, wind turbines can be linked to differe nt voltage levels (see Fig. 3). Small turbines can be connected to the distribution network at voltages ranging from 0.4 kV to 33 kV, and if the group is large enough, we may proceed to a higher voltage level (66 kV) in the case of onshore farms, and finally, numerous offshore wind turbines can be connected at voltages exceeding 100 kV.

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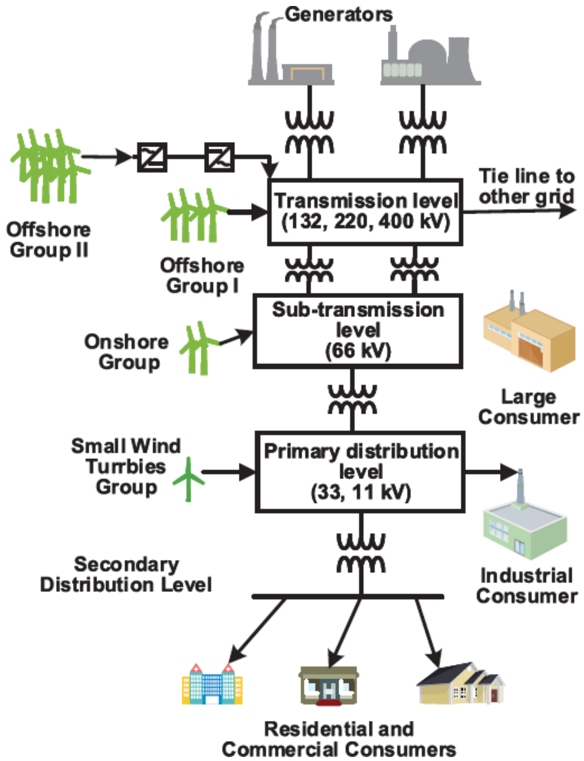

Figure 3: Power system grid with wind integration

Furthermore, to reduce losses and supply volatility, HVDC is preferred in offshore wind generators that are far from transmission lines. This steady expansion and penetration must be matched by tools and data that assist operators in managing the grid with resiliency and reliability.

II. WIND ENERGY INTEGRATION ISSUES

As a clean and ecologically friendly energy source, wind energy is one of the most essential contributors to modern electric systems. The intermittent nature of wind energy systems, as well as turbine technology and protection difficulties, present additional hurdles for successful and cost- effective grid integration [15] [17]. This section discusses the effects of wind energy integration on grids, which must be taken into account in order to preserve the reliability and quality of energy delivered to customers.

A. Prediction of Output Power

Operators were interested in knowing the details of the generation that would help them in the process of unit commitment and the unit's production cost, in addition to spinning reserves, before wind power was introduced into the grid. In many countries, the growing amount of renewable energy in the energy mix, particularly wind turbines, has prompted operators to rethink supply management in order to maintain grid reliability and enhance efficiency to integrate power from wind turbines and other intermittent energy sources [18]. In the case of high wind turbine integration, prediction is critical in lowering production costs because the absence of forecast necessitates the presence of significant quantities of spinning reserves. Furthermore, unforeseen ramp events can jeopardize grid dependability. Finally, as a source of electricity, wind turbines have made forecasting valuable for network management [19].

However, because wind energy is one of the most difficult meteorological commodities to anticipate, there is no optimum approach for predicting it. Each methodology has advantages and disadvantages that may be useful in some circumstances and improper in others [20].

B. Support for Reactive Power/Voltage

Induction generators, which by their very nature consume reactive power (i.e., they require a reactive power source for excitation), are the most common machinery used to create electricity from wind energy. As a result, unlike synchronous machines, they do not have the advantage of supplying the grid with reactive power [42]. Many studies looked into ways to improve wind turbines' ability to provide reactive power support during voltage drops. Opila et al. [43] investigated wind turbines'

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potential to offer reactive electricity to the grid. According to the authors, one of the variables that leads to a reduction in available reactive power is the limits imposed for the value of voltages at the point of common coupling (PCC).
To comply with the Danish grid code, Mohseni [44] proposed a control approach to boost the reactive power support of wind turbines connected to the AC grid via voltage sourceconverters. According to the study, the grid-side converter on wind turbines should be permitted to overload during a transient fault to prevent the DC link connection voltage values from exceeding the legal limit.

