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# Study of the Effect of Wind Power Penetration on the Power Grid

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***Abstract*— Wind power generation is highly unreliable due to the unpredictable nature of wind speed. It is essential to examine how wind power grid connections impact the electricity system to ensure its safe and dependable operation. In addition to reviewing the effects of large-scale wind farm grid connections on the power system and their corrective measures, this paper discusses the current state of wind power development both domestically and internationally.**

***Index Terms*— Power quality, Power system, Renewable energy, Wind power generation, Wind power grid connection.**

## I. INTRODUCTION

Energy and environmental issues are worsening due to rapid industrial development and the exhaustion of fossil fuels. Wind power is the fastest-growing renewable energy source globally. India's power grid is relatively robust at present. Many planned or existing wind farms are located at the end of the power system or in vulnerable areas.

Additionally, connecting wind energy to the grid is very challenging because of its unpredictability and volatility. The impact of these characteristics on the electrical grid is not immediately noticeable when wind farm capacity is low. However, as wind farm capacity increases, its influence on the system becomes more significant. Therefore, a detailed analysis of these effects is necessary to ensure the safe and stable operation of the electricity system.

This article mainly focuses on how large-scale wind farm grid connections affect power system stability, operational costs, dispatching, power quality, and the necessary corrective measures.

## II. CURRENT STATUS OF WIND POWER DEVELOPMENT

### *A. Overview of wind power development*

Due to its many advantages, wind power generation has become the fastest-growing and most commercially promising sector in the development and utilization of renewable energy in today's world. As a result, wind power has garnered increasing attention from governments, businesses, and consumers across various countries. Notably, large-scale integration of wind power into the grid is becoming increasingly common. The capacity of new wind farms is growing in line with the power system, and their operational benefits are increasingly clear.

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At the Global Wind Day 2025 event on June 15, 2025, Pralhad Joshi, India's Union Minister, announced that "India has achieved 51.5 GW of wind capacity, a 150% growth over a decade, and is now exporting turbines and components worldwide… We are moving steadily towards the 100 GW wind target by 2030, including 30 GW from offshore projects, supported by strong policy reforms and a robust manufacturing ecosystem.".

Worldwide wind power generation is expected to contribute 15% of the global power supply by 2030. North America and Europe hold the world's largest wind power capacities, with their wind sectors among the top globally. Wind power accounts for approximately 40% to 50% of Denmark's electricity and about 25% to 30% in Germany, with specific areas even exceeding 55%. Additionally, the cost of producing wind energy has dropped significantly worldwide—from about ₹12.70 per kilowatt-hour in the early 1980s to around ₹4.07 in the late 1990s, and further down to ₹1.66–₹2.49 per kilowatt-hour in recent years—making it one of the most affordable sources of electricity. As for installed wind power capacity, China leads the world, followed by the US and Germany, according to current data. India ranked fourth with 45 GW of installed capacity as of 2023. This is tabulated as per Table 1.

TABLE I: COMPARISON OF KEY WIND POWER MARKETS

| Country | Total Capacity (GW) | % of Electricity Mix | Key Policy/Note |
|---|---|---|---|
| China | 441 | ~6-7% | Global leader in capacity |
| USA | 147.5 | ~10% | Strong growth in offshore |
| Germany | 69 | 25-30% | Energiewende policy driver |
| India | 45.4 | ~5% | Target: 100 GW by 2030 |

*B. Overview of India's Wind Power Development*

India has abundant wind energy deposits, making it the world's largest wind energy producer. According to the Ministry of New and Renewable Energy (MNRE), the Government of India, India's onshore wind power resources total 695 GW, while its offshore wind resources amount to 70 GW, bringing the total to approximately 765 GW. Based on current average investment costs for domestic wind projects, the investment per kilowatt is approximately 6,000 to 7000 Rupees. This vast potential for resource development is sure to foster a thriving wind power industry. India's wind energy sector began to develop in 1986 with the establishment of its first wind farm in Tamil Nadu. Initially, most were 100-watt units installed in remote areas for farmers and herders to use independently. The growing focus on renewable, clean energy stems from the decline in primary energy sources and the public's strong interest in environmental issues. Over the past two decades, the wind power industry in India has seen significant growth. In 2007, India added 3,449 MW of new wind capacity, representing approximately 17.2% of the global new installations that year and ranking India seventh worldwide. As of 2024, India's total installed wind capacity is approximately 45.4 GW (45.4 million kW), making it the world's fourth-largest wind energy market.

## III. GRID-CONNECTED WIND FARMS' EFFECTS ON THE GRID AND CORRECTIVE ACTIONS

*A. Wind power grid connection's effect on grid stability*

*The impact of wind power grid integration on transient grid stability.*

The integration of wind power into a grid with substantial existing wind capacity will modify the grid's transient stability, as the initial current distribution, line transmission capacity, and system inertia are all affected.

