**FMDB** *Transactions on Sustainable Applied Sciences*

# Applied Analysis of Power Quality Challenges in Grid-Connected Wind Energy Systems Using Technical, Economic, and Mathematical Approaches

**Kalpana D. Vidhate[1,*], Pragya Nema[2]**

[1]Department of Electrical Engineering, Dr Vithalrao Vikhe Patil College of Engineering, Ahmednagar, Maharashtra, India.
[2]Department of Electrical and Electronics Engineering, Prestige Institute of Engineering Management and Research, Indore, Madhya Pradesh, India.
ghadge.kalpana@gmail.com[1], dr.pragyanema@ymail.com[2]

**Abstract:** There is a significant disparity between the supply of electricity and the demand for it, which causes load shedding to occur in rural areas of the Indian state of Maharashtra. Therefore, to address this issue, it has been suggested that utilising additional renewable wind energy in areas with significant wind potential should be considered. If a large wind energy system is coupled to a weak grid, power quality problems will occur. As a consequence, it is essential to conduct studies on grid-connected wind farms to deepen one's understanding of Power Quality problems, their causes, and their analysis. To analyse the wind energy system in terms of the power quality (PQ) influence on the system and its management during induction generator and induction motoring modes at constant speed, variable speed, and gust speed, technical, economic, and mathematical analyses have been utilised. Emphasis has been placed on analysing power quality issues in grid-connected wind farms.

**Keywords:** Power Deficiency; Renewable Energy; Quality Characteristics; Mathematical Analysis; Wind Energy System Analysis; Power Quality Management; Grid-Connected Wind Farms.

**Received on:** 03/06/2024, **Revised on:** 21/08/2024, **Accepted on:** 14/12/2024, **Published on:** 03/06/2025

**Journal Homepage:** https://www.fmdbpub.com/user/journals/details/FTSASS

**DOI:** https://doi.org/10.69888/FTSASS.2025.000533

**Cite as:** K. D. Vidhate and P. Nema, "Applied Analysis of Power Quality Challenges in Grid-Connected Wind Energy Systems Using Technical, Economic, and Mathematical Approaches," *FMDB Transactions on Sustainable Applied Sciences*, vol. 2, no. 1, pp. 57–74, 2025.



## 1. Introduction

In North Maharashtra, India, people face load shedding due to a significant gap between electricity demand and supply [18]. In summer, this power gap widens significantly, and to address this, temporary heavy load shedding is implemented. The system is affected by the heavy load shedding [19]. The use of conventional power plants in Maharashtra state is high, increasing pollution and affecting the environment. Steam power plants produce the majority of power [21]. Factors like their inefficiency, the deterioration of the quality of the coal used to maintain the older plants, the calorific value of the coal, the age of the transmission and distribution networks and the losses they incur, among other things, have an impact on both the plant's generation capacity and the quality of the electric power produced. Therefore, in the Indian subcontinent, it is imperative to

[*]Corresponding author.

switch from steam power plants to renewable energy sources such as solar and wind power [1]; [11]. Renewable energy is available at no cost, though the initial investment is high [17]. Once the renewable plant is erected, small regular maintenance is required, and running costs are tremendously reduced. Wind energy is pollution-free and protects our environment and nature. Hence, wind energy is also called green energy [5]; [32]. The power quality of grid-connected wind energy systems is negatively impacted by the growing number of induction generators connected to the system. Consequently, there is a need to focus more on investigating the causes of these poor power-quality concerns. This work aims to investigate and evaluate the power quality of a grid-connected wind energy system operating in the fixed-speed, variable-speed, and gust-speed modes of induction generators, as well as in the induction-motoring mode [2].

## 2. Wind Power in North Maharashtra

### 2.1. Overview

The wind potential in north Maharashtra is high, as shown in Figure 1, and also the installed renewable energy capacity in India is shown in Figure 2.

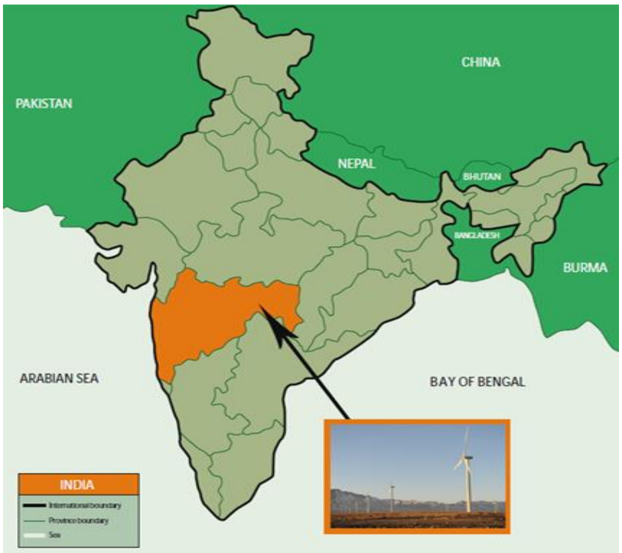



**Figure 1:** Location of case study in Maharashtra, Panchpatta, India [3]

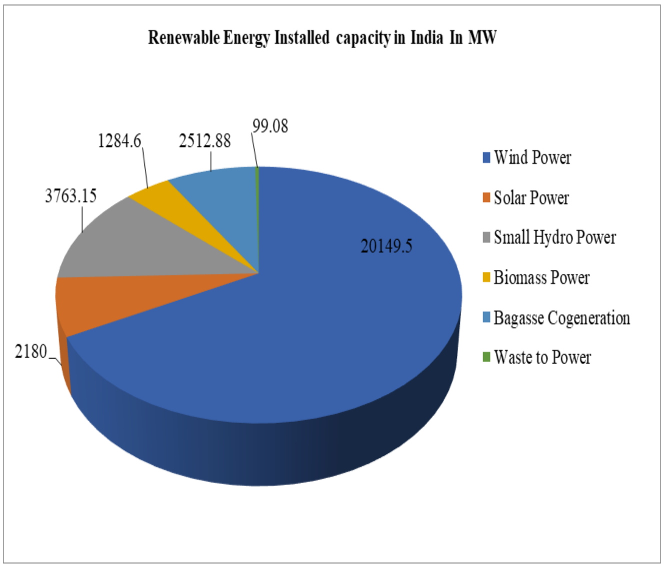



**Figure 2:** Renewable energy installed capacity in India [4]

The contributions of renewable energy from different Indian states are illustrated in Figure 3.

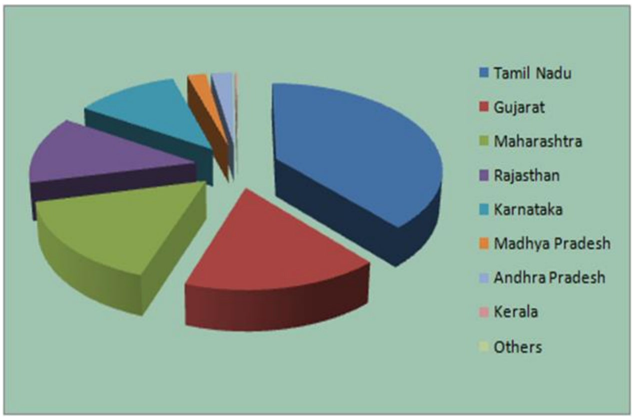



**Figure 3:** Renewable energy installed capacity in India [4]

The seasonal penetration of high-power to the grid is between May and September, medium between November and February, and low in the remaining months [34]. The 600 wind turbines are erected with different power capacities, such as 1MW, 1.25MW, etc. The wind farm has a capacity of approximately 600MW. The two fixed induction generators generate power.

Whenever the wind velocity is between 3 m/sec and 8 m/sec, the sensor detects the small generator and generates power proportional to the wind velocity. Whenever wind velocity is between 9 m/sec and 24 m/sec, the sensor detects the big generator, and the selected generators are activated to generate power in proportion to the wind velocity. Wind energy starts at 690 volts and gradually increases to 33 kV distribution voltage. An additional 132 kV/220 kV high-voltage wind power system is added to the system [33].

### 2.2. Impact of Highly Penetrated Wind Farm

With the assistance of a high gearbox ratio, a 3-ø induction motor can function as a 3-ø induction generator in a wind farm. However, because numerous induction generators are in use, there is a greater need for reactive power, which is supplied by the utility [6]. To start induction generators, a soft starter with thyristor variable-firing-angle control is employed. As a result, reactive power management is a major problem that affects the system power factor and, in essence, creates an additional load [7]. In this case, because power electronics is used as a non-linear load, harmonics are generated [8]. Switching between small and large induction generators, and vice versa, occurs in two fixed-speed induction motors operating as induction generators. This continuous switching is responsible for generating harmonics [9]. Voltage dips/sags occ ur due to the start of high-capacity induction motors, overload, short circuits, etc. A load that causes significant current variation, especially the reactive component, can cause voltage flicker. Large capacitors are used for reactive power compensation to prevent voltage swell and sudden switching off of large loads. System faults are creating the voltage swell [10]. The system power factor is affected by a large reactive power requirement due to the induction motor operating as an induction generator. To sum it up, the system's power quality has been affected, and wind power is not particularly cost-effective; therefore, its integration into the grid is limited [11].