To support both active and reactive powers, Xie et al. [45] and Liu et al. [46] presented a fault ride-through capability augmentation technique for doubly fed induction generator- based wind turbines. The right design of wind turbine control systems is critical for efficient wind power plant usage when replacing conventional generators.

However, the ability of wind power plants to generate or absorb reactive power is dependent on the grid's strength and transmission line length. [47] Wind turbines can provide reactive power support, according to the findings of the study. In order to avoid instability issues, coordination between the various reactive power sources linked with the wind turbine is also required. Wind turbines can improve grid side flexibility by generating and absorbing reactive electricity, which improves voltage prole [48].

C. The Impact of Frequency

The addition of wind-generated electricity to the electrical grid helps to reduce overall system inertia, and the effect is particularly noticeable in smaller isolated systems [21], [22]. Most wind power plants' control systems isolate the mechanical system from the electrical system in the event of a disruption, which decreases the wind power plants' contribution to network inertia [23].
The installation of an auxiliary controller to the wind turbine central control unit, according to Morren et al. [24], can adjust the torque set point to make it adaptable to changes in grid frequency by taking use of the wind turbine mass during a disturbance.

Conroy and Watson [25] presented a controller based on grid frequency to manage the output power of a permanent magnetsynchronous generator (PMSG).

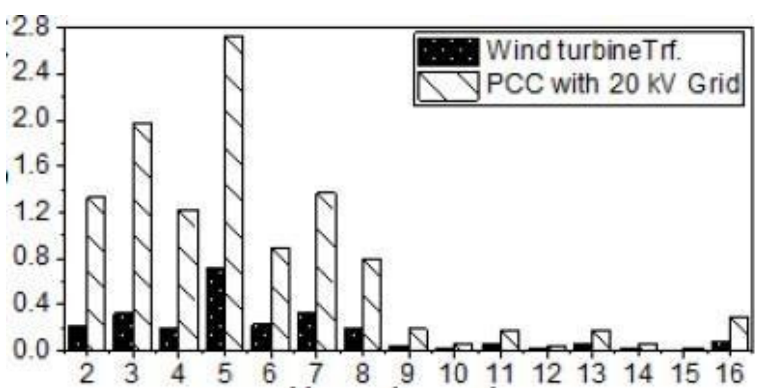
During frequency oscillations, another control approach was explored on a PMSG wind turbine in [26]. During a disturbance, the wind turbine can act like a traditional generator and offer inertiasupport by utilising the wind turbine's hidden kinetic energy. In order to deal with the frequency fluctuation of electricalnetworks, the basic frequency control approach was established in [27]. Siemens has developed a full-converter- based wind turbine generator that can adjust frequency dependent on the state of the power supply [28]. Other options, including as energy storage devices, kinetic energy extraction, and load control, can be used to address the frequency degradation problem caused by wind energy's highpenetration [29].

D. Harmonics/Power Quality Issues Impact

Wind turbines, like other conventional generators, must provide electricity of acceptable power quality (one of which is minimal harmonic emissions) [70]. Wind turbine integrationinto the grid will introduce harmonics at various network levels.

We need to understand the elements that contribute to harmonic emission in order to study them and develop strategies to reduce them. In a wind turbine system, harmonics are produced by cables used in the collector bus, turbine transformers, filters, capacitors, power factor correction devices, and power electronic converters [50] [52]. [53] [54] address wind turbine harmonic models for types 1, 2, 3, and 4.

The harmonic power flow method, the distorted and non- distorted current method, the superposition method, the Harmonic state estimate method, and the IEC current and voltage phasor method are among the approaches covered in [55].



