*International Research Journal of Innovations in Engineering and Technology (IRJIET)*

ISSN (online): 2581-3048
Volume 8, Issue 3, pp 278-284, March-2024
https://doi.org/10.47001/IRJIET/2024.803042

# Grid Integration Challenges for Wind Farms

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***Abstract* - The integration of wind farms with the grid is of utmost importance to harness the benefits of renewable energy sources, reduce costs, meet growing energy demands, and make the Earth more environmentally friendly. Over the last decade there has been significant transformation from conventional generation sources to variable energy resources and proposes areas for future research and innovation. However, integrating such variable energy sources can pose potential challenges that may impact grid stability. Therefore, it is essential to review technical challenges and develop mitigation plans to overcome them. In this paper, a comprehensive review of grid challenges in terms of Wind farm starting, grid voltage profile, active power flow, network power quality, Transient system performance short circuit current calculation is discussed along with their corresponding mitigation plans is presented to ensure that the benefits of natural resources can be fully utilized without compromising the strength and security of the grid system [1]. The paper concludes by highlighting the encountered challenges and suggesting potential areas for future research and innovation. This paper serves as a valuable resource for researchers, practitioners, and policymakers interested in understanding and addressing the technical challenges associated with integrating wind farms with the grid[2-5].**

***Keywords:*** Wind turbine generator, short Circuit strength, Voltage stability, PCC, grid Impedance, LVRT Power grid, steady state stability, transient stability, ETAP.

## I. Introduction

Large wind farm usually located in remote areas and are connected through transmission or distribution line. Hence, the grid impedance is increased which lead to voltage fluctuations and easily disconnection of wind farm from the grid [6]. High grid impedance also impacts the protection scheme operation as short circuit current contribution changes with and without grid connection.

To measure grid strength, the short-circuit ratio (SCR) is calculated which also represents the voltage stiffness of a grid. A low short-circuit ratio indicate weak grid strength and can potentially impact protection system coordination relay settings. System short-circuit strength is measured by calculating the short-circuit ratio at a resource's point of interconnection. The SCR is a screening measure to identify weak areas of the grid at a specified point (i.e. bus); therefore, a system consisting of numerous generators and transmission lines will have a different SCR at each bus. [7]. In order to calculate the Short circuit strength & determining the settings of protection devices, the accurate power system modelling is vital. This paper will provide a review on grid voltage profile, active power flow, network power quality, Transient system performance and finally detailed information on Short circuit sources, modeling, an overview of the short-circuit ratio calculation method &model verification.

## II. Wind Turbine Model

Wind turbines are divided into five main groups (according to IEC 61400-27) based on machine type, speed control capabilities, and operational characteristics [8].

### 1) Type I: Squirrel-cage induction generator

Type I wind turbines use an induction generator directly connected to the grid without a power converter. The drop in line voltage in an induction machine following a three-phase fault to ground causes loss of excitation, resulting in supply of substantial transient current into the fault during the sub transient period (first few cycles), eventually leading the ac component to decay to zero.[7]

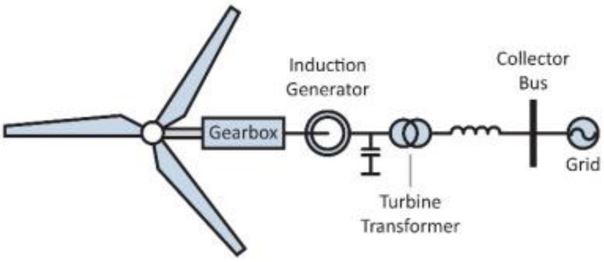


**Figure 1.1: Type I Squirrel Cage Induction Generator Model**

### 2) Type II: Squirrel-cage wound rotor induction generator with external rotor resistance

Type II wind turbines resemble Type I wind turbines, but they are equipped with variable rotor resistance and utilize a variable rotor resistance nonsynchronous machine. This modification aims to ensure a more consistent power output from the wind turbines despite fluctuations in wind speed. The short-circuit behavior of Type II machines is similar to Type I machines with different impedances [7].

