Transactions on Energy Systems and Engineering Applications

Article

Investigations and power quality improvement of optimally located large scale RES integrated with conventional distribution system with custom power devices

Tanvi Upadhyay[1,*] and Jitendra Jamnani[2]

1 Electrical Engineering Department, Pandit Deendayal Energy University, Gandhinagar, India
* Correspondence: Tanvi.uphd20@sot.pdpu.ac.in

Received: 16 December 2023; Accepted: 10 February 2025; Published: 14 May 2025

Abstract: Non-conventional energy sources are gaining popularity since they have no carbon footprint. As the world's population rises and technology advances, so does the need for power. A conventional grid is combined with renewable energy sources (RES) to supply this need. This link compromises the electrical grid's capacity to run safely and securely despite its benefits. Concerns about system power quality are the most prominent difficulty since they directly influence consumer devices and grid system performance. This article examines the power quality issues and associated worldwide standards for a conventional power network. This article presents simulated examinations of the impact of Photovoltaic (PV) and Wind Energy Conversion System (WECS) on the power quality of the Distribution System using the Modified IEEE 33 Node Radial Distribution Test System. This inquiry considers power quality concerns such as voltage fluctuations, voltage magnitude changes, and system harmonics. The Particle Swarm Optimisation (PSO) approach is used to find the ideal position for the PV system. The D-STATCOM is used to improve the system's voltage profile and harmonics. For simulational analysis, the MATLAB/Simulink software environment is employed.

1. Introduction

The non-conventional energy sources are considered as green energy sources since they generate electricity using natural resource including solar radiation, wind, water, wave currents and earth heat. They leave the ecosystem with very small to zero carbon footprints. As a result, they provide a dependable source of energy generation that is safer for the environment [1].

Renewable Energy Sources (RES) include solar photovoltaic (PV), wind, ocean and geo-thermal energy. The two most popular non-conventional energy sources are solar and wind energy [1]. A solar power

How to cite this article: Tanvi Upadhyay; Jitendra Jamnani. Investigations and power quality improvement of optimally located large scale RES integrated with conventional distribution system with custom power devices. *Transactions on Energy Systems and Engineering Applications*, 6(1): 601, 2025. DOI:10.32397/tesea.vol6.n1.601

plant has an installed capacity of 849.47 MW and a wind power plant has an installed capacity of 824.87 MW globally. China is at the forefront of the development of solar and wind energy based technologies, providing 40% and 36% respectively. With a 22% share, the European Union is the second highest donor to the wind energy sector, while the United States is the third highest producer with a 16% share. In terms of solar energy, Japan contributed 8.7% in 2022, while the United States contributed 11.1%, placing them second and third respectively. India makes for 6.8% of the world's installed solar energy capacity and 4% of the world installed wind energy capacity [2]. The overall installed capacity of RES power plants was 100.68 MW in 2021, and it is increased to 186.07 MW in 2023, according to the Ministry of Power, India. Solar power plants occupy 16.9% share and wind power plants holds 10.2% share from 186.07 MW. The remaining are held by other Renewable Energy Sources [3].

The effects of unconventional energy sources on the electric system have been discussed by a number of authors [4–9]. Reference [4] provides a thorough analysis of power quality problems, associated standards and mitigation strategies for AC and DC systems. Another author investigated the effects of micro-grid on power quality with the important goal of investigating supra-harmonics in the system [5]. It also includes a comparison of several methods for enhancing the power quality of the system. Authors have defined power quality, discussed associated international standards and impacts on power quality of the system [5]. In [6], authors looked into how much solar rooftop system penetration might affect the voltage profile of residential grids. To increase the voltage of the system, they also designed the dynamic voltage support (DVS) method. When a wind power plant is connected to the grid, there are issues with the quality of the power because of interdependency of reactive power and voltage [7]. The authors also looked into the need for reactive power adjustment. The authors of [8] examined current developments in power electronics applications for RES interconnection with a grid. Additionally, it examined the way distinct power electronics technologies affected the system's integration of solar and wind power plants in terms of power quality. D-STATCOM was employed by the authors of [9] to apply sinusoidal pulse width modulation to reduce voltage sag and voltage swell based power quality concerns. The D-STATCOM modelling was also provided. The control design and dynamic modelling of D-STATCOM with the consideration of ultra-capacitors as an energy storage for power quality improvement were reported in [10]. Another author discussed the D-STATCOM's performance for a distribution network, consisting of RES systems under various load conditions [11]. Hysteresis controller is used in [12] to imitate the D-STATCOM in order to reduce harmonics in the system.

The headings for this research article are as follows: Issues with power quality in electrical systems are discussed in Section 2 along with the relevant standards. Power quality issues brought on by the incorporation of RES are detailed in Section 3. Solar photovoltaic (PV) and wind energy conversion system (WECS) are modelled and simulated in Section 4. The conventional power system that is taken into consideration for the study is described in Section 5. The particle swarm optimization (PSO) method is explained in Section 6. Section 7 covers understanding and design of D-STATCOM. Discussions and outcomes are under Section 8. The conclusion of the article is contained in Section 9.

2. Power Quality: Issues and Related Standards

According to IEEE 1100-2005, the idea of powering and grounding electrical apparatus in a way that ensures dependable working of apparatus, and it is nearby equipment, is defined as the power quality of any electrical system [13]. Another way to describe power quality is the utility system's capacity to produce an electrical supply that is distortion and disturbance free in terms of system voltage and frequency [13].