Provided that the regional power grid is sufficiently resilient to restore the terminal voltage and continue operating continuously after the fault is cleared, the grid's transient voltage stability can be maintained. The wind turbine may experience instability due to overspeed operation. It will be unable to restore terminal voltage after the system fault is cleared if the regional power grid is inadequate. This could compromise the transient voltage stability of the regional grid. To ensure transient voltage stability, it is necessary to either install dynamic reactive power compensation devices within the wind farm and leverage the dynamic reactive support capacity of variable-speed wind turbines to reinforce grid voltage during transient events and recovery, or to employ protection mechanisms to disconnect the wind farm or individual turbines. Reference [2], which studied changes in wind turbine grid connection, connection point, terminal voltage, and turbine speed after system failure under various reactive power compensation strategies using PSCAD simulations, helps confirm that reactive power compensation techniques are reasonably applied in wind power grid-connected systems. The literature [3] combines simulation and analysis to examine how wind power connection impacts the power grid under real conditions of the Indian Wind Farm, determining the wind farm's reactive compensation capacity and the relationship between rotor slip and export power factor. The main bus voltage cannot stabilize if a three-phase short circuit occurs in a grid line when the wind farm is fully operational and connected to the grid. This is because the wind farm must be shut down quickly. The voltage at each major grid node and the relevant power angle of the primary unit will show damped oscillations. It will ultimately stabilize if the wind farm is promptly decommissioned after a fault.

*Wind turbines with low voltage ride-through (LVRT).*

Wind turbines can remain connected to the grid and supply reactive power to help restore voltage until the grid stabilizes when the voltage at the turbine's connection point drops. Low-voltage ride-through, commonly referred to as "riding through" the low-voltage period, describes this phenomenon. Regardless of the fault's duration or severity, the wind turbine will immediately disconnect from the grid if a fault occurs while wind power in the grid is relatively low. This is known as passive self-protection, which maximizes the turbine's safety. While this is a reasonable approach, when wind power constitutes a significant part of the grid, continuing to use passive protection methods to disconnect during faults can hinder system restoration and may even worsen the fault, ultimately leading to the disconnection of all other units. Effective low-voltage ride-through procedures must be implemented to maintain the stability of the wind farm grid during such events, and turbines should be equipped with the necessary low-voltage ride-through capabilities. To achieve low-voltage ride-through during grid asymmetric faults, Reference [4] combined the DC-side Crowbar circuit with a grid-side converter control method designed for such faults.

The standards for LVRT differ by country and region. The grid operator in northern Germany enforces strict LVRT requirements for wind farms and turbines, given the region's high wind power share. During a fault, the wind farm will shut down, and the turbine's speed will drop to zero. If either the wind farm or turbine lacks low-voltage ride-through capabilities, the reactive and active power on the transmission line will fluctuate before settling near zero. However, a wind farm with low-voltage ride-through capabilities can still supply some active power during a failure, helping maintain the overall power balance and supporting grid recovery.

*B. Effects of wind power integration on grid operational expenses and dispatching procedures*

*Impact of wind power penetration on system operating costs.*

Compared to thermal power generation, wind power units have much lower operating expenses. However, the variable and intermittent nature of wind power output makes it challenging to meet the power system's actual operating needs, especially given current forecasting capabilities. To maintain system stability and balance, a specific amount of spinning reserve must be established based on the original operation mode to ensure reliable system operation after connecting wind power to the grid. Connecting wind power influences the power system in two main ways: it shares some load with conventional units, helping to reduce fuel costs, but also increases the system's reliability costs. For example, a recently completed wind power project in the US is discussed in Reference [5], which offers a simple method to estimate wind power costs, examines the main factors influencing these costs, and shows how modern technology can lower them. According to the literature [6], the environmental cost, based on pollution discharge fees and Indian ecological value standards, is used to analyze the environmental benefits of wind power and compare its economic efficiency with that of thermal power. The findings indicate that wind power is economically efficient and has significant development potential.