### 2.3. The Significance of Power Quality in Massive Wind Farms

Reliability and efficiency in integrating wind power into the grid depend on maintaining high power quality. Electronic devices, including wind energy inverters and converters, are particularly sensitive to nonlinear disturbances, and poor power quality can negatively affect their service life and performance [12]. Consequently, to reduce the negative effects of low power quality on the wind energy system's overall performance, these concerns must be addressed promptly. Several power quality issues may arise from the use of various wind energy technologies, and they may also affect grid operation, transmission, and power generation. Power quality has been affected by the unexpected grid connection of a wind energy system, the erratic and unpredictable nature of wind power generation, the fluctuating output of induction generators, and the driving mode of operation [13]. Massive amounts of wind energy can be introduced into a weak grid system, affecting the wind energy system's overall operation in economic, mathematical, and mechanical terms due to complications arising from poor power quality [14].

## 3. System Development

### 3.1. Case study

The case study includes 30 wind turbines and 20 feeders, as depicted in Figures 4, 5, 6 and 7. The wind farm in Figure 5 has a capacity of 600 MW and 600 turbines.

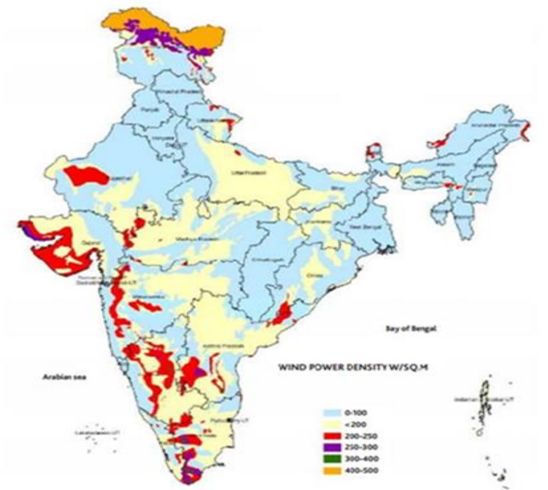



**Figure 4:** Wind power density in India [15]

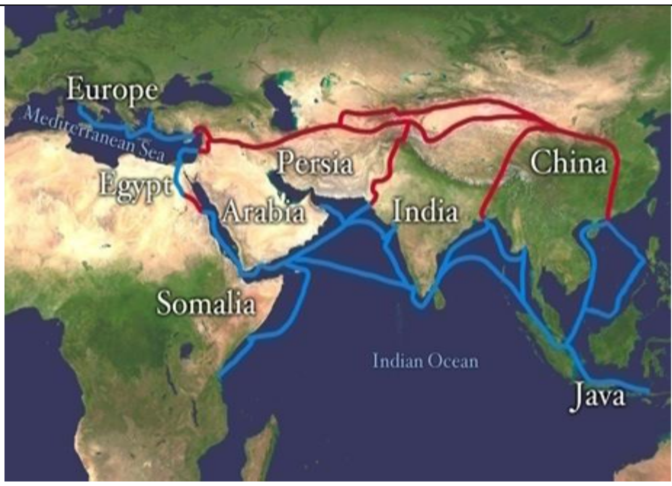



**Figure 5:** Location of India in the world renewable energy zone [16]

Figure 6 wind farm simulation is neatly laid out, making the intricate case study easy to follow.

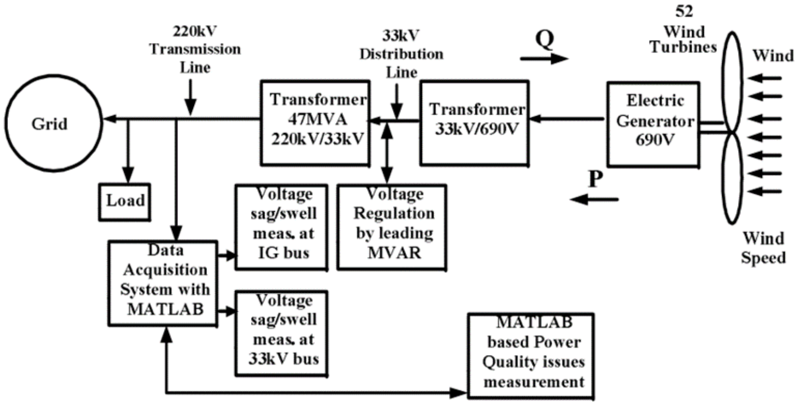



**Figure 6:** Block diagram for wind turbine system

The case study uses technical equipment such as a wind turbine, gearbox, induction generator, transformer, capacitor bank, underground cable, grid system, load, etc., [7]; [8]; [20].

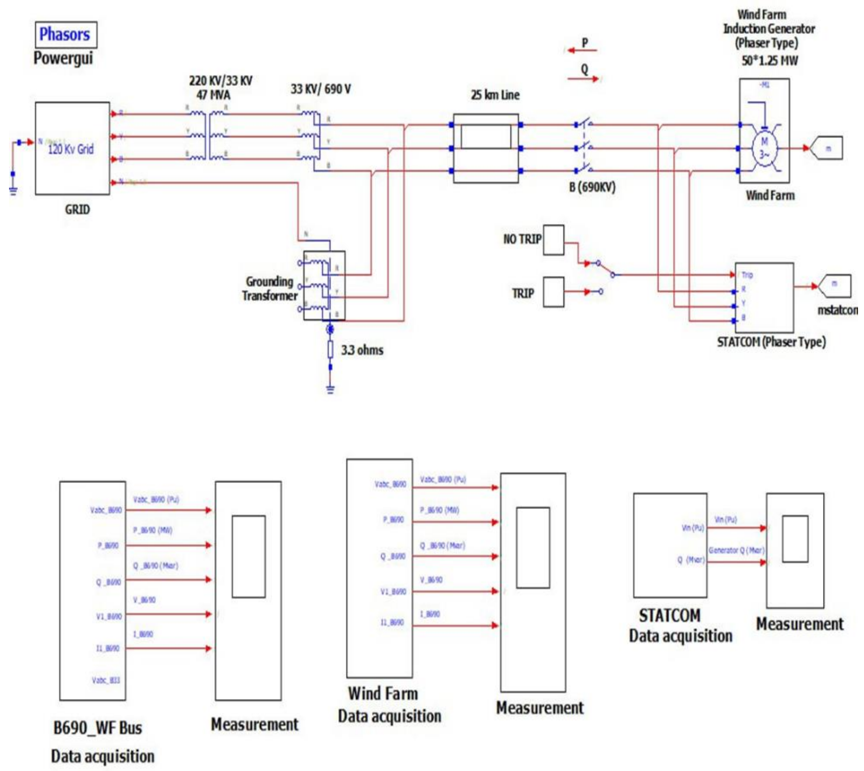



**Figure 7:** Case study of a heavy penetration, fixed speed wind energy system in Maharashtra, India, using MATLAB/SIMULINK

In accordance with IEC and IEEE standards, the power quality of the entire wind farm is presented herein. In wind farms, two types of wind turbines are used: 1.25 and 1.5 MW. To avoid the complexity of 600 wind turbines in a wind farm during MATLAB-based operation, 52 wind turbines are used at certain distances in hilly areas of the Maharashtra region.

### 3.2. Mathematical Modelling of Case Study

The case study's comprehensive modelling is presented below. A sensor can detect the two fixed-speed induction generators. Wind speed is divided into two categories: G1 (3-8 m/sec) and G2 (9-24 m/sec). The corresponding induction generator speed is adjusted in accordance with G1 and G2. Due to the increased use of induction generators, reactive power requirements rise, affecting the power factor. This study begins with a technical, economic, mathematical, and MATLAB-based simulation analysis of the power quality issues of a grid-connected wind farm. Specifically, the power quality issues considered in this case are voltage sag, voltage swell, harmonics, power factor, and reactive power. Subsequently, their (PQ) relationship with economy, loss, and profit under the induction generator and induction motoring mode of wind farm operation is examined. Let the notations have been considered as $w$ = Wind velocity, $x$ = Variable, $r$ = Gear ratio, and their correlations expressed from (a) to (f) as follows:

$$w = w_1 = w_2 = w_3 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots w_n \quad (1)$$

$$x = x_1 = x_2 = x_3 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots x_n \quad (2)$$

$$r = r_1 = r_2 = r_3 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots r_n \quad (3)$$

$r k \kappa$

$$r \propto w = r_1 \propto w_1 = r_2 \propto w_2 = r_3 \propto w_3 \cdots\cdots\cdots r_n \propto w_n \quad (4)$$

$$r = \kappa w = r_1 = \kappa w_1 = r_2 = \kappa w_2 = r_3 = \kappa w_3 \cdots\cdots\cdots r_n = \kappa w_n \quad (5)$$

$\kappa$ = Gear ratio constant, i.e. 1:76

$$\mathrm{i} = \mathrm{i_m} \text{ or } \mathrm{i_g} \quad (6)$$

$$\mathrm{i} = \mathrm{f(r_1)} = \mathrm{f(x)} = \begin{cases} 1, & r_1 > 875 \text{ rpm} \\ 0, & r_1 < 875 \text{ rpm} \end{cases} \quad (7)$$

$$\mathrm{i}^{\dagger} = \mathrm{f}^{\dagger}(\mathrm{r_1}) = \mathrm{f(x)} = \begin{cases} 1, & r_1 > 438 \text{ rpm} \\ 0, & r_1 < 438 \text{ rpm} \end{cases} \quad (8)$$

$$\mathrm{i}^{\dagger\dagger} = \mathrm{f}^{\dagger\dagger}(\mathrm{r_1}) = \mathrm{f(x)} = \begin{cases} 1, & r_1 > 1533 \text{ rpm} \\ 0, & r_1 < 1533 \text{ rpm} \end{cases} \quad (9)$$