The voltage, current and frequency of the system are principally responsible for a number of power quality issues. The system's voltage fluctuations, sag, swell, unbalance and flicker are the main power quality problems [14]. Voltage or current waveform distortion is related to other power quality problems. It encompasses the system's harmonics, noise, notching, inter-harmonics and transients [14].

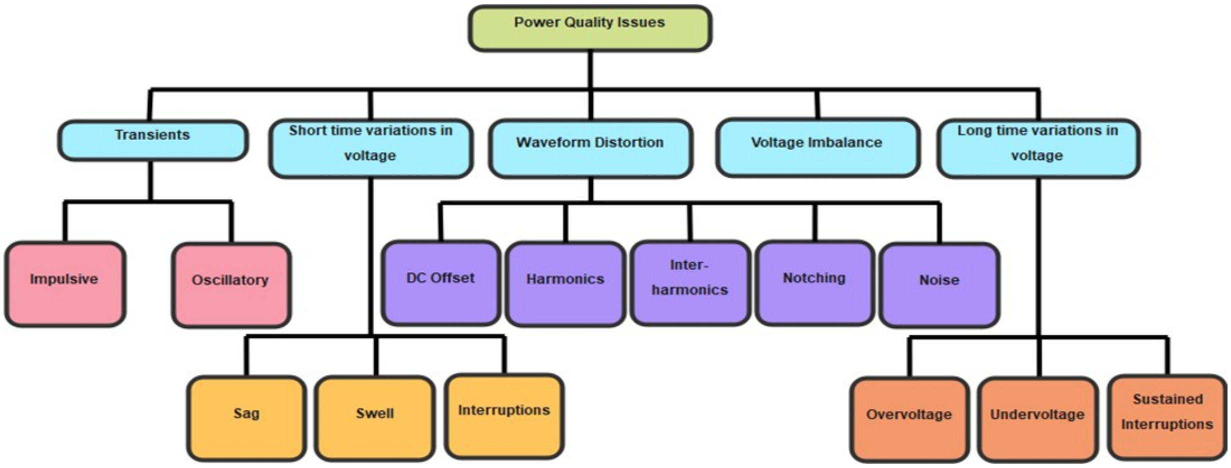

Figure 1. Classifications of Power Quality Issues.

Systematic changes in the voltage magnitude are known as voltage fluctuations. Transients are another problem with power quality. It is divided into two forms, (i) Impulsive and (ii) Oscillatory, as shown in Figure 1. In terms of non-power frequency, impulsive transients are defined as instantaneous changes in voltage, current or both. Its rising and falling time period serves as a signal for its unidirectional characteristics. In contrast to impulsive transients, oscillatory transients are bidirectional [15]. Three terms – interruption, sag and swell are used to describe short term voltage changes. Sag is defined by IEEE 1159 – 2009 as a decrease in voltage magnitude of 10% - 90% of its rated value at power frequency for a period of time ranging from a half cycle to one minute [15]. Another problem with power quality is long term voltage variations. Undervoltage, Overvoltage and Continuous interruptions are the three categories. Undervoltage is characterized as a voltage drop of 10% - 20% over a period of more than 60 seconds at its fundamental frequency [16]. Overvoltage is defined as a 10% - 20% rise in voltage magnitude over its rated voltage for more than a minute at its power frequency. A sustained interruption is defined as a voltage magnitude that approaches value for a period longer than a minute. Voltage imbalance is the ratio of zero or negative sequence component to positive sequence component [16]. The power quality problem associated with the system's frequency is waveform distortion. As depicted in Figure 1, it is separated into five groups. A waveform with a DC offset has a DC value present in terms of voltage and current [17]. Sinusoidal current or voltage waveforms with integer multiples of the power frequency are called harmonics. Inter-harmonics are sinusoidal shaped current or voltage waveforms with non-integer multiples of the power frequency [17]. A voltage distortion that occurs on a regular basis is referred to as notching. Electrical signals with a frequency of less than 200 kHz in the phase conductor's current or voltage are referred to be noise [18]. Table 1 presents the causes and impacts of various power quality problems on the power system [18].

There are numerous international standards that pertain to the system's power quality. IEEE 519 is a global standard that specifies acceptable behaviours and suggested harmonic limits for voltage and current in the system [19]. This criterion guarantees that an electrical utility provides clean power to all of its customers. Additionally, it guarantees that an electrical utility must safeguard all electrical equipment against excessive harmonics. This harmonic current of equipment with an input current of less than 16 A is restricted by IEC 61000-3-2. Limits for harmonic current are stated in IEC 61000-3-4 for equipment with an input current greater than 16 A [19]. Electric power quality monitoring is mandated by IEEE 1159-1995. The necessary techniques for determining power quality are presented in IEEE 1159-1995. It also includes information on power quality monitoring of electrical power systems, such as a definition of the term and information on impacts on power quality of the electrical grid and consumer electronics [19]. A reference

Table 1. Power Quality Issues and Effects.

Power Quality Issues	Causes	Effects
Transients	Lightening, Cable Switching, Capacitor Bank Energizing	Derangement of Electrical Apparatus
Short Time variations in Voltage	Fault on System, Switching on Large Load	Power Losses Increases, Vandalization of load
Long Time variations in Voltage	Large Load Operation, Capacitor Bank Switching	Poor regulation capabilities, Transformer operation
Voltage Imbalance	Unbalanced Three Phase Load, Large Single Phase Load	Reduced efficiency of power converters
Harmonics	Non-linear Loads, Power Electronics Converter	Decreased efficiency of Converters

on equipment sensitivity under brief disturbances caused by voltage sag is IEEE 1205-1995. Limits for harmonic distortion in voltage and current are also covered. Required methods and indices for voltage sag are known as IEEE P164 [19].