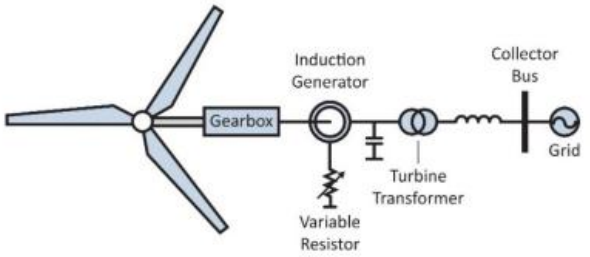


**Figure 1.2: Type II Squirrel Cage Wound Rotor Induction Generator with External Rotor Resistance Model**

### 3) Type III: Doubly-fed asynchronous generator

Type III wind turbines use double-fed induction machines where the stator is directly connected to the grid and the rotor is connected through a back-to-back power converter. A crowbar system is used for power electronics converter protection (used to divert the induced rotor current protecting the rotor-side converter against over currents and the dc capacitors against over voltages) during faults. The effects of the crowbar resistance can dictate the ac fault contribution [7].

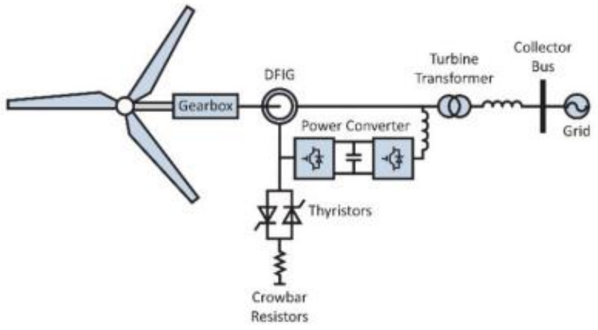


**Figure 1.3: Type III Double-Fed Nonsynchronous Generator Model**

### 4) Type IV: Full power converter generator

For Type I's and Type II's, the short-circuit behavior is dominated by the individual generator characteristics in contrast to Type III and Type IV generators. For Type IV's, a power converter drives the electrical behavior during a fault as the generator is connected to the grid through a full-scale power convertor that is sensitive to excessive currents. In order to protect the power electronics devices during a fault close to the plant, a current limiter is designed into the power converter. Rather than the common voltage source behind an impedance short-circuit equivalent used to model most generators, the Type IV design is represented as a simple current source for maximum short-circuit contribution. Type IV machines use different control modes (reactive power control, voltage control, reactive power control with fault-ride-through) that affect the fault current contribution during a disturbance [7].

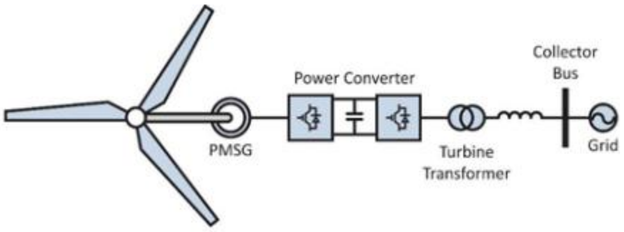


**Figure 1.4: Type IV Full Power Converter Generator Model**

### 5) Type V: Synchronous generator mechanically connected through a torque converter

The Type V turbine exhibits typical synchronous generator behavior during faults and can be modeled similarly to synchronous generators. Figure 1.5 shows a network diagram model of a type V synchronous generator mechanically connected through a torque converter [7].

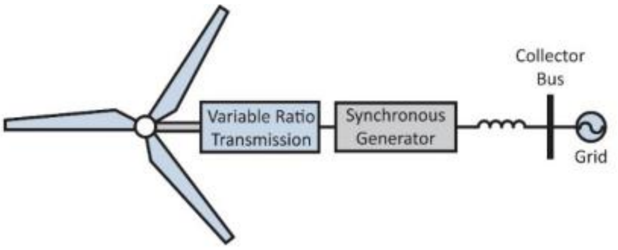


**Figure 1.5: Type V Synchronous Generator Model**

Out of these 5 types, the DFIG is the most preferable one due to its capability of variable speed, grid support, and fault ride-through in a cost effective way. Almost 78% of the total wind installed capacity has employed DFIGs for the generation of electricity [9].

## III. Wind Farm & Grid Integration Challenges

The integration of wind power into the grid presents several challenges that impact system stability, power quality, and overall reliability. Major challenges are:

1. Intermittency:

Wind energy generation is inherently variable due to changing wind speeds.

2. Power Quality Issues:

Wind turbines can introduce harmonics and transients into the power system.