Reactive Power =re,

Power Factor = pf (Cos Ø)

$$\mathrm{P} \propto \frac{1}{\mathrm{re}} \text{ and pf } \propto \frac{1}{\mathrm{re}} \quad (10)$$

$$\mathrm{P_1} \propto \frac{1}{\mathrm{re_1}} \quad (11)$$

$$\mathrm{P_2} \propto \frac{1}{\mathrm{re_2}} \quad (12)$$

$$\mathrm{P_n} \propto \frac{1}{\mathrm{re_n}} \quad (13)$$

$$\mathrm{pf} \propto \frac{1}{\mathrm{re}} \quad (14)$$

$$\mathrm{pf_1} \propto \frac{1}{\mathrm{re_1}} \quad (15)$$

$$\mathrm{pf_2} \propto \frac{1}{\mathrm{re_2}} \quad (16)$$

$$\mathrm{pf_n} \propto \frac{1}{\mathrm{re_n}} \quad (17)$$

ƥ = price of power (selling power); ₱ = wind power

At 0.5 cycle to 1 minute;

$\underline{\underline{V}} \propto$ Voltage Sag, a decrease of voltage from 0.1 to 0.9 p.u. rms (18)

$\overline{\overline{V}} \propto$ Voltage Swell, an increase in voltage from 1.1 to 1.8 p.u. rms (19)

$$\underline{\underline{V}}_{sag} = \begin{cases} 1 & v < 0.1 \text{ to } 0.9 \text{ p.u. rms at } 0.5 \text{ cycle to } 1 \text{ minute} \\ 0 & v = \text{rated voltage} \end{cases} \quad (20)$$

$$\overline{\overline{V}}_{swell} = \begin{cases} 1 & v \geq 1.1 \text{ to } 1.8 \text{ p.u. rms at } 0.5 \text{ cycle to } 1 \text{ minute} \\ 0 & v = \text{rated voltage} \end{cases} \quad (21)$$

The notations have been considered as follows:

$$v = \begin{cases} \underline{\underline{V}}_{sag}, & v < 690V, \text{wind generator voltage}, 0.1 \text{ to } 0.9 \text{ p.u. rms at } 0.5 \text{ cycle to } 1 \text{ min.} \\ \overline{\overline{V}}_{swell}, & v \geq 690v, 1.1 \text{ to } 1.8 \text{ p.u. rms at } 0.5 \text{ cycle to } 1 \text{ minute} \end{cases} \quad (22)$$

This is a constraint on voltage sag and voltage swell conditions for a grid-connected wind farm.

**Table 1:** Monthly voltage, current, power and frequency of the wind farm

| Windy Months | Voltage Function | | | Current | | | Power | | Frequency |
|---|---|---|---|---|---|---|---|---|---|
| | $V_{RY}$ | $V_{YB}$ | $V_{BR}$ | $I_R$ | $I_Y$ | $I_B$ | Active Power P MW | Reactive Power Q MVAR | |
| Oct. to Jan | 139.75 | 139.72 | 139.12 | 109.94 | 118.20 | 114.75 | 27.30 | 3.51 | 49.85 |
| June | 139.47 | 139.99 | 138.79 | 150.66 | 162.12 | 158.61 | 37.92 | 0.62 | 49.72 |
| July. | 141.14 | 140.74 | 140.49 | 129.66 | 140.36 | 138.70 | 33.07 | 1.17 | 49.87 |
| Aug. | 139.10 | 139.35 | 139.06 | 118.99 | 123.41 | 122.54 | 31.22 | 1.42 | 49.81 |
| Sept. | 140.62 | 139.84 | 139.64 | 136.55 | 147.06 | 145.29 | 33.11 | 2.92 | 49.79 |

Table 1 indicates the nature of active and reactive power. During the winter season, it is the lowest of all. It is highlighted as 27.30 MW and 3.51 MVAR. At the beginning of the rainy season, it increases to 37.92MW and 0.62 MVAR, respectively.

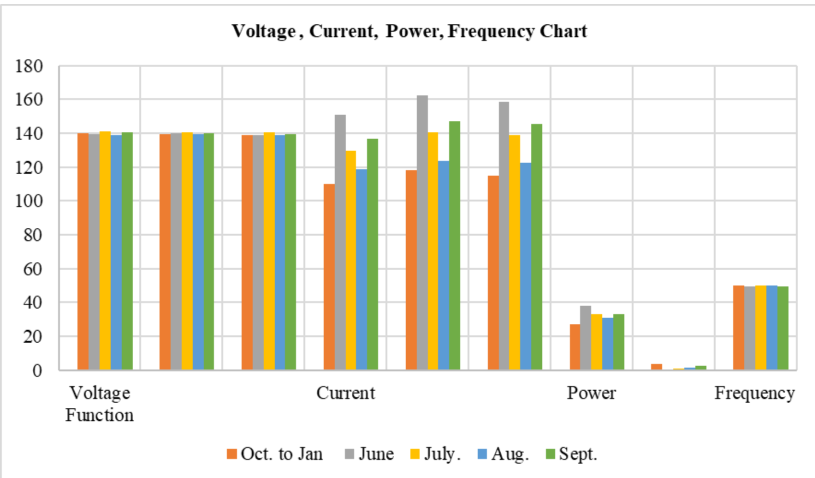



**Figure 8:** Graphical representation of monthly voltage, current, power and frequency of the wind farm

The monthly average voltage, current, power, and frequency of wind farms are presented in Table 1 and Figure 8. Reactive power management has been identified as a major concern, and the utility system satisfies the demand for reactive power:

As þ =price of power (selling power); ₱ =wind power

$$₱ = f(\varpi 1, R1, I1) \quad (23)$$

$$R = þ * ₱ \quad (24)$$

$$R_1 = þ_1 * ₱_1 \quad (25)$$

$$R_2 = þ_2 * ₱_2 \quad (26)$$

$$R_n = þ_n * ₱_n \quad (27)$$

$$R = \sum_{i=0}^{n} þ_i ₱_i = \sum_{i=1}^{n} R_1 \quad (28)$$

This is in accordance with the Linear Programming Problem (LPP). R=Revenue of power; þ =price of power. As per the time series analysis, feeder-wise wind power generation details are given below,

**Table 2:** Feeder 1 voltage, current, power, power factor and frequency of wind farm

| No. | Voltage $V_{RY}$ | Current $I_R$ | Current $I_Y$ | Current $I_B$ | Active Power P | Reactive Power Q | Power Factor *cosØ* |
|---|---|---|---|---|---|---|---|
| 1 | 35.42 | 74.80 | 83.31 | 84.83 | 4.92 | 1.46 | 0.95 |
| 2 | 35.45 | 50.50 | 52.03 | 53.94 | 2.62 | 1.57 | 0.85 |
| 3 | 35.10 | 42.46 | 43.27 | 44.39 | 2.26 | 1.83 | 0.87 |
| 4 | 35.17 | 74.40 | 76.32 | 80.58 | 3.95 | 1.52 | 0.93 |
| 5 | 35 | 28.74 | 26.87 | 32.57 | 0.93 | 1.15 | 0.63 |
| 6 | 34.84 | 37.53 | 37.36 | 47.33 | 2.18 | 1.44 | 1.0 |

Table 2 indicates that the Feeder 1-based wind farm's nature of active power: power factor and reactive power. The maximum active and reactive power obtained were 4.92MW and 1.46 MVAR, respectively, and the minimum active and reactive power obtained were 0.93 MW and 1.15 MVAR, respectively. Similarly, the maximum power factor obtained is 1.0, and the minimum is 0.63.

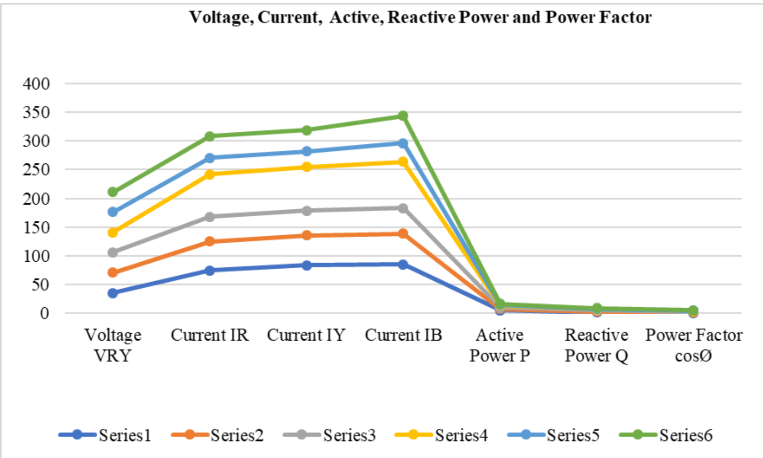



**Figure 9:** Graphical representation of feeder-1 voltage, current, power and frequency of the wind farm

Table 2 and Figure 9 indicate the monthly voltage, current, power and frequency of the wind farm in a systematic way.