3. Power Quality Issues due to RES Integration

Grid integration of RES adds power quality (PQ) difficulties into the system; including i) voltage related to PQ issues, ii) harmonics. Voltage fluctuations, voltage sag, voltage swell are voltage related PQ concerns caused by the intermittent nature of RES and grid disturbances. Power electronics converters are at the heart of renewable energy systems and are responsible for the existence of harmonic. These challenges are divided into two categories: Renewable Side and Utility Side.

3.1. Renewable Energy Side

The output of a RES system might fluctuate erratically due to the unpredictability and non-control of wind and PV solar. This uncertainty has an impact on the system's voltage. It introduces voltage sag, swell and fluctuations into the system [20]. A mismatch between the load generation of power causes fluctuations in the system's output power. This can cause the system to start flickering. Only devices or local utility systems are impacted by power quality issues when RES penetration is low [20]. Power quality problems have an impact on overall system operating parameters when the penetration level is high.

3.2. Grid Side

Disruptions on the grid may have an impact on the system's power quality. Voltage disturbance is brought on by the fault if it happens in the system. Under the L-G fault state, it results in voltage sag in one phase and voltage swell in other two phases [8]. After the failure has been fixed, voltage fluctuations may be introduced. A mismatch between the power of the load and the power of the generator results from imbalanced loads. The power will fluctuate as a result. In addition, 90% of the system's load is non-linear, which introduces harmonics in the system [8].

4. Modelling and Simulation of Renewable Energy Sources

4.1. Photovoltaic Array System

The solar array system for integration with a traditional power system consists of a photovoltaic (PV) array, an inverter and a filter. The following equations perform mathematical modelling based on a single diode equivalent circuit [21]. The PV array system is shown in Figure 2.

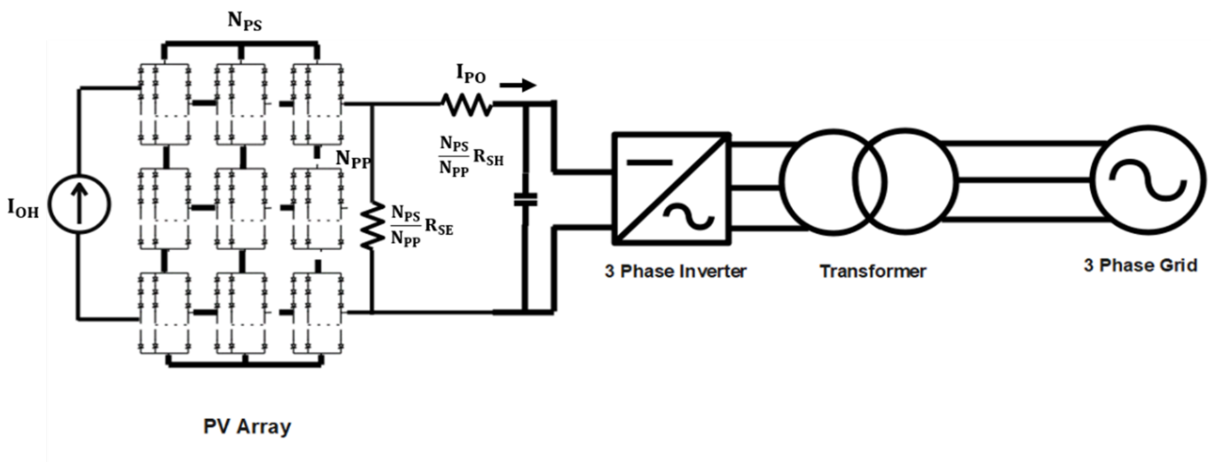

Figure 2. Photovoltaic Array System.

$$I_{PO} = I_{OH} - I_D - I_{PA}, \tag{1}$$

$$I_{OH} = \left(I_{SC} + k_i \left(T_C - 298\right) \frac{G}{1000}\right), \tag{2}$$

$$I_D = I_0 \left(\frac{V + I_{PO} \frac{N_{PS}}{N_{PP}} R_{SE}}{V_t \, N_{PS}} \right), \tag{3}$$

$$I_0 = I_{RS} \left(\frac{T_C}{298} \right)^{\frac{3}{A}} \frac{q \, V_t}{e^{A\,k\left(\frac{1}{T_C} - \frac{1}{298}\right)}}, \tag{4}$$

$$I_{PA} = \frac{V + I_{PO} \left(\frac{N_{PS}}{N_{PP}}\right) R_{SE}}{\left(\frac{N_{PS}}{N_{PP}}\right) R_{SH}}. \tag{5}$$

The PV array's output current is given by Equation (1). Equation Equation (2) provides the photon current (I_{OH}), I_D is the current flowing through the PV modules as shown in Equations (3) and (4) is presenting current I_O which is diode saturation current and I_{PA} shown in Equation Equation (5) is current flowing through equivalent shunt resistance of PV modules (R_{SH}) [21]. R_{SE} is the equivalent series resistance offered by the PV modules. V is the voltage that the PV array achieves. I_{SC} is the short circuit current of PV array. T_C is the real time temperature in kelvin. G is the real time irradiance in W/m^2. A is the ideality factor of PV Module and k_i is the temperature coefficient of short circuit current of PV module [22].