3. Angular and Voltage Stability:

Wind farms' dynamic behaviour can affect the grid's angular stability (rotor angle stability) and voltage stability.The impedance path between wind farms and the grid involves transformers, underground cables, and overhead lines. Transformers primarily affect voltage profiles through leakage reactance. Overhead line parameters significantly influence voltage profiles, with transmission lines having higher inductive reactance. Real power flow causes in-phase voltage drop, while reactive power flow induces angular shift. Connecting large wind farms to higher voltage networks is crucial for managing reactive power transfer and optimizing performance [1].

4. Reactive Power Support:

Wind turbines need to provide reactive power to maintain voltage levels. Proper coordination and control are essential to ensure grid stability.

5. Fault Ride-Through Capability:

During grid faults (such as short circuits), wind turbines must continue operating.

6. Socioeconomic and Environmental Challenges:

Wind farms can impact nearby communities, affecting land use, noise levels, and visual aesthetics.

7. Electricity Market Challenges:

Integrating wind power affects electricity markets, pricing, and grid operation. Market rules and mechanisms need to adapt to accommodate renewable energy sources.

## IV. Literature Review

A study has been conducted on the voltage stability of integrating wind power into the grid, and the findings have been published. The research reveals that as the capacity of the wind farm increases, the margin of voltage stability decreases. It is observed that even with the use of a crowbar, the voltage stability of the DFIG wind turbine is at its weakest during fault clearance.

To improve the voltage stability of wind power grid integration, it is recommended to enhance the fault ride-through capability. Appropriate measures, such as STACOM and SVC, should be implemented to prevent a second trip. A method for sizing STATCOM is proposed to boost the LVRT capability of wind farm grid integration. It is shown that a STATCOM size within the range of 0.8 to 1.0 p.u. strikes an optimal balance between the voltage stability margin and the overall system cost[10]. On the same topic, a review article published [9] summarized that Voltage stability in wind-integrated power systems is a concern for grid security and reliability. This article provides [9] a detailed analysis of voltage instability complexities and implications for wind power integration. Development and implementation of grid codes are crucial due to wind power's intermittent nature. Integration of wind farms in developed countries has led to voltage instability issues, shifting focus from power quality to stability concerns. Techniques including FACTS devices and WAMS are discussed to address voltage instability challenges. Real-time monitoring systems like WAMS are emphasized for swift action against instability events. Comprehensive Voltage Stability Indices aid in identifying weak buses and assessing overall stability. Advanced forecasting, adaptive control systems, and energy storage solutions are recommended for maximizing wind power benefits. Further research is needed to analyze the integration impacts of other renewable energy resources with wind farms. Challenges in reactive power management in WPPs include limitations in power electronics and turbine distance from substations, affecting the ability to supply reactive power effectively. In both conventional and WPPs, reactive power balance relies on generators, line impedance, and load reactive components, with limitations impacting voltage stability [11].

## V. Grid System Strength

### A) System strength

A power system with low system strength will have one or more of the following:

1. Wider area undamped voltage and power oscillations.
2. Generator fault ride-through degradation.
3. Mal-operation or failure of protection equipment to operate.
4. Prolonged voltage recovery after a disturbance.
5. Larger voltage step changes after switching capacitor or reactor banks.
6. Instability of generator / dynamic plant voltage control systems.
7. Increased harmonic distortion (a by-product of low system strength and higher system impedances).
8. Deeper voltage dips and higher over-voltages (e.g. transients).

The need for system strength System strength is important for the maintenance of normal power system operation, for the power systems dynamic response during a disturbance, as well as for returning the power system to stable operating conditions. Adequate system strength is required to ensure [12].

### B) System strength calculation method

Short-circuit ratio (SCR) is a calculation used to screen weak grids. This method has been taken from the screening of weak grid conditions near high-voltage dc converters and is currently being applied to wind farm [13]. SCR described as the voltage stiffness of the grid. The voltage stiffness of the grid is determined in a two-step process. The first process is to perform three-phase fault analysis at the interconnection/collector bus where a source under study is connected to the grid. The second process calculates the ratio of the short-circuit capacity, at the interconnection bus where the source of fault current is located, to the megawatt rating of the source of fault current. Based on this definition, SCR is given by the following:

$$SCR = SSC_{MVA} / PR_{MW} \quad \text{-------- Equation 1}$$

$SSC_{MVA}$ is the short-circuit MVA capacity at the bus in the existing network before the connection of the new generation source, and $PR_{MW}$ is the rated megawatt value of the new connected source. However, there is currently no industry-standard approach to calculate an SCR index of a weak system with high penetrations of wind and solar power plants or other inverter-based resources. This is an in this field which needs focus on as large penetration of inverter based resources into the power system.