**Table 3:** Feeder 2 voltage, current, power, power factor and frequency of wind farm

| No. | Voltage $V_{RY}$ | Current $I_R$ | Current $I_Y$ | Current $I_B$ | Active Power P | Reactive Power Q | Power Factor *cosØ* |
|---|---|---|---|---|---|---|---|
| 1 | 34.94 | 39.21 | 41.93 | 44.13 | 2.43 | 0.76 | 0.95 |
| 2 | 34.81 | 37.25 | 38.47 | 41.93 | 2.24 | 0.85 | 0.93 |
| 3 | 35.70 | 45 | 46 | 45.84 | 2.62 | 0.63 | 0.97 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | 34.62 | 79.40 | 85.71 | 88.97 | 5.18 | 0.74 | 0.98 |
| 5 | 34.31 | 32.28 | 32.32 | 39.67 | 2.04 | 0.73 | 0.94 |

Table 3 indicates that the Feeder 2-based wind farm operates in active power mode: power factor and reactive power. The maximum active and reactive power obtained were 5.18 MW and 0.74 MVAR, and the minimum active and reactive power obtained were 2.04 MW and 0.73 MVAR, respectively. Similarly, the maximum power factor obtained is 0.98, and the minimum is 0.93.

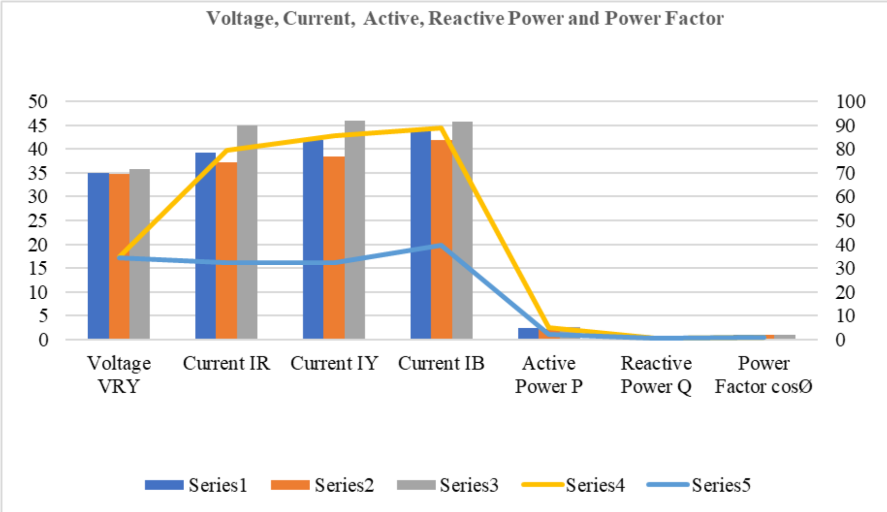



**Figure 10:** Graphical representation of feeder-2 voltage, current, power and frequency of the wind farm

Table 3 and Figure 10 indicate the monthly voltage, current, power and frequency of the wind farm in a systematic way.

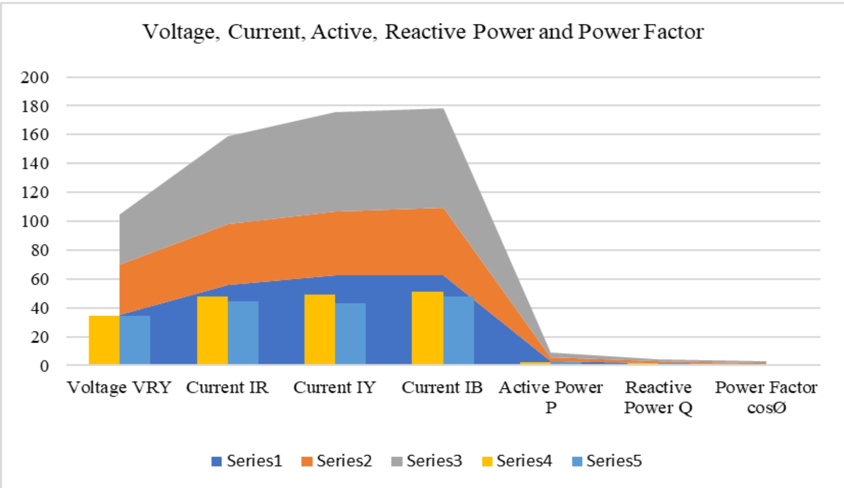



**Figure 11:** Graphical representation of feeder three voltage, current, power and frequency of wind farm

Table 4 indicates that the Feeder 3-based wind farm operates in active power mode: power factor and reactive power. The maximum active and reactive power obtained were 3.71 MW and 1.56 MVAR, and the minimum active and reactive power obtained were 2.28 MW and 1.29 MVAR, respectively. Similarly, the maximum power factor obtained is 0.92, and the minimum is 0.86.

**Table 4:** Feeder 3 voltage, current, power, power factor and frequency of the wind farm

| No. | Voltage $V_{RY}$ | Current $I_R$ | Current $I_Y$ | Current $I_B$ | Active Power P | Reactive Power Q | Power Factor *cosØ* |
|---|---|---|---|---|---|---|---|
| 1 | 34.92 | 55.90 | 62.38 | 62.38 | 3.31 | 1.37 | 0.92 |
| 2 | 34.97 | 41.85 | 44.63 | 46.95 | 2.28 | 1.29 | 0.87 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | 34.63 | 61.36 | 68.29 | 69.01 | 3.71 | 1.56 | 0.92 |
| 4 | 34.74 | 47.77 | 48.95 | 51.15 | 2.64 | 1.34 | 0.89 |
| 5 | 34.60 | 44.21 | 43.23 | 47.88 | 2.49 | 1.47 | 0.86 |

Table 4 and Figure 11 indicate the monthly voltage, current, power and frequency of the wind farm in a systematic way. Table 5 indicates the nature of active power in the Feeder 4-based wind farm: power factor and reactive power.

**Table 5:** Feeder 4 voltage, current, power, power factor and frequency of wind farm

| No. | Voltage $V_{RY}$ | Current $I_R$ | Current $I_Y$ | Current $I_B$ | Active Power P | Reactive Power Q | Power Factor *cosØ* |
|---|---|---|---|---|---|---|---|
| 1 | 34.86 | 27.25 | 28.78 | 31.61 | 5.38 | 0.34 | 0.84 |
| 2 | 34.61 | 45.24 | 47.21 | 52.13 | 2.66 | 0.12 | 0.91 |
| 3 | 34.52 | 62.11 | 64.70 | 64.66 | 3.56 | 1.12 | 0.96 |
| 4 | 34.42 | 59.63 | 59.97 | 63.33 | 3.45 | 0.11 | 0.95 |
| 5 | 34.36 | 33.53 | 32.24 | 37.98 | 1.76 | 0.1 | 0.85 |

The maximum active and reactive power obtained were 5.38 MW and 0.34 MVAR, and the minimum active and reactive power obtained were 1.76 MW and 0.71 MVAR, respectively. Similarly, the maximum power factor obtained is 0.96, and the minimum is 0.84.

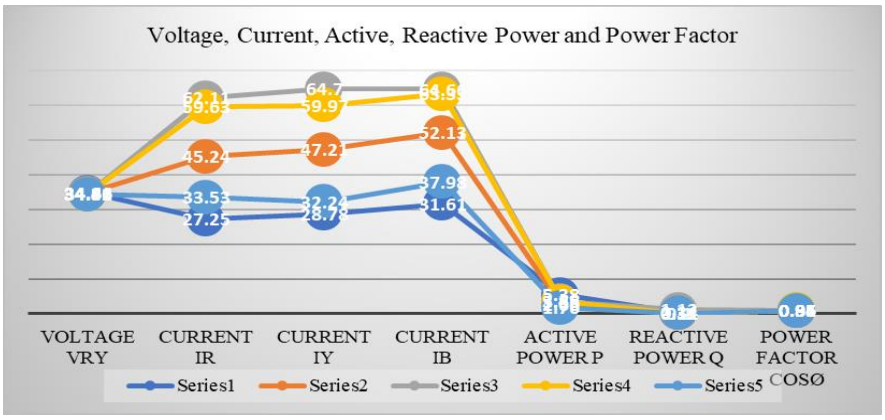



**Figure 12:** Graphical representation of feeder four voltage, current, power and frequency of the wind farm

Table 5 and Figure 12 indicate the monthly voltage, current, power and frequency of the wind farm in a systematic way.

**3.3. Power Quality (PQ) Issues**

- Harmonics (H)
- Power Factor (cosØ)
- Reactive Power (Re)
- Voltage Sag ($V_{sag}$)
- Voltage Swell ($V_{swell}$)

The original data of the above and the predictable data are to be verified. Enter the values of Re, H, power factor, voltage, and frame, and the system will be set up accordingly. Four variables are considered Re = 1, H = 2, Power factor = 3, voltage = 4.

**Table 6:** Power quality issues distribution of the wind farm

| P or PQ | Harmonics (H) | Power Factor (cosØ) | Reactive Power (Re) | Voltage Sag $\underline{V}_{sag}$ | Voltage Swell $\overline{V}_{swell}$ |
|---|---|---|---|---|---|
| 3 | 1 | 3 | 2 | 2 | 2 |
| 2 | 1 | 1.5 | 2.5 | 3 | 3 |
| 5 | 2 | 1 | 5.3 | 2 | 2 |
| 4 | 3.1 | 2 | 2 | 4.1 | 4.1 |
| 5 | 1.5 | 2 | 2 | 3.1 | 3.1 |

Table 6 indicates the distribution of power quality issues in a connected wind farm. Harmonics, power factor, reactive power, voltage sag, and voltage swell are highlighted herewith. Formula of Power Quality:

$$PQ= 0.2Re+0.6H+0.3pf+0.9V \quad (29)$$

Put the values of Re, H, PF and V.