*The impact of wind power grid connection on grid dispatching and operation.*

The unpredictable, sporadic nature of wind is solely responsible for dispatch issues and the need for additional reserve capacity when integrating wind power into the grid. When wind power is unpredictable, the grid must allocate sufficient capacity for wind energy based on a more cautious strategy to manage its variances; on the other hand, when wind power can be reliably forecasted, it can be treated as a negative load in the load forecast, allowing conventional generation plans to be aligned with anticipated load and wind power, similar to traditional power system dispatch methods. This improves the start-up coordination of generators and reduces overall grid operating costs. Reference [7] proposed the nominal environmental compensation cost of thermal power units, including the cost of wind power reserve capacity. It developed an ecological economic dispatch model using wind turbines within a power market framework. To lessen the impact of wind power connections on grid dispatching and reserve capacity requirements, wind power forecasting is essential and urgently needed. Reference [8] explores short-term wind power prediction using a combination of wavelet analysis and artificial neural networks. The wavelet transform reduces the signal into various frequency bands, and a neural network models and forecasts each subsequence. Finally, the prediction results are combined. Reference [9] develops a neural network model for wind power prediction, investigates how measured power and atmospheric data at different altitudes influence prediction outcomes, and builds an error-band prediction model based on neural networks, achieving accurate error-band forecasting.

### *C. Impact of wind power grid connection on power quality*

The grid connections of wind farms will have a limited impact on power quality. Its main components include voltage, frequency, harmonics, flicker, voltage fluctuations, and voltage sag. Several factors, such as wind turbine type, control strategy, wind farm layout, the short-circuit capacity of the linked system, and line characteristics, influence the level of impact. This influence increases as wind farms' capacity grows. The effects of wind power penetration on power quality from different perspectives are discussed in Reference [10]. The control methods for addressing power quality issues caused by various grid connection technologies are summarized in Reference [11].

*Frequency.*

The key difference between wind farms and traditional power sources is the unpredictability of wind farm output. The irregular and fluctuating wind power often causes redistribution of power flow in systems connected to wind farms. This affects both the system's frequency and voltage. If a region's wind power capacity exceeds a certain percentage of its total capacity, measures must be taken to enhance its ability to regulate frequency. Reference [12] developed a Simulink simulation model, proposed a strategy to improve wind power generation with a flywheel, and analyzed an integrated control method for the wind power-flywheel system's power and frequency. This helps stabilize wind turbine output fluctuations and assists in grid frequency regulation by utilizing real-time wind speed data. The results show that the wind power-flywheel system can help regulate grid frequency, similarly to traditional generators, providing steady power when needed.

*Reactive Power.*

Voltage deviation is a steady-state problem of the power grid. Large fluctuations in wind speed result in significant variations in wind turbine output, leading to voltage deviations at specific nodes in the power grid that exceed the limits set by national standards. The impact of wind power integration on the system can be reduced through measures such as decommissioning some wind turbines or installing reactive power compensation devices within the wind farm to raise voltage levels or limit the amount of wind power fed into the grid. The voltage level and stability of the power grid in the wind power integration area can be improved by strengthening the grid infrastructure and using double-fed variable-speed wind turbines that can regulate both voltage and reactive power. Relying solely on the rapid modulation of capacitor banks is insufficient to meet control requirements during substantial fluctuations in wind generation when reactive power consumption is large and rapidly changing. To control reactive power and voltage in the power grid and the wind farm, it is necessary to install dynamic reactive power compensation devices within the wind farm. These devices can quickly supply reactive power in response to changes in wind speed. Reactive power control methods were analyzed in Reference [13].

*Harmonics.*

The harmonics generated by the generator itself are unaffected by the type of wind turbine. The actual source of harmonic currents is the power electronic components of the wind turbine. The level of harmonic interference, which relates to the short-circuit capacity of the electrical grid, the unit's output power, or wind speed, depends on the design of the converter and filter system. Fixed-speed wind turbines produce minimal harmonic current, and their power electronic components operate intermittently. The wind turbine itself must address harmonic interference because the converter in a variable-speed, constant-frequency wind turbine is always in operation. Harmonic distortion can be minimized by using PWM switching converters and high-quality filters. Grid harmonics are analyzed with the wavelet technique in Reference [14]. The simulation results demonstrate that this method can effectively identify both steady-state and time-varying harmonic currents in the power system, thereby fulfilling the role of the active power filter's harmonic detection component.

*Voltage fluctuation and flicker.*

Voltage fluctuations and flicker caused by grid-connected wind turbine operation result from inconsistent power output. The active power fluctuations, driven by the dynamic nature of wind speed, depend on local wind conditions and turbulence intensity, with an uncertain frequency. Conversely, the variability in wind turbine power output mainly comes from rapid wind speed changes, tower shadow effects, wind shear, and yaw errors, with its fluctuation frequency closely tied to the turbine's rotational speed. The flicker issue associated with fixed-speed wind turbines is especially significant and, in some cases, has become a key factor limiting the installed capacity of wind farms. Under typical conditions, the flicker intensity produced by variable-speed wind turbines is only about 0.25% of that generated by fixed-speed turbines. Reference [15] replicated the IEC flicker meter and added a correction mechanism to calibrate the flicker testing system in the low-frequency range. The results indicate that the corrected system exhibits good accuracy within this range and meets the testing criteria for flicker caused by wind power grid integration.