### C) Special Indian Grid code for wind Turbine Connection

The collective capacity of the wind generator at the connection point exceeds 10 MW and where PPA has not yet been tied up [14].

1. Wind farms shall have the ability to limit the active power output at grid connection point as per system operator's request.
2. Wind farms shall maintain power factor between 0.95 lagging and 0.95 leading at the PCC.
3. The wind generating machines shall be equipped with fault ride through capability.
4. During system faults, wind turbines must adhere to the operational zone depicted in the provided figure. Wind farms may be disconnected if their operational point falls below the line shown.

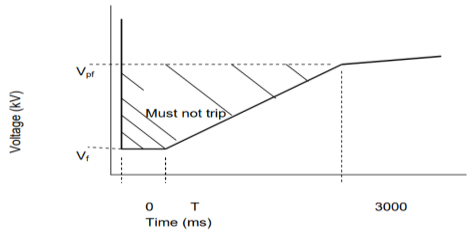


**Figure 1.5: Fault ride through characteristics**

Where, $V_f$ = 15% of Nominal System voltage $V_{pf}$ = Minimum voltages (80% of Nominal System Voltage)

5. Fault clearing time for various system nominal voltage levels.

**Table 1: Fault clearing time and voltage limits**

| Nominal system voltage (kV) | Fault clearing time, T(ms) | Vpf (kV) | Vf (kV) |
|---|---|---|---|
| 400 | 100 | 360 | 60 |
| 220 | 160 | 200 | 33.0 |
| 132 | 160 | 120 | 19.8 |
| 110 | 160 | 96.25 | 16.5 |
| 66 | 300 | 60 | 9.9 |

The recommended setup for the grid connecting transformer involves a delta connection on the wind farm side and a grounded wye connection on the transmission system (grid) side. Delta connection on the high-voltage side of the grid connecting transformer is prohibited. Alternative transformer configurations, such as wye-wye or wye-wye with a delta-connected tertiary, are also permissible for the grid connecting transformer. If the wind farm connects directly to an existing utility substation, standard utility practices shall be followed.

## VI. Case study: Short Circuit Current Calculation for a Practical WPP Connection Grid

In this paper a case study is being analyzed to calculate the maximum 3 phase fault current that can be through on 33 kV Bus Grid of WTG Transformer . For this case a practical 3 MW WTG is connected to 33 kV Utility grid through a 3.8 MVA WTG Step-up transformer. The length of 0.69 kV Cable is taken 120 m, length of 33 KV single circuit transmission line is taken 500 m and length of 33 KV double circuit transmission line is taken 2000 m. The block diagram of such has been mentioned. First, the manual calculation is to be performed to check the maximum fault current flow in the event of 3 phase fault & then the result shall be verified with ETAP Simulation soft. For the manual calculation, Ohmic and MVA method are adopted for accuracy verification.

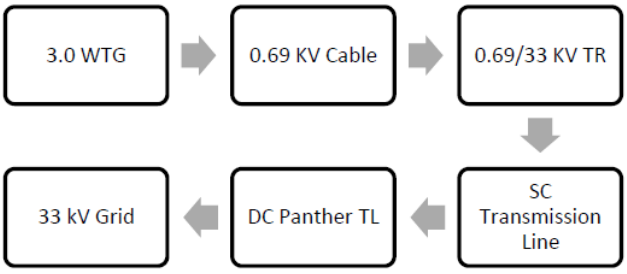


**Figure: 1.6: WTG-Grid Interconnection Block Diagram**

**Table 2: Equipment data**

| Sl. No | ID | Parameters | No |
|---|---|---|---|
| 1 | WTG | 0.69 kV, 3.0 MW, Type-3 | 01 |
| 2 | Power Cable | 5 R X 500mm2 (cu)<br>Re : 0.099 Ω/1000 m<br>X : 0.088 Ω/1000 m | 120 m |
| 3 | WTG TR | 0.69/33 kV, 3.8 MVA, %Z 7.5, R/X 0.078 | 01 |
| 4 | TL-1 | Single Ckt | 0.5km |
| 5 | TL-2 | Double Ckt | 20 km |
| 7 | Power Grid | Short Circuit MVA – 1503 @ 33 kV. | |