**3.3.1. Harmonics**

H=harmonics, C=cost of H or loss of H

Re=Reactive power

$$C_1^1 = \text{Loss or cost of Reactive Power} \quad (30)$$

e.g.- 3rd harmonics

$$H_1C_1,\ H_1 = 3xC_1 \quad (31)$$

$$H_1C_1,\ H_1 = 3xC_1 \quad (32)$$

$$H_nC_{HnHn,}\ H \leq 3\%\ \text{THD ie under control},\ H \geq 3\%\ \text{THD ie critical} \quad (33)$$

$$Re_{1\ X}\ C_1^1 \quad \text{or} \quad pf_1 \propto 1/\ C_1^1 \quad (34)$$

$$Re_{2\ X}\ C_2^1 \quad \text{or} \quad pf_2 \propto 1/\ C_2^1 \quad (35)$$

$$Re_{n\ X}\ C_n^1 \quad \text{or} \quad pf_n \propto 1/\ C_n^1 \quad (36)$$

V= Voltage, U= Vsag or Vswell, $C_1^{11}$ = loss of sag or swell or cost

$$U_1X\ \ C_1^{11} \quad (37)$$

$$U_2X\ \ C_1^{11}U_nX\ \ C_n^{11} \quad (38)$$

$$C^{1\,=}\ \text{cost}C_1 = \sum_{i=1}^{n}(H_iC_i + Re_iC_{i1} + V_iC_{i11}) \quad (39)$$

$$\text{Profit} = \pi = R - C_{i1} \quad (40)$$

$$^{\text{Profit} = \pi =}\ \pi_1 = \sum_{i=1}^{n}(\text{þ}_i\text{₱}_i) - \sum_{i=1}^{n}(H_iC_i + Re_iC_{i1} + V_iC_{i11}) \quad (41)$$

$\Pi$ = profit, $R$ = Revenue $C_1$ = constant

$P_i \geq 0,\ H_i \geq 0,\ Re_i \geq 0,\ V_i \geq 0.$
$R_i \geq 1500$
$660 \leq V \leq 750$
$V = 690v$
$660v \leq 690v$ Sag(v)
$750v \geq 690v$ Swell(v)

Put the correct value from past data:

$$\Pi= \begin{cases} \text{PQ} \\ \text{Reactive power, Harmonics, Power factor, voltage sag or swell} \end{cases} \quad (42)$$

$$PQ= f(Re, H, pf, v) \quad (43)$$

The multiple regression tool can be used for the same. Put the values of Re, H, pf, v from the past data:

$$PQ= 0.2Re+0.6H+0.3pf+0.9V \quad (44)$$

Put the probable values of $\mathrm{Re}, \mathrm{H}, \mathrm{pf}, \mathrm{v}$. Enter the PQ values as per the Power Quality Analyser, based on the recorded data:

$$PQ \propto P \quad (45)$$

Here, the Induction motor works as an Induction Motor only in a wind turbine due to the non-availability of wind, i.e., wind period. Wind is not available during I.M. mode:

Loss function Π1 = cost function+ cost (46)

Total loss= C1 (as it is of previous case) + new constant of Induction motor mode (47)

Power is received from the utility during the Induction motoring mode, and wind power is injected into the grid during Induction generator mode:

X= variable, $X_1$, $X_2$, $X_3$-----------Xn (48)

**Table 7:** Power generation capacity of the case study

| Time in sec | RY in KV | YB in KV | BR in KV | IR in Amp | IY in Amp | IB in Amp | Active Power P in MW | Reactive Power Q MVAR |
|---|---|---|---|---|---|---|---|---|
| 1 | 139.75 | 139.72 | 139.15 | 109.9 | 118.2 | 114.75 | 27.3 | 3.51 |
| 2 | 140.62 | 139.84 | 139.64 | 135.6 | 147.06 | 145.29 | 33.11 | 2.92 |
| 3 | 139.47 | 139.99 | 138.79 | 150.7 | 162.12 | 158.61 | 37.92 | 0.62 |
| 4 | 139.1 | 139.35 | 139.06 | 119 | 123.41 | 122.34 | 31.22 | 1.42 |
| 5 | 141.14 | 140.75 | 140.49 | 129.7 | 140.26 | 138.7 | 33.07 | 1.17 |

Table 7 indicates the Power generation capacity of the case study Grid-connected wind Farm. The highest active power identified is 37.92MW, and the lowest is 27.3MW. Also, the highest reactive power is 3.51 MVAR, and the lowest is 0.62 MVAR. New cost due to Induction motoring mode:

$$\mathrm{C}_1^{1\star} \propto \mathrm{R}_1 \quad (49)$$

$$\mathrm{C}_1^{1\star}\mathrm{R1} \quad (50)$$

$$\mathrm{C}_1^1 = \sum_{i=0}^{n}(\mathrm{C}_i^{1\star})\mathrm{R}_n \quad (51)$$

$$\mathrm{C}_1^1 = \sum_{i=1}^{n}(\mathrm{H}_i\mathrm{C}_i + \mathrm{Re}_i\mathrm{C}_{i1} + \mathrm{V}_i\mathrm{C}_{i11}) + \sum_{i=0}^{n}(\mathrm{C}_i^{1\star})\mathrm{R}_i \quad (52)$$

**3.4. Power Generation Data Analysis**

The detailed power generation capacity. A case study is illustrated in Table 6. The fixed wind speed and PQ are illustrated in Table 7. The variable wind speed part I and PQ are illustrated in Table 8. The variable wind speed, part II and PQ are illustrated in Table 9. The gust wind speed and PQ are illustrated in Table 10.

**Table 8:** PQ and fixed wind speed

| Time (sec) | Wind velocity (m/sec) | Voltage (volts) | Active Power (P) MW | Reactive Power (Q) MVAR |
|---|---|---|---|---|
| 0.5 | 12 | 590 | 45 | 30 |
| 1 | 12 | 600 | 42 | 25 |
| 1.5 | 12 | 690 | 49 | 20 |
| 2 | 12 | 691 | 49.5 | 19 |
| 2.5 | 12 | 690 | 48.5 | 22 |
| 3 | 12 | 692 | 49 | 20 |
| 3.5 | 12 | 690 | 49.5 | 18 |

Table 8 indicates the relationship between power quality PQ and wind speed. The highest active power is 49.5MW, and the minimum is 42 MW. The highest reactive power is 30 MVAR, and the lowest is 18 MVAR. Table 8 presents the PQ and fixed wind speed for the case study of a grid-connected wind farm.

**Table 9:** PQ and variable wind speed part-I

| Time in sec | Wind velocity m/sec | Voltage in volts | Active Power P MW | R.P.Q (Q) MVAR |
|---|---|---|---|---|
| 9 | 15 | 690 | 37 | 16 |
| 9.5 | 13 | 690 | 35 | 15 |
| 10 | 12 | 700 | 40 | 13 |
| 10.5 | 12.5 | 690 | 43 | 14 |
| 11 | 12 | 690 | 42 | 14 |
| 11.5 | 12.5 | 690 | 46 | 16 |
| 12 | 12 | 690 | 42 | 13 |
| 12.5 | 11 | 685 | 40 | 15 |
| 13 | 10 | 685 | 33 | 10 |
| 13.5 | 8 | 684 | 26 | 8 |
| 13 | 6 | 680 | 20 | 7 |
| 14 | 5 | 681 | 15 | 5 |
| 14 | 4 | 680 | 12 | 3 |
| 15 | 3 | 683 | 7 | 2 |
| 16 | 2 | 680 | 0 | 0.15 |

Table 9 shows the relationships between active and reactive power and wind speed. The highest active power is 46 MW, and the minimum is 7 MW. The highest reactive power is 16 MVAR, and the lowest is 2 MVAR. Table 10 indicates the PQ and Variable wind speed part I of the case study of a connected wind farm.

**Table 10:** PQ and variable wind speed part-II

| Time (sec) | Wind velocity (m/sec) | Voltage in volts | Active Power P MW | R.P.Q in MVAR |
|---|---|---|---|---|
| 0.5 | 2 | 685 | 0 | 0.1 |
| 1 | 3 | 680 | 0.8 | 0.3 |
| 1.5 | 5 | 690 | 2 | 0.5 |
| 2 | 7 | 691 | 5 | 0.9 |
| 2.5 | 9 | 690 | 12 | 2 |
| 3 | 11 | 692 | 19 | 5 |
| 3.5 | 12 | 690 | 25 | 10 |
| 4 | 13 | 700 | 29 | 14 |
| 4.5 | 15 | 705 | 35 | 17 |
| 5 | 17 | 709 | 40 | 18 |
| 5.5 | 19 | 689 | 42 | 19 |
| 6 | 21 | 687 | 44 | 21 |
| 6.5 | 23 | 680 | 47 | 25 |
| 7 | 25 | 685 | 47.5 | 26 |
| 7.5 | 21 | 700 | 46 | 25 |
| 8 | 19 | 702 | 44 | 23 |

Table 10 shows the relationships between active and reactive power and wind speed. The highest active power is 47.5 MW, and the minimum is 0.8 MW. The highest reactive power is 26 MVAR, and the lowest is 0.1 MVAR.