The PV array is connected to the power grid by a 3 phase IGBT based inverter. To extract maximum power from the PV array, maximum power point tracking (MPPT) is employed [22]. The inverter is controlled using a method based on the d-q coupling theory. The PV array system is modelled under STC as well as under different irradiance levels. The PV parameters are shown in Table 2.

Table 2. PV Array and PV Inverter Parameters.

PV Array Characteristics				
Irradiance Level (W/m^2)	1000	800	600	400
Maximum Power (MW)	1.5	1.2	0.9	0.6
Optimum Operating Voltage (V_{MPP})	2200	2200	2200	2200
Optimum Operating Current (I_{MPP})	662	510	380	260
No. of Modules in Series	80	80	80	80
No. of Modules in Parallel	80	65	48	33

PV Inverter Specifications			
Max. DC Power (MW)	1.7	Max. AC Output Current	80.3
Max. DC Input Voltage	2500	Rated AC Power (MVA)	1.53
Max. DC Input Current	680	Nominal AC Voltage (kV)	11
Min. DC Input Voltage	2200	AC Power Frequency (Hz)	50

4.2. Wind Energy Conversion System (WECS)

A wind turbine, motor system, induction generator and filter makes up the wind energy conversion system (WECS). The marker offers two different WECS configurations, one is fixed speed and another is variable speed. The variable speed arrangement is frequently utilised for grid integration [23]. This article employs DFIG (Doubly Fed Induction Generator) configuration which comprises AC – DC –AC converter to regulate the induction generator's speed and offer decoupling between the mechanical and electrical frequencies of the turbine. In Figure 3, the arrangement is displayed. The maximum power that can be extracted is determined using Equation Equation (6). It is possible to synchronise a wind turbine with an induction generator by utilising a drive train [24].

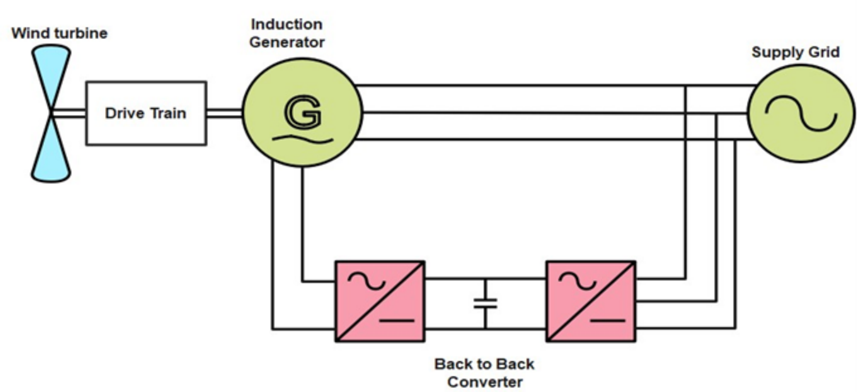

Figure 3. Wind Energy Conversion System (WECS).

$$P_{MA} = \frac{1}{2}\rho\, A_W\, V_{W_I}^3\, C_P(\lambda, \beta) \tag{6}$$

P_{MA} is the wattage output of a wind turbine. $V_{W_I}^3$ denotes wind velocity in meters per second. ρ is the density of air in kilograms per cubic meter. A_W is the swept area of the turbine in m^2. The tip speed ratio is denoted by β. C_P is the turbine performance coefficient and is a function of λ and β [24]. The tip speed ratio (TSR) is the ratio of the wind turbine's rotor tip speed to the wind speed, because it is directly related to the turbine's power output. The TSR is optimized for different wind speeds to attain a maximum value. The highest value can be discovered by plotting the C_P vs. λ graph with different pitch angles β [25]. Table 3 shows the parameters of WECS under varying wind speed conditions.

Table 3. Wind Energy Conversion System Parameters

Wind Turbine Parameters				
Wind Speed (m/s)	4	7	10	13
Turbine Output Power (MW)	0.85	0.9	1.0	1.5
Initial Wind Speed (m/s)	4	4	4	4

Induction Generator Parameters			
Rated Power (MVA)	1.65	Rated Frequency	50 Hz
Rated Voltage (Stator) (V)	575	Rated Voltage (Rotor) (V)	1975

Converter Specifications			
Max. DC Power (MW)	1.7	Max. Output Current (A)	150
Max. DC Input Voltage (V)	2100	Rated AC Power (MVA)	1.65
Max. DC Input Current (A)	810	Nominal AC Voltage	11 kV
Min. DC Input Voltage (V)	1975	AC Power Frequency (Hz)	50 Hz

5. System Under Study

The modified IEEE 33 Node Radial Distribution Test System is considered in this paper as shown in Figure 4. System consisting 66 kV substation with 100 MVA short circuit capacity. The substation transformer is rated 8 MVA, 66 kV/11 kV. Node 1 is representation of substation node. Node 2 to Node 18 are 11 kV feeders.

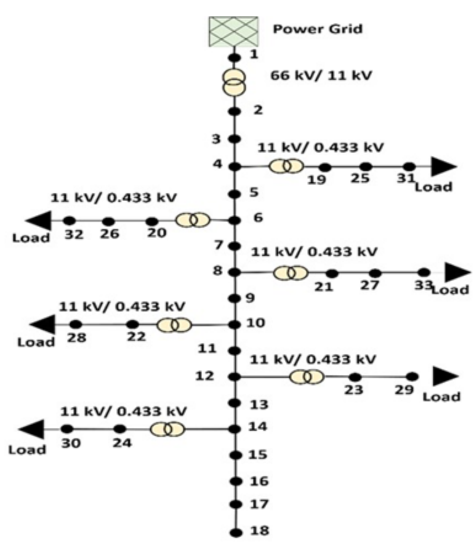

Figure 4. Modified IEEE 33 Node Radial Distribution System.