Harmonic order vs Current Magnitude

Figure 5(a): Harmonic at PCC and one wind turbine level

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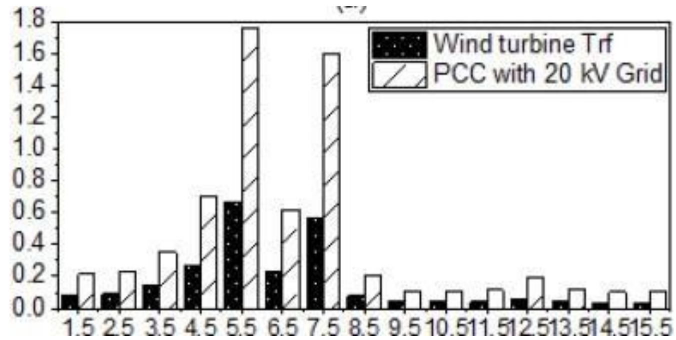

Figure 5 (b): Inter harmonic at PCC and one wind turbine level

A single turbine produces very few harmonics, but this rate increases for a wind farm near the point of common coupling (PCC), as seen in Fig. 5. When compared to the harmonic values obtained for one turbine on the HV-side of the transformer, the values of the harmonic measured at the point of common coupling (PCC) increase as the integration increases in Fig. 5 (a). The inter harmonic value in Fig. 5 (b) follows the same pattern as the harmonic in Fig. 5 (a). The 5th, 7th, 11th, 13th, and 17th harmonics [51] are the most common harmonics pumped by wind turbines. In [52], inter-harmonics and harmonics are thoroughly examined. Furthermore, wind turbines make a negligible contribution to the transmission system's short-circuit capacity, weakening the transmission link and increasing harmonic levels in the voltage. Several research looked into the problems with harmonic injection caused by wind turbine grid integration.

E. Grid Resistance and Reliability

Frequency support by ensuring the balance between supply and demand within the electricity system and having a prompt response in times of unbalance by reducing generation or demand are the building blocks of network reliability. 2) Support the voltage by keeping it within the grid's operational limitations during routine or emergency operations to avoid the system from collapsing. The traditional generation system offers these services as a necessary aspect of its operation, but the introduction of renewable energy sources like wind turbines as a source of electricity has altered the grid's dynamics.

F. Protection Challenges

A short circuit is one of the most common types of power system failure. As a result, protection devices are meant to act as a shield, preventing equipment loss or damage from either providers or consumers in the case of an electrical short circuit. Planners reassess these devices' settings in the future expansion of power networks by studying short circuit test results.

Assessing the contribution of wind turbines to the transmission network's short current is critical in order to understand their influence and the stress they can cause to network elements. The impact of wind turbines and their contribution to the short current is determined by their type. [104] [107] contain detailed models of wind turbines and theirproperties.

III. MITIGATION TECHNIQUE TO SOLVE WIND INTEGRATION ISSUE

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) [31]. Many researchers 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. Advanced Monitoring and ControlStrategies

The purpose of wind turbine control systems is to ensure that the turbine operates within the permissible limits due to wind speed actuation, and also to obtain the maximum possible power from the wind [32]. Also, the control devices enable theparticipation 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 controlling parameter and techniques used in wind turbines.

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Table 1: Monitoring and control strategies for wind turbines

Controlling Parameter	Ref.	Technique
Grid Integration Control	[34]-[36]	Frequency Regulation Reactive Power Control
Torque control (MPPT)	[37]-[40]	Collective and Individual Pitch Control
Pitch Angle Control	[41]	Optimal Torque Control Sliding Mode control

B. 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) [42]. 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 reduce the peak load demand and electricity price in the competitive electricity market.

Shi et al. [49] 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. The authors used real-time model prediction-multi-objective cross-entropy energy management algorithms combined with Hilbert Huang's transformation 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 was reduced.

Gan *et al.* [30] 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.

C. 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% [33]. 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.

IV. CONCLUSION

This article reviewed and discussed the challenges of wind energy integration into the electricity grids and shed light 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 the challenges. Therefore, the policymakers will consider this article as a guideline in developing their future strategies, and the enthusiastic researcher will and their future research directions. Nowadays, many of the discussed challenges have been overcome by wind turbine manufacturers to reduce network problems and even to help in solving other relevant issues. Additionally, it is expected that many other 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 one of the most critical concerns for energy storage companies and manufacturers. Thus, researchers should pay more attention to this area and _nd 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 dispatch ability and reliability. Besides, the employment of new

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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.

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