**Table 11:** PQ and gust wind speed

| Time (sec) | Wind velocity in m/sec | Voltage in volts | Active Power P MW | Reactive Power Q MVAR |
|---|---|---|---|---|
| 0.5 | 3 | 690 | 1 | 0.3 |
| 1 | 7 | 680 | 3 | 1 |
| 1.5 | 12 | 695 | 10 | 2 |
| 2 | 12 | 699 | 14 | 4 |

| | | | | |
|---|---|---|---|---|
| 2.5 | 18 | 685 | 19 | 7 |
| 3 | 20 | 680 | 25 | 10 |
| 3.5 | 12 | 690 | 30 | 18 |
| 4 | 16 | 705 | 32 | 19 |
| 4.5 | 24 | 679 | 35 | 22 |
| 5 | 3 | 670 | 25 | 12 |
| 5.5 | 9 | 672 | 17 | 9 |
| 6 | 15 | 700 | 19 | 11 |
| 6.5 | 25 | 670 | 13 | 7 |
| 7 | 11 | 680 | 14 | 8 |
| 7.5 | 17 | 700 | 15 | 9 |
| 8 | 5 | 689 | 9 | 4 |
| 8.5 | 12 | 690 | 5 | 1 |
| 9 | 24 | 670 | 7 | 2 |
| 9.5 | 16 | 680 | 9 | 3 |
| 10 | 3 | 675 | 3 | 0.5 |

Table 11 shows the relationship between active and reactive power and gust wind speed. The highest active power is 35 MW, and the minimum is 1 MW. The highest reactive power is 22 MVAR, and the lowest is 0.3 MVAR. Table 11 indicates the PQ and Gust wind speed of the connected wind farm.

### 4. Power Quality Analysis

The power quality of the wind energy system has been examined at various wind velocities [24].

### 4.1. At the Rated Speed (12 M/S), or a Fixed Wind Speed

For instance, in this scenario, two fixed-speed IGMaximumpower extraction from wind turbines is achieved at a rated wind speed of 12 m/s [25]; [27]. This scenario results in constant maximum power generation, as shown in Figures 13 and 14, along with a decrease in reactive power demand and an improvement in power factor [27].

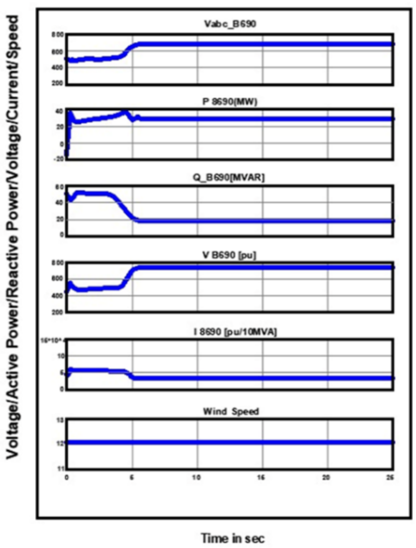



**Figure 13:** PQ at constant speed with respect to time on the X axis [22]

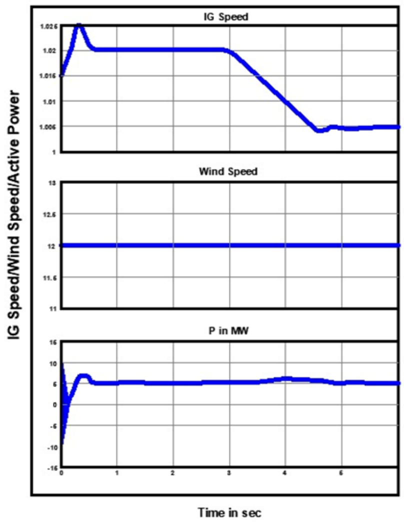



**Figure 14:** Rated wind speed 12 m/sec w.r. t. time in X axis [22]

The synchronisation of electricity generation with grid feeding is crucial from the outset. Every waveform begins with a transitory condition, from which the state of the electrical power system can be inferred. Apart from the instance mentioned above, the wind's characteristics are also significant. In this instance, the two fixed speeds function as a constant speed; hence, their impact on the electric power supply is minimal.

### 4.2. At the Fluctuating Speed of the Wind, or Changing Wind Gusts (IG)

Variable wind velocity in this context is defined as 3-24 m/s.As a result, when wind velocity increases and voltage and power factor profiles decrease, the need for reactive power increases. The maximum wind power is extracted at the waveform's centre, and it gradually decreases at the system's beginning and end (Figure 15). The power quality parameters of wind energy systems are also affected by varying wind start-up and shutdown waveforms, as depicted in Figures [26] and [28]. According to grid code requirements, variable intermittent wind velocities cause deviations in the power quality characteristics of the wind energy system. [29]; [30]. These power-quality parameters are shown in Figures 15 and 16 and are listed.

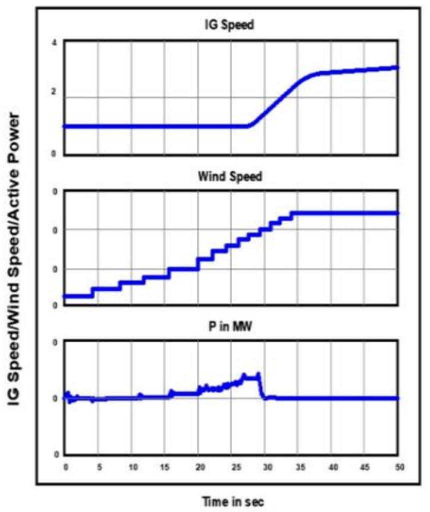



**Figure 15:** PQ at variable wind speed with respect to time on the X axis

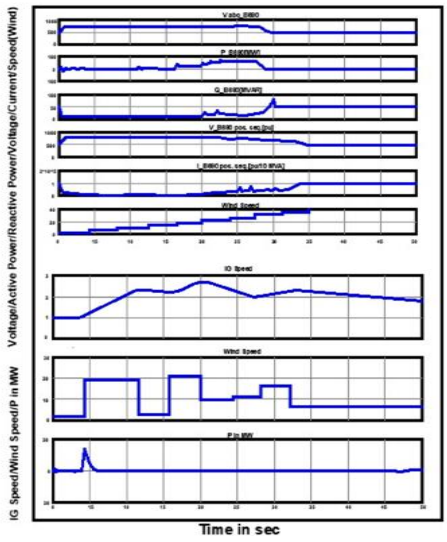



**Figure 16:** PQ at gust wind speed with respect to time on the X axis

Variations in wind speed, whether sudden or random, affect various power factors, voltage levels, and active power. The instability of variable wind power is a significant problem that warrants greater focus.

### 4.3. When the Wind is Gusting, or When the Wind is IG

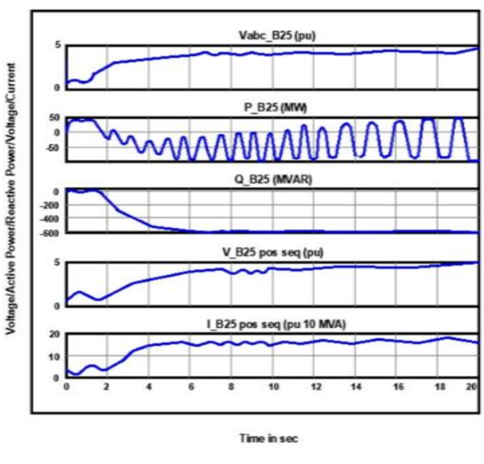



**Figure 17:** Simulation waveforms at gust wind speed

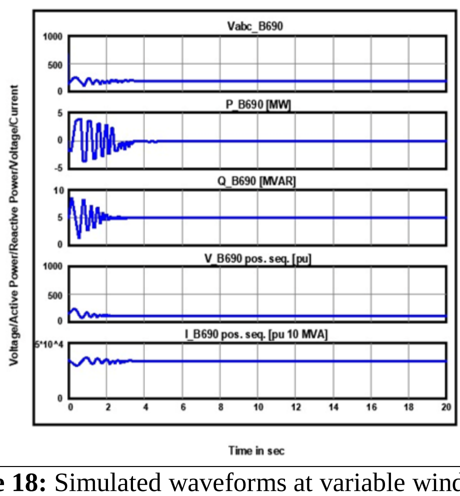
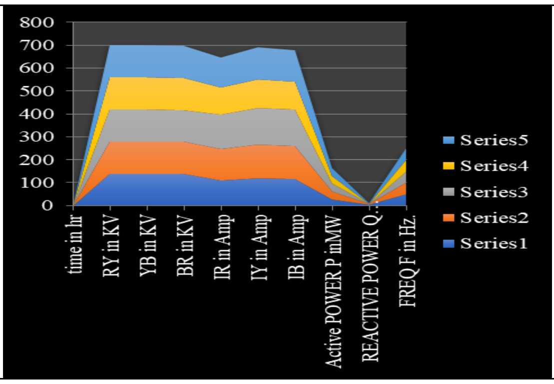
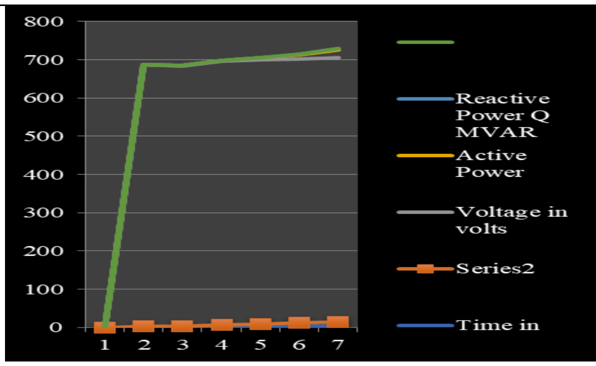



**Figure 18:** Simulated waveforms at variable wind speed with respect to time on the X axis

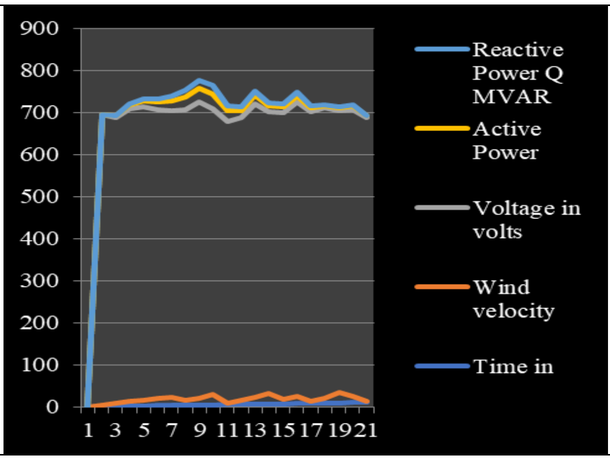
The entire wind power generation process is affected by abrupt wind speeds, which also cause the voltage profile to decrease, the reactive power demand to increase, and the power factor to decrease in the deviation mode of operation of the wind energy system. It is safe to turn off the wind turbines during this mode of operation due to the extreme mechanical strains and forces the wind energy system experiences during gusty wind conditions. Figures 17 and 18 depict the behaviour of the wind energy system during wind gusts.