The system has 6 distribution transformers connected at Node 4, Node 6, Node 8, Node 10, Node 12 and Node 14 respectively. The transformers at Node 4, Node 8 and Node 12 are rated at 1600 kVA, 11 kV/ 0.433 kV and Node 6, Node 10 and Node 14 are rated 1000 kVA, 11 kV/ 0.433 kV. Node 19 to Node 33 are 0.433 kV feeders. Moreover, Node 28 to Node 33 are nodes consisting linear and non-linear load. Table 4 shows the summary of the system. The load parameters of the system are shown in Table 5.

Table 4. Summary of System under Study.

Total Generation	3.21 MW	2.30 MVAR
Total Load	3.02 MW	2.23 MVAR
Total Losses	0.192 MW	0.068 MVAR
No. of Buses	33	–
No. of Branches	32	–
No. of Loads	7	–
No. of Substation	1	–

Table 5. Load Parameters of System.

Node No	Phase A		Phase B		Phase C	
	P(kW)	Q(kVAR)	P(kW)	Q(kVAR)	P(kW)	Q(kVAR)
28	501.2	362.9	498.1	368.4	510.1	358.3
29	395.9	303.9	403.3	315.6	385.3	323.2
30	503.7	351.6	510.4	365.6	495.6	345.3
31	530.6	356.6	520.2	350.2	535.1	342.6
32	497.2	308.2	505.6	320.2	490.2	296.9
33	249.4	134.6	255.3	128.3	240.2	141.4

Non Linear Rectifier Load – 346.7 kW, 315.1 kVAR

6. Particle Swarm Optimization (PSO)

The cooperative and gregarious behavior many species adopt to meet their needs drives particle swarm optimization (PSO). It primarily focuses on the population and behavior of the horde of fish and flock of birds that make up the population [26]. The optimization approach is based on identifying the best particle on individual and global scales and the particle's current location to determine the particle's upcoming travel in space. It also takes into account the particle's velocity [26].

$$v_{i,m+1} = \omega v_{i,m} + C_1 r_1 (p_{i,b} - x_{i,m}) + C_2 r_2 (g_{b,t} - x_{i,m}), \tag{7}$$

$$x_{i,m+1} = x_{i,m} + v_{i,m+1}, \tag{8}$$

where r_1 and r_2 are random values between $[0, 1]$, m is the number of particles in the search space, and i is the number of iterations considered. The acceleration factors are C_1 and C_2. The inertia weight is ω.

Voltage variation is minimized by applying the PSO approach to discover the ideal spot for the integration of RES. Below is a list of the algorithm for PSO [27].

- Step I: Enter information on the bus voltage, the line impedance and the susceptance.
- Step II: Establish the number of variables, particle population, upper and lower bounds for each variable, number of iterations, inertia weight and acceleration factors.

- Step III: Using random numbers and velocities, with $i = 0$, initialize the unsettled population.
- Step IV: Initialize the bus count with $b = 0$.
- Step V: Apply the below objective function to determine the minimal value of each particle:

$$f = \min\left(\sum_{b=1}^{N} \frac{v_{b,PL} - v_{b,rated}}{v_{b,rated}}\right), \tag{9}$$

  where $b = 1 : N$
  $N =$ number of buses
- Step VI: Check whether the particle is within the given boundaries. If the particle does not fall between the top and lower bounds, it is discarded as a solution.

$$-0.06 \leq f \leq 0.06$$

- Step VII: For each particle, the estimated value is analogized with the best value for the peculiar particle. Therefore, that value is listed as the individual's best p_{be} and if that value is lower than p_{be}, the linked particle's position is upgraded.
- Step VIII: The particle associated to the lowest p_{be} is regarded as the best particle globally or g_{be}.
- Step IX: Equations (7) and (8) update the position and velocities of particle.

7. D-STATCOM : A Mitigation Technique

Figure 5 depicts a D-STATCOM, a distribution static synchronous compensator. A voltage source converter (VSC), a DC link capacitor, a line filter and a coupling transformer are all included in a D-STATCOM [28]. It is a shunt connected to the system. By changing the voltage drop between VSC and the point where D-STATCOM is connected, the current is compensated. Power quality problems like voltage fluctuations, voltage and current THD, voltage sag and voltage swell are mitigated or reduced using D-STATCOM. PWM and d-q coupling theory can be used to control D-STATCOM [28]. The following equations can be used to design the device.

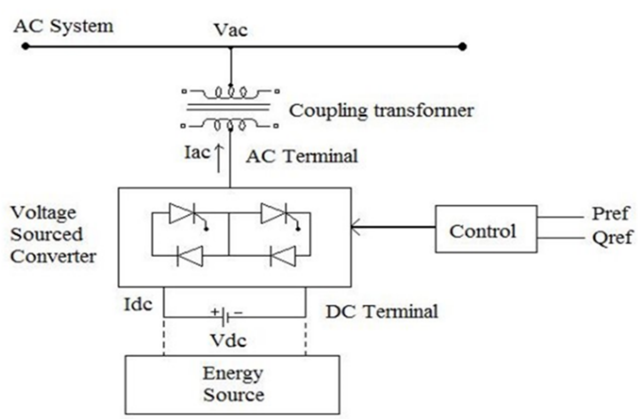

Figure 5. Configuration of D-STATCOM.