*Voltage Sag.*

The sudden start-up of wind turbines is typically the cause of voltage sags during the connection of wind power grids. More significant is the voltage sag caused by fixed-speed wind turbines that use induction motors as generators. The central management system of the wind farm can be used to control the voltage and output of wind turbines during startup, preventing multiple units from operating at once and reducing the voltage sag caused by wind turbine operation. Any wind turbine can be used in a wind farm with this control technique.

Reference [16] proposed a method for determining the probability distribution of the voltage stability margin in a system incorporating wind farms. The program computes the sensitivity matrix, correlating voltage stability margin with wind speed, to determine the semi-invariant of each order and the central distance of the wind speed distribution for each wind farm. The probability distribution of the voltage stability margin is determined by inverting the Gram-Charlier series.

TABLE II: SUMMARY OF POWER QUALITY IMPACTS AND MITIGATION STRATEGIES

| Impact | Primary Cause | Mitigation Strategies |
|---|---|---|
| Frequency Variation | Intermittent power output | Flywheel energy storage, improved forecasting, spinning reserves |
| Voltage Deviation | Fluctuating output, lack of reactive power | Static VAR Compensators (SVCs), STATCOMs, DFIG control |
| Harmonics | Power electronic converters (VSCF turbines) | PWM techniques, high-quality filters, and active power filters |
| Voltage Flicker | Tower shadow, wind shear, yaw error (Fixed-speed) | Use of variable-speed turbines, dynamic compensation |
| Voltage Sag | Turbine start-up (especially fixed-speed) | Soft-starters, centralized management to stagger start-up |

*D. Effects of wind power grid connectivity on additional factors*

*Effect on grid loss.*

integration of wind power generation will inevitably impact power grid losses, as it primarily depends on the system's power flow. The effect of connecting wind power to the grid on network loss may vary depending on the location of generation, the relative capacities of load and generation, and the network's configuration.

*Impact on relay protection.*

The sensitivity and protective range of line protection will also be impacted by the wind power grid connection, particularly with distance relay. When a short circuit occurs at the end of the line, a wind turbine positioned X from the line's end will send a short-circuit current to the fault point, lowering the fault current value that the line protection K detects and, consequently, the protection K's sensitivity as depicted in Figure 1.

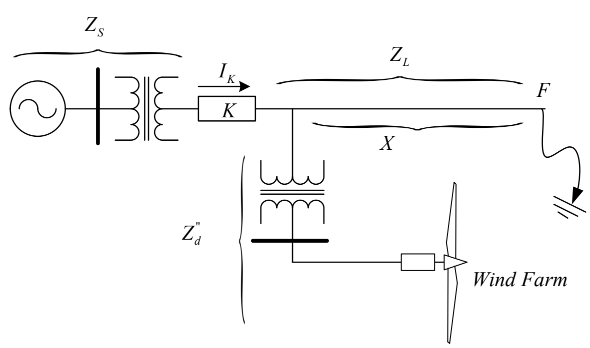


Figure 1. The impact of wind power generation on protection when the line fails

At specific locations along the line, the quick-break protection cannot be activated, creating a dead zone where fault clearance is delayed. The backup overcurrent protection is the only way to address the fault without modifying the protection system if the wind power connection point is within this dead zone. This increases the fault's impact on the power grid. The quick-break, overcurrent protection, and other control devices may fail to coordinate if the quick-break protection setting is altered, which could result in malfunctions. The concept of configuring system relay protection after connecting the wind farm to the grid is discussed with an example in Reference [17]. Once the wind farm is connected, the relay protection setup should be carefully calculated and analyzed based on the grid's structure and the wind farm's size and capacity.

To enhance the reliability of the protection action, Reference [18] analyzed the protection behavior after the wind farm was connected. It achieved this by simulating the short-circuit current of a wind farm during a three-phase ground fault on a transmission line and comparing it with the three-phase short-circuit current of the transmission line without a wind farm.

## IV. Conclusion

- Even while wind power in India has grown significantly in recent years, it still makes up a very small part of all electricity generation. Large-scale grid-connected wind farm research and development should receive more attention to meet the demands of both environmental and economic advancement.
- Integrating wind power into the grid presents several challenges and requires additional efforts in grid management, protection, planning, and other areas. Improvements in technical research and development are necessary, as are ongoing advances in new power electronic components. Furthermore, the negative impacts of wind power integration on the system must be mitigated.
- Enhancing the grid architecture, installing reactive power compensation devices, and increasing oversight of wind power connection points are effective strategies to optimize wind power grid integration.

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