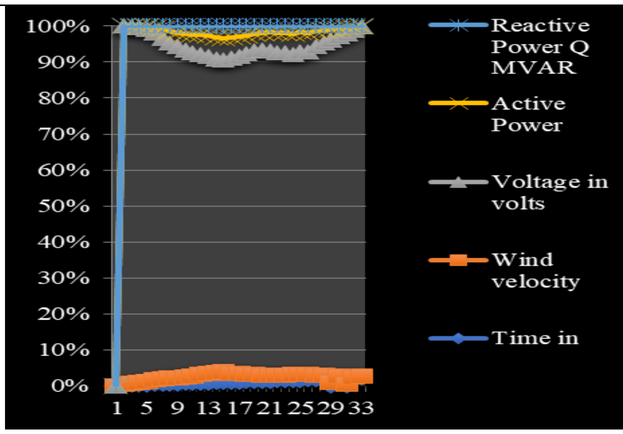



| **Figure 19:** Power performance curve [23] | **Figure 20:** Fixed wind speed and related PQ issues [23]; [24] |
|---|---|

Figures 19 and 20 show the power performance of the wind farm and the power quality issues associated with its fixed-speed operation. Figure 21 indicates variable wind-speed-related and gust wind-speed-related power quality issues.




| **Figure 21:** Variable wind speed and related PQ issues as per Table 3 | **Figure 22:** Gust wind speed and related PQ issues-Table 4 |
|---|---|

Figure 22 shows how the percentages of reactive power, active power, voltage, and wind speed change over time. Figure 23 shows the comparative analysis of constant, variable, and gust wind speeds with PQ issues under grid-connected wind farm operation. Grid codes are not permitted to introduce wind power into the grid system while the gust wind speed is operating. Due to the extreme mechanical stresses and vibrations, operating wind turbines at speeds above 25 m/s poses significant challenges. Therefore, from a safety perspective, it is preferable to pitch the wind turbine blades parallel to the wind and apply the brakes. Power quality degradation appears to be greater in variable-speed wind energy systems than in fixed-speed systems, according to observations of waveforms from MATLAB simulations [30]; [31].

Wind energy systems' operation involves continuous switching, and MATLAB models show a significant spike in reactive power consumption. The line exhibits an increasing order of harmonic level when it is weakly loaded [35]. As a result, during the operation, the load on the entire line must be balanced. The power factor has been affected by the induction generators joining the grid, which are increasing its voltage and frequency deviations [36]. It has been noted that the growing capacity of wind farms affects all aspects of power quality. Real-time power quality issue data from power quality analysers are analysed and validated against MATLAB simulation results. A grid-connected wind farm's induction generator mode of operation raises many power quality concerns, such as cost of generation, cost of loss, profit, reactive power and power factor economic impact, harmonic impacts to the cost of power generation, etc., which are then highlighted with mathematical modelling equations and inferred for the economy.

In the same way, wind turbines operating in induction-motoring mode will obtain electricity from the utility rather than feed wind power into the grid as they would in induction-generator mode. This occurs when wind is unavailable. Based on power quality testing across a variety of wind farms, power quality analysts have determined that power quality problems such as reactive power, harmonics, and power factor are affected by variable wind speed operation. Additionally, during gusts, the entire wind farm must shut down because the wind turbines' structures cannot withstand the high mechanical stress. Disconnecting the wind turbine from the grid during grid-connected operation is required for its safety.

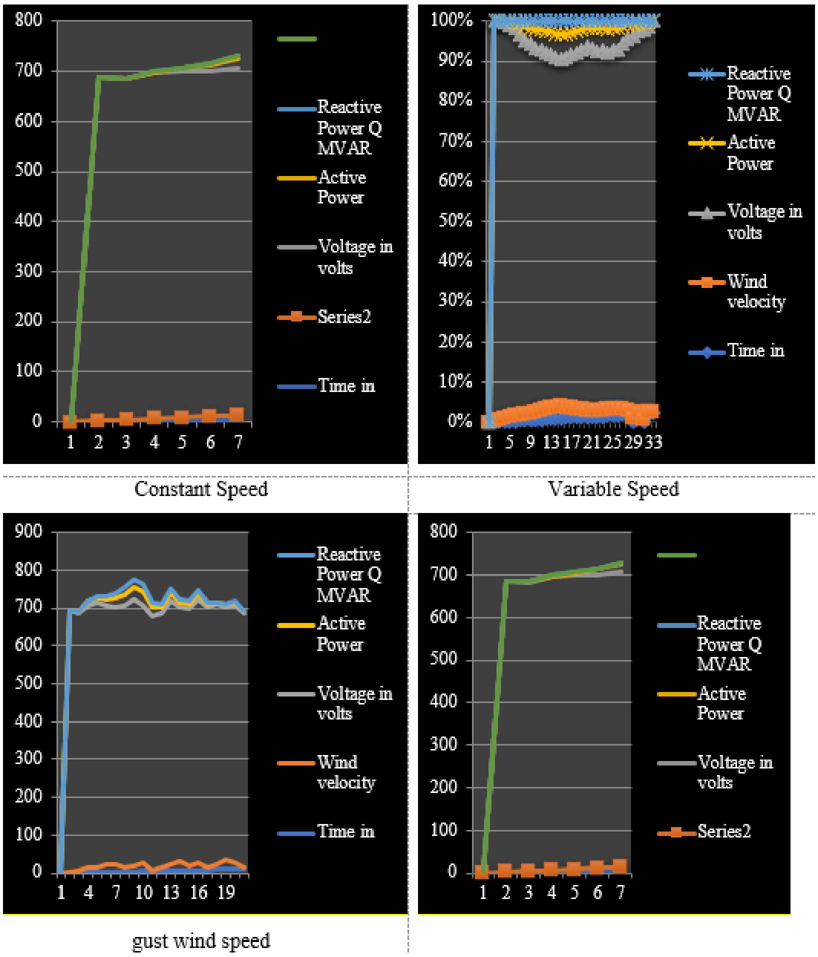



**Figure 23:** Comparison of constant speed, variable speed and gust wind speed with PQ issues [23]

Reactive power management, power factor, loading, application, and wind turbine starting can cause voltage sags or other issues when operating at a fixed speed. Therefore, specific power devices, such as DSTATCOMs, are developed and constructed based on the type and severity of power quality problems, and their performance is compared with acceptable values. When the wind farm operates in grid-connected mode, custom power devices eliminate poor power quality issues and improve overall power quality.

## 5. Conclusion

The work notes that the rise of grid-connected wind power affects the power system's power quality. In a fixed-speed wind turbine, power generation reaches its peak, and the system operates at its rated capacity when the wind velocity equals the rated speed of 12 m/s. The wind turbine's pitch-blade angle wastes wind energy when the wind speed exceeds the rated wind speed, because power generation remains proportional to the 12 m/s wind speed. The turbine has the potential to generate more electricity, but its output is limited to the 12 m/s rated wind speed and the corresponding power generation. Reactive power requirements rise, and power factor falls as the number of induction generators (IG) decreases. In this instance, variable wind generation produces more electricity as wind speed increases, but it also directly affects the electric power system's voltage and frequency. It is therefore essential to stabilise the voltage and frequency using power electronics. Power quality (PQ) in the power system is directly affected by the use of power electronics, and regulating the fluctuating output power is a crucial responsibility.

According to the Indian grid code, it can be difficult to maintain compliance with all grid rules on the generating and grid sides of the power system, particularly when using renewable energy. Gust speeds have a big impact on the system's power quality. Wind speeds more than 24 m/s are regarded as hazardous because they have the potential to produce extreme mechanical strains and forces that could cause the wind turbine to collapse. As a result, it is recommended to halt electricity production from wind turbines during blustery weather and wait for the wind speed to settle before restarting. Mathematical modelling has identified important characteristics of the wind farm's cost-effective use of wind turbines, wind power losses and profits, wind power injection into the grid during induction generator mode, and additional costs during induction motoring mode.

**Acknowledgment:** The authors express their gratitude to Dr Vithalrao Vikhe Patil College of Engineering and Prestige Institute of Engineering Management and Research for their continuous support.

**Data Availability Statement:** The research includes data on Power Quality Challenges in Grid-Connected Wind Energy Systems Using Technical, Economic, and Mathematical Approaches.