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \tag{10}$$

$$\frac{1}{2}C_{DC}\left\{V_{DC}^2 - V_{DC1}^2\right\} = k_1 3 V_{L-L} L_{L-L} a t \quad (11)$$

$$L_r = \frac{\sqrt{3}V_{DC}}{12 a f_s i_{cr}} \quad (12)$$

where V_{L-L} is the line to line voltage of the system, m is the modulation index, V_{DC} is the DC link voltage, k_1 is the factor for overloading, f_s is the switching frequency of VSC, i_{cr} is the ripple line current, which is 10% - 15% of line current, C_{DC} is the DC link capacitor and L_r is the filter inductor [29].

UsingEquation (10), DC link voltage is calculated. The value of DC link capacitor and AC filter inductor is found out using Equations (11) and (12) respectively [30]. The location of D-STATCOM is found using the analysis of the voltage profile of each bus for different levels of penetration of RES. The location of D-STATCOM is at bus 18 [30]. Table 6 lists the D-STATCOM system parameters.

Table 6. Parameters of D-STATCOM

Parameter	Value
DC Link Voltage	25 kV
DC Link Capacitor	307 μF
AC Ripple Inductor	93.96 mH
Switching Frequency	10 kHz

8. Results and Discussions

A load flow analysis examines the impact of high RES penetration rate. Using PSO algorithm, the optimal location of RES is found which is at bus 18. The penetration of RES is ranging from 1 MW to 2.5 MW.

8.1. Impacts on Voltage Profile

As demonstrated in Table 7, the voltage without RES integration is less than 1 P.U. at each node. The introduction of RES into the system raises the voltage to 1.04 – 1.05 P.U. from 1 P.U. The D-STATCOM is integrated to control the voltage across all nodes. As demonstrated in Table 7, D-STATCOM keeps the voltage between 1.00 P.U. and 1.04 P.U. Figure 6 compares different instances for load node 28 to node 33, the node closest to the substation, node 4 and the node farthest from the substation, node 18.

As shown inFigure 6, without integration of RES, the voltage is less than one P.U. However, with the integration of the optimal position of RES at Node 4, the voltage is enhanced to more than 1.05 P.U. from 0.99 P.U. It has been regulated since the establishment of D-STATCOM.

8.2. Impacts on Voltage Fluctuations

Voltage waveform variations increased as a result of RES connections. It may have variations due to non-linear loads and switching of big loads without RES integration, but these are avoidable, as shown in Figure 7. Because of intermittent nature of PV system and the unpredictable wind speed, variations increased significantly after RES integration, as illustrated in Figures 8 and 9 depicts the results of connecting D-STATCOM to the system. The variations are decreased to an acceptable level, as indicated in the Figure 9.

Table 7. Impacts on Voltage Profile

Node No	Without RES Integration	With Optimally Located RES	With Optimally Located RES and D-STATCOM
		Voltage (P.U.)	
1	1.0000	1.0000	1.0000
2	0.9986	1.0510	1.0350
4	0.9870	1.0560	1.0340
6	0.9956	1.0480	1.0220
8	0.9945	1.0500	1.0270
10	0.9738	1.0430	1.0250
12	0.9833	1.0420	1.0260
14	0.9630	1.0460	1.0310

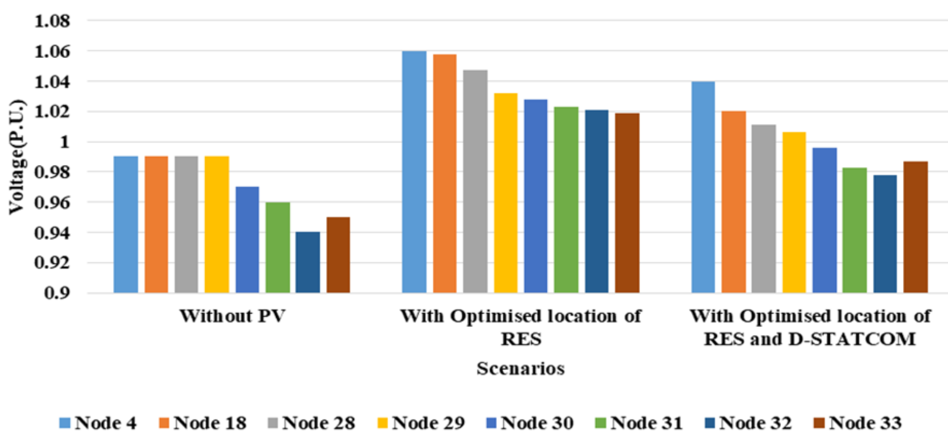

Figure 6. Impacts on Voltage Profile.

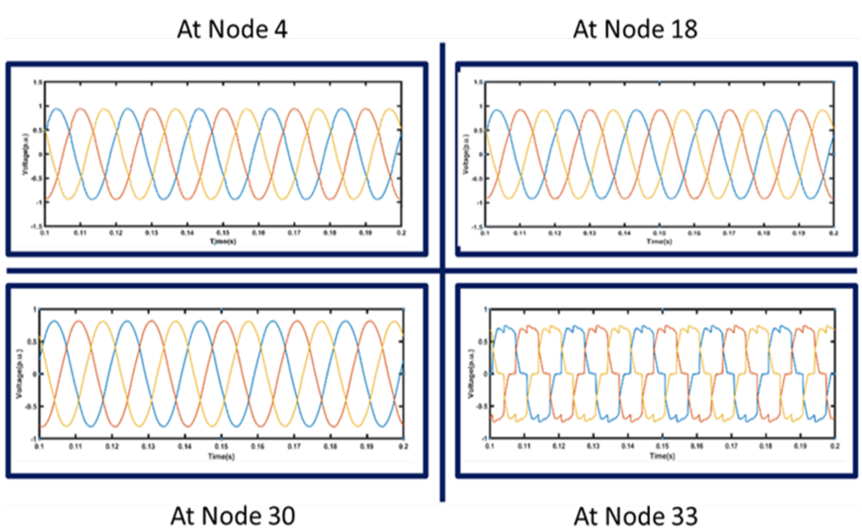

Figure 7. Voltage fluctuations without integration of RES.