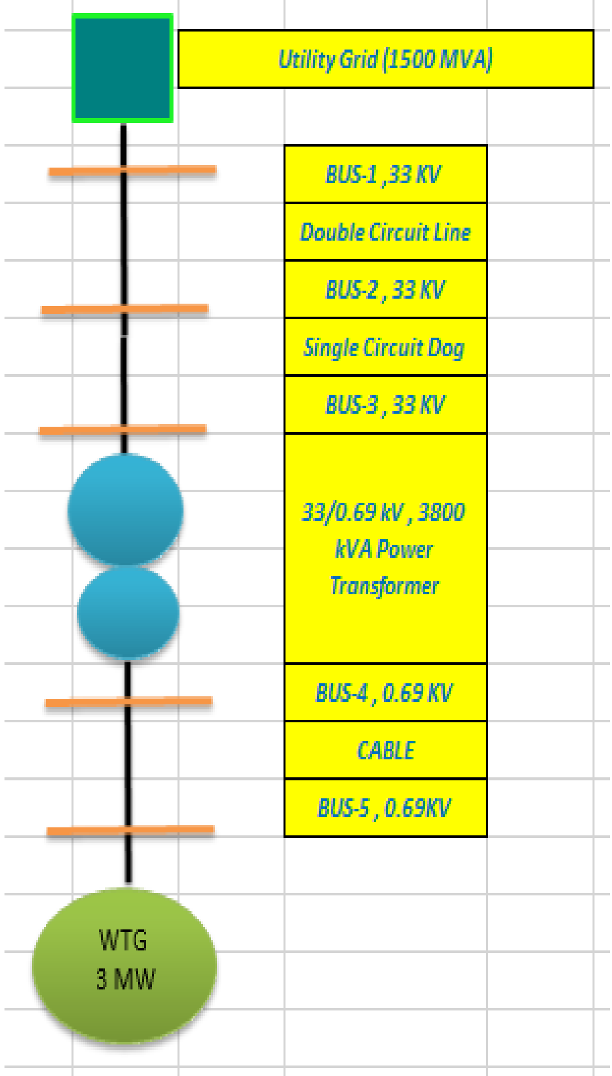


**Figure: 1.7: Single Line Diagram**

Total Single Circuit Transmission Line Impedance is 0.34 Ω, double circuit line impedance is 0.18 Ω & cable impedance 0.019 Ωat @75 Degree Celsius.

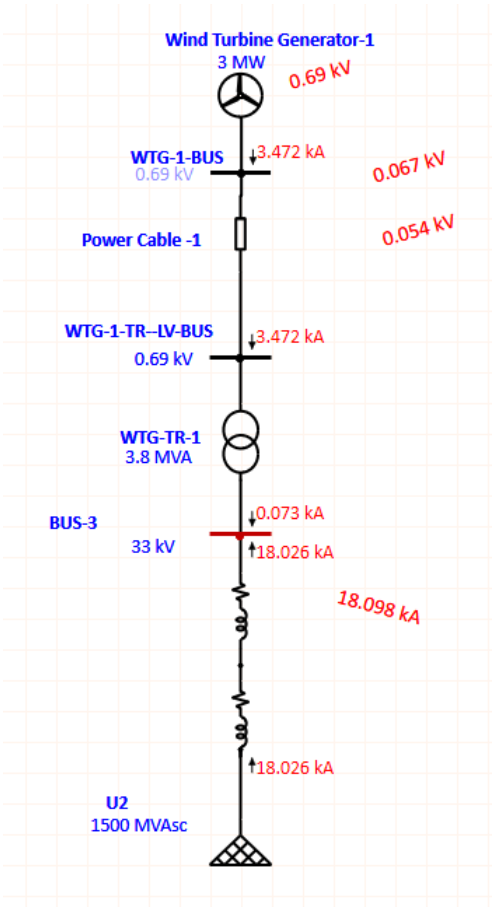
### a) Fault calculation using MVA Method