**Funding Statement:** The authors confirm that no external funding was received for the preparation of this manuscript or the conduct of the research.

**Conflicts of Interest Statement:** The authors declare that there are no conflicts of interest related to this work. All sources of information have been appropriately cited and referenced.

**Ethics and Consent Statement:** The authors confirm that ethical approval was obtained where required and that informed consent was obtained from the organisation and all individual participants involved in the study.

**References**

1. H. J. Su, H. Y. Huang, and G. W. Chang, “Power Quality Assessment of Wind Turbines by Matlab/Simulink,” *Asia-Pacific Power and Energy Engineering Conference*, Chengdu, China, 2010.
2. M. G. Sugirtha and P. Latha, “Analysis of power quality problems in grid-connected wind power plant,” *International Conference on Recent Advancements in Electrical, Electronics and Control Engineering,* Sivakasi, India, 2011.
3. Y. Popat, S. Shrivastava, and H. Saxena, “Current scenario and future scope of solar energy in India,” *Science and Research (SAR) Journal*, vol. 1, no. 2, pp. 57-66, 2018.
4. N. Sumathy and S. Leninprakash, “A novel STATCOM control scheme for grid-connected wind-driven induction generator for power quality improvement,” *International Conference on Advances in Power Conversion and Energy Technologies (APCET),* Mylavaram, Andhra Pradesh, India, 2012.
5. N. Joshi and N. Mohan, “A novel scheme to connect wind turbines to the power grid,” *IEEE Trans. Energy Conversion*, vol. 24, no. 2, pp. 504–510, 2009.
6. A. Ranjan, S. P. Karthikeyan, A. Ahuja, K. Palanisamy, I. J. Raglend, and D. P. Kothari, “Impact of reactive power in power evaluation from wind turbines,” *J. Electromagnetic Analysis and Application*, vol. 1, no. 1, pp. 15–13, 2009.
7. W. Z. Gandhare and G. R. Bhagwatikar, “Power pollution due to grid-connected wind electric converter,” *IEEE International Conference on Control Applications. Conference Proceedings (Cat. No.00CH37162)*, Anchorage, Alaska, United States of America, 2000.
8. E. Muljadi, C. P. Butter, J. Chacon, and H. Romanowitz, “Power quality aspects in a wind power plant,” *IEEE Power Engineering Society General Meeting*, Montreal, Quebec, Canada, 2006.
9. V. Yuvaraj, E. P. Raj, A. Mowlidharan, and L. Thirugnanamoorthy, “Power quality improvement for grid-connected wind energy system using FACTS device,” *Proceedings of the Joint INDS'11 and ISTET'11*, Klagenfurt am Wörthersee, Austria, 2011.
10. K. V. Bhadane, M. S. Ballal, and R. M. Moharil, “Investigation for Causes of Poor Power Quality in Grid Connected Wind Energy - A Review,” *Asia-Pacific Power and Energy Engineering Conference*, Shanghai, China, 2012.
11. H. Sharma, S. Islam, and C. V. Nayar, “Power quality simulation of a variable speed wind generator connected to a weak grid,” *Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441)*, Orlando, Florida, United States of America, 2000.
12. A. Salehi-Dobakhshari and M. Fotuhi-Firuzabad, “Integration of large-scale wind farm projects including system reliability analysis,” *IET Renew. Power Gener.*, vol. 5, no. 1, pp. 89–98, 2011.
13. D. M. Patel, A. R. Nagera, and K. C. Roy, “Application of static compensator to improve the power quality of grid-connected induction generator-based wind farm,” *IEEE-International Conference on Advances In Engineering, Science And Management (ICAESM),* Nagapattinam, Tamil Nadu, India, 2012.
14. K. V. Bhadane, M. S. Ballal, and R. M. Moharil, “Wavelet transform-based power quality analysis of grid-connected wind farm - An investigation of Power Quality Disturbances,” *2014 International Conference on Advances in Electrical Engineering (ICAEE)*, Vellore, India, 2014.
15. N. R. Chaudhuri and B. Chaudhuri, “Considerations towards coordinated control of DFIG-based wind farms,” *IEEE Trans. Power Delivery*, vol. 28, no. 3, pp. 1263–1270, 2013.

16. N. T. Linh, “Power quality investigation of grid-connected wind turbines,” *4th IEEE Conference on Industrial Electronics and Applications*, Xi'an, China, 2009.
17. Z. Wang, B. Yuwen, Y. Lang, and M. Cheng, “Improvement of operating performance for the wind farm with a novel CSC-type wind turbine–SMES hybrid system,” *IEEE Trans. Power Delivery*, vol. 28, no. 2, pp. 693–703, 2013.
18. W. S. Mota, L. S. Barros, F. M. P. Pamplona, A. N. Epaminondas, E. R. B. Filho, A. M. Formiga, and A. Santos, “Dynamic Simulation of Wind Energy Units Connected to a Power System,” in *Proc. Brazilian Conf. on Automatics (CBA)*, Gramado, Brazil, 2004.
19. P. Anandavel, K. Rajambal, and C. Chellamuthu, “Power Optimization in a Grid-Connected Wind Energy Conversion System,” *International Conference on Power Electronics and Drives Systems*, Kuala Lumpur, Malaysia, 2005.
20. L. Ching-Yin, C. Li-Chieh, T. Shao-Hong, L. Wen-Tsan, and W. Yuan-Kang, “The impact of SCIG wind farm connecting into a distribution system,” *Asia-Pacific Power and Energy Engineering Conference*, Wuhan, China, 2009.
21. O. A. Giddani, G. P. Adam, O. Anaya-Lara, G. Burt, and K. L. Lo, “Enhanced performance of FSIG wind farms for grid code compliance,” *SPEEDAM*, Pisa, Italy, 2010.
22. M. Wei and Z. Chen, “Fast control strategy for stabilizing fixed-speed induction generator-based wind turbines in an islanded distributed system,” *IET Renew. Power Gener.*, vol. 7, no. 2, pp. 144–162, 2013.
23. E. G. Shehata, “Active and reactive power control of doubly fed induction generators for wind energy generation under unbalanced grid voltage conditions,” *Electric Power Components and Systems*, vol. 41, no. 6, pp. 619–640, 2013.
24. A. D. Hansen, P. Sorensen, L. Janosi, and J. Bech, “Wind farm modelling for power quality,” *IECON'01. 27th Annual Conference of the IEEE Industrial Electronics Society (Cat. No.37243)*, Denver, Colorado, United States of America, 2001.
25. H. Li and Z. Chen, “Overview of different wind generator systems and their comparisons,” *IET Renew. Power Gener.*, vol. 2, no. 2, pp. 123–138, 2008.
26. S. K. George and F. M. Chacko, “Comparison of different control strategies of STATCOM for power quality improvement of grid-connected wind energy system,” *International Multi-Conference on Automation, Computing, Communication, Control and Compressed Sensing (iMac4s)*, Kottayam, India, 2013.
27. G. Chicco, P. Di Leo, F. Scapino, and F. Spertino, “Experimental Analysis of Wind Farms connected to the High Voltage Grid: the Viewpoint of Power Quality,” *First International Symposium on Environment Identities and Mediterranean Area*, Corte-Ajaccio, France, 2006.
28. T. F. Brady, “A simulation solution of the integration of wind power into an electricity generating network,” *Proceedings of the 2009 Winter Simulation Conference (WSC)*, Austin, Texas, United States of America, 2009.
29. T. P. Sunil and N. Loganathan, “Power quality improvement of a grid-connected wind energy conversion system with harmonics reduction using FACTS device,” *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM)*, Nagapattinam, Tamil Nadu, India, 2012.
30. V. Khare, S. Nema, and P. Baredar, “Status of solar wind renewable energy in India,” *Renewable and Sustainable Energy Reviews*, vol. 27, no. 11, pp. 1–10, 2013.
31. M. S. Ballal, K. V. Bhadane, and R. M. Moharil, “Enhancement of distributed generation by using a custom power device,” *J. Electronic Science and Technology*, vol. 13, no. 3, pp. 246–254, 2015.
32. M. S. Ballal, K. V. Bhadane, R. M. Moharil, and H. M. Suryawanshi, “A control and protection model for the distributed generation and energy storage systems in microgrids,” *J. Power Electronics*, vol. 16, no. 2, pp. 748–759, 2016.
33. K. V. Bhadane, M. S. Ballal, A. Nayyar, and D. Patil, “A comprehensive study of harmonic pollution in large penetrated grid-connected wind farm,” *MAPAN–Journal of Metrology Society of India*, vol. 35, no. 4, pp. 1–21, 2020.
34. K. V. Bhadane, M. S. Ballal, R. M. Moharil, H. R. Kulkarni, and H. Prasad, “Enhancement of fault ride-through capability of grid-connected wind farm,” *Int. J. Power Electronics*, vol. 13, no. 3, pp. 267–280, 2021.
35. K. V. Bhadane, T. H. Jaware, D. P. Patil, and A. Nayyar, “Wind energy system grid integration and grid code requirements of wind energy system,” *Control and Operation of Grid Connected Wind Energy System*, vol. 1, no. 3, pp. 247–273, 2021.
36. K. Bhadane, P. Sanjeevikumar, B. Khan, M. Thakre, A. Ahmad, and T. Jaware, “A Comprising Study on Modernization of Electric Vehicle Subsystems, Challenges, Opportunities and strategies for its Further Development,” *4th Biennial International Conference on Nascent Technologies in Engineering (ICNTE)*, Navi Mumbai, India, 2021.