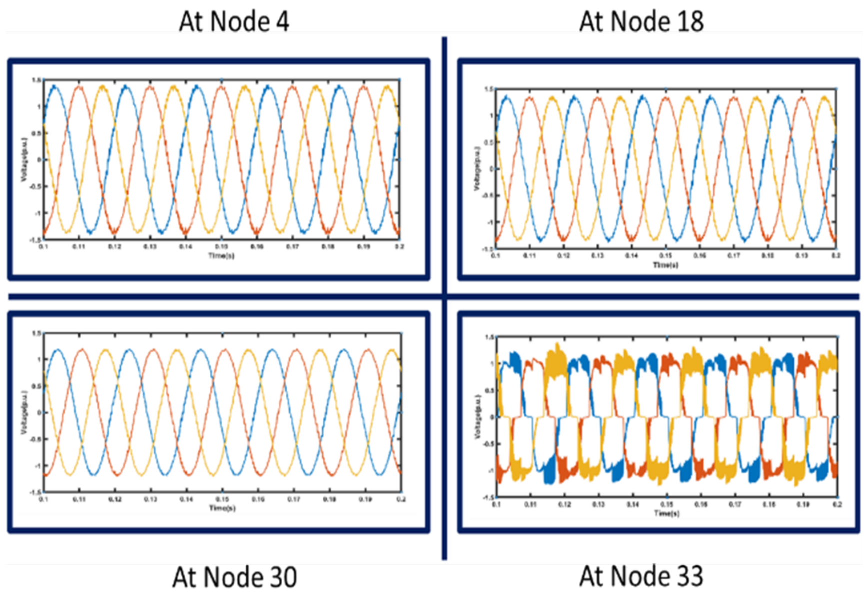

Figure 8. Voltage fluctuations with optimally located RES.

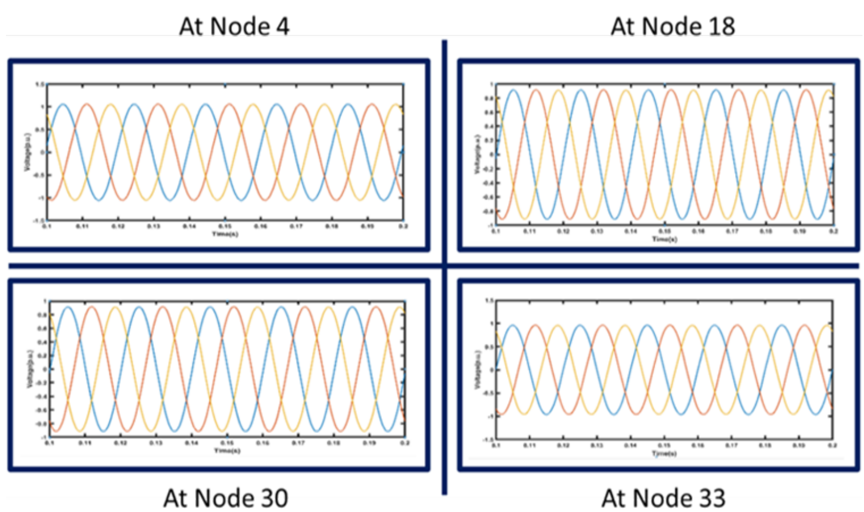

Figure 9. Voltage fluctuations with optimally located RES and D-STATCOM.

8.3. Impacts on Harmonics

Non-linear loads in the conventional system cause harmonics in the system. Because of the power electronics involved with renewable energy systems, the voltage and current harmonics distortion increased with the incorporation of RES. Table 8 shows the current THD (Total Harmonic Distortion) and voltage THD without RES integration, optimally located and integrated RES into system and optimally located RES and D-STATCOM integrated into system. Table 8 shows that, in the absence of RES integration, the appearance of harmonics in the system is attributed solely to non-linear loads. THD in voltage and current must be less than 5%, according to IEEE 519 [31]. Except for node 33, all nodes have current and voltage THD less than the prescribed limit, because node 33 is connected to a non-linear load, it has a greater THD.

The harmonics in the system have increased from 1% - 2% to 4% - 5% with the integration of RES. When D-STATCOM is connected to the system, the harmonics in the system are significantly reduced.