| | | | | |
|---|---|---|---|---|
| Source (Grid) | Source | = | 1503 | MVA |
| Transmission Line-1 | TL-1 | = | 3178.26 | MVA |
| Transmission Line-2 | TL-2 | = | 5979.53 | MVA |
| WTG Transformer | TR | = | 50.67 | MVA |
| WTG Cable | Cable | = | 334.39 | MVA |
| WTG | WTG | = | 52.63 | MVA |
| Fault Calculation- MVA Method - Fault @BUS-1 | | | | |
| Source (Grid) | Source | = | 1503 | MVA |
| Network Reduction Technique : TL-1 in series with TL-2 | $TL_{New}$ | = | 2075.23 | MVA |
| TL new in series with Transformer | $Tr_{New}$ | = | 49.46 | MVA |
| Tr New in series with Cable | $Cable_{New}$ | = | 43.09 | MVA |
| Cable in series with WTG | $WTG_{New}$ | = | 23.69 | MVA |
| Net MVA feeding to Bus -1 by WTG & System | | = | 23.69 | MVA |
| Total MVA @ Grid Bus-1 ( WTG new II Grid Bus Old) | | = | 1526.89 | MVA |
| **Symmetrical Fault Current to be fed @33 KV Voltage @ Bus-1** | | **=** | **26.715** | **KA** |
| Fault Calculation- MVA Method - Fault @BUS-3 | | | | |
| Source (Grid) | Source | = | 1503 | MVA |
| Network Reduction Technique : Source(Grid) in Series with TL) | $TL_{New}$ | = | 871.75 | MVA |
| Cable in series with WTG | $Cable_{New}$ | = | 45.47 | MVA |
| Cable New is series with Transformer | $Tr_{New}$ | = | 23.97 | MVA |
| Total MVA from Source Side ( Tr Series with Cable & with WTG)) | $Tr_{New1}$ | = | 895.71 | MVA |
| **Symmetrical Fault Current to be fed @33 KV Side on Transformer Bus-3)** | | **=** | **15.671** | **KA** |

### b) Fault calculation using Ohmic Method

| | | | | |
|---|---|---|---|---|
| Grid Impedance (Source) | Source | = | 0.724 | Ω |
| Total Impedance of Line -1 | ZTL1 | = | 0.343 | Ω |
| Total Impedance of Line -2 | ZTL2 | = | 0.182 | Ω |
| **Symmetrical Fault Current to be fed @33 KV Voltage @ Bus-1** | | **=** | **26.300** | **KA** |
| **Symmetrical Fault Current to be fed @33 KV Voltage @ Bus-3** | | **=** | **15.252** | **KA** |

### c) Fault calculation using ETAP Software [15]



### d) Result Comparison & Discussion

The manual calculation using MVA method, Ohmic method and simulated through ETAP software for the Symmetrical Fault Current to be fed @33 KV Side on Transformer Bus-3) are summarized in the below table.

**Table 3: Result**

| Sl. No | MVA method | Ohmic method | ETAP |
|---|---|---|---|
| 1. | 15.671 kA | 15.252 kA | 18.026 kA |

The results obtained indicate a 2% error in both the MVA and Ohmic methods, which is acceptable. However, the error marginally increases when comparing manual calculations to simulations. Therefore, the accuracy of all three methods could be further evaluated using field data. Moreover, the results obtained in this study can serve as a reference for the selection and sizing of equipment ratings, particularly circuit breakers, and for further studies on the topic.

## VII. Conclusion

In Conclusion, the study found that though there's a small 2% error in both the MVA and Ohmic methods, when we compare manual calculations to simulations, the error goes up slightly. So, it's a good idea to check the accuracy of all three methods using real-world data and can guide future research.

Further, to make wind power grids more stable, available FACTS device like STATCOM and SVC should be implemented to prevent problems like secondary trips. It's important to choose the right size for STATCOM, somewhere between 0.8 to 1.0 p.u., to balance stability and cost. We can also use advanced technology like forecasting and energy storage to make wind power more reliable, even when it's not always windy. It's a good idea to study how other renewable energy sources can work together with wind farms.

We need to create better ways to measure voltage stability and to monitor the system in real-time so we can fix problems quickly. And we should make sure that all the rules for connecting wind power to the grid are followed, so the system stays stable and reliable.

## ACKNOWLEDGMENT

I would like to express my sincere gratitude to Prof. A. P. Kinge and Prof. Dr. S. G. Kanade for their invaluable guidance and unwavering support throughout the process of writing this research paper. Their expertise, encouragement, and insightful feedback have been instrumental in shaping the direction of our study and refining its content. Their dedication to excellence and passion for academic inquiry have truly inspired and motivated us. We are deeply thankful for their mentorship and contributions, which have significantly enriched the quality of this work.

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**Citation of this Article:**

Ashutosh Mishra, Prof. Dr. S. G. Kanade, Prof. A. P. Kinge, “Grid Integration Challenges for Wind Farms”, Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 8, Issue 3, pp 278-284, March 2024. Article DOI https://doi.org/10.47001/IRJIET/2024.803042

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