Table 8. Impacts on Harmonics

Node No	Voltage THD (%)			Current THD (%)		
	Without RES	With RES	With RES + D-STATCOM	Without RES	With RES	With RES + D-STATCOM
4	3.67	9.73	2.89	0.70	2.75	0.20
28	2.67	6.86	3.69	1.44	2.90	1.37
29	2.94	7.59	3.53	1.36	2.77	1.08
30	2.98	7.72	3.31	1.25	2.60	1.18
31	2.99	7.94	2.70	0.89	2.11	1.06
32	2.71	7.09	3.01	1.07	2.37	1.04
33	22.70	40.22	8.44	7.89	8.52	6.64

9. Conclusions

Grid integration of RES is feasible to reduce CO2 emissions. It helps to minimize the load on the conventional grid. However, it does provide certain obstacles in comparison to the reliable and secure operation. Power quality difficulties, low voltage ride through capability, and active – reactive power control are all part of challenges of grid integration. This article investigated power quality issues in the system due to integration of RES. It contains the system's voltage profile, voltage fluctuations and harmonics. The voltage magnitude of the system increased from 1 P.U. due to the connectivity of PV and WECS, which may produce voltage instability in the system. Voltage fluctuations can cause devices to flicker. It can also cause Undervoltage or overvoltage. The higher harmonics in the system cause equipment to overheat. As a result, in order to work with RES sources, mitigation strategies must be used.

MATLAB/Simulink is used to model the PV array system and the wind energy conversion system. Modified IEEE 33 Node Radial Distribution Test System is analyzed and simulated as a conventional system in this paper. The ideal site for the integration of RES is determined using the PSO algorithm. The D-STATCOM is used to mitigate power quality issues caused by the integration of RES into the traditional system. The harmonic analysis is carried out without the RES integration scenario, with optimally located RES integrated with system and optimally located RES and D-STATCOM into the system. The effects of RES integration on voltage profile and voltage fluctuations are included in this article with optimal location of RES and D-STATCOM. To conduct simulation studies and investigations, the MATLAB/Simulink software environment is used.

Funding: This research received no external funding.

Author contributions: Conceptualization: Tanvi Upadhyay, Jitendra Jamnani; Methodology: Tanvi Upadhyay, Jitendra Jamnani; Software: Tanvi Upadhyay; Validation: Jitendra Jamnani; Formal Analysis: Jitendra Jamnani; Investigation: Tanvi Upadhyay, Jitendra Jamnani; Resources: Tanvi Upadhyay; Writing-Original Draft Preparation: Tanvi Upadhyay; Writing-Review and Editing: Jitendra Jamnani; Supervision: Jitendra Jamnani.

Disclosure statement: The authors declare no conflict of interest.

References

[1] Temitope Raphael Ayodele, Adiasa Jimoh, Josial L Munda, and Agee J Tehile. Challenges of grid integration of wind power on power system grid integrity: A review. *International journal of renewable energy research*, 2(4):618–626, 2012.

[2] IEA. World energy outlook 2022. *Paris, France: International Energy Agency (IEA)*, 2022.

[3] Government of India Ministry of Power. Power sector at a glance - all india. https://powermin.gov.in/en/content/power-sector-glance-all-india. Accessed: n.d. (date unknown).

[4] Eklas Hossain, Mehmet Rida Tur, Sanjeevikumar Padmanaban, Selim Ay, and Imtiaj Khan. Analysis and mitigation of power quality issues in distributed generation systems using custom power devices. *IEEE Access*, 6:16816–16833, 2018.

[5] Ammar Ahmed Alkahtani, Saad T. Y. Alfalahi, Abedalgany Abedallah Athamneh, Ali Q. Al-Shetwi, Muhamad Bin Mansor, M. A. Hannan, and Vassilios G. Agelidis. Power quality in microgrids including supraharmonics: Issues, standards, and mitigations. *IEEE Access*, 8:127104–127122, 2020.

[6] Rakibuzzaman Shah, N. Mithulananthan, R.C. Bansal, and V.K. Ramachandaramurthy. A review of key power system stability challenges for large-scale pv integration. *Renewable and Sustainable Energy Reviews*, 41:1423–1436, January 2015.

[7] Muhammad A. Saqib and Ali Z. Saleem. Power-quality issues and the need for reactive-power compensation in the grid integration of wind power. *Renewable and Sustainable Energy Reviews*, 43:51–64, March 2015.

[8] Varun Kumar, A. S. Pandey, and S. K. Sinha. Grid integration and power quality issues of wind and solar energy system: A review. In *2016 International Conference on Emerging Trends in Electrical Electronics amp; Sustainable Energy Systems (ICETEESES)*, page 71–80. IEEE, March 2016.

[9] Ravilla Madhusudan and G Ramamohan Rao. Modeling and simulation of a distribution statcom (d-statcom) for power quality problems-voltage sag and swell based on sinusoidal pulse width modulation (spwm). In *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM-2012)*, pages 436–441. IEEE, 2012.

[10] M. G. Molina and P. E. Mercado. Dynamic modeling and control design of dstatcom with ultra-capacitor energy storage for power quality improvements. In *2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, page 1–8. IEEE, August 2008.

[11] A. R. Gidd, A. D. Gore, S. B. Jondhale, O. V. Kadekar, and M. P. Thakre. Modelling, analysis and performance of a dstatcom for voltage sag mitigation in distribution network. In *2019 3rd International Conference on Trends in Electronics and Informatics (ICOEI)*, page 366–371. IEEE, April 2019.

[12] Lakhinana Dinesh, Harish Sesham, and Vasupalli Manoj. Simulation of d-statcom with hysteresis current controller for harmonic reduction. In *2012 International Conference on Emerging Trends in Electrical Engineering and Energy Management (ICETEEEM)*, page 104–108. IEEE, December 2012.

[13] M.H.J. Bollen. What is power quality? *Electric Power Systems Research*, 66(1):5–14, July 2003.

[14] Ieee guide for application of power electronics for power quality improvement on distribution systems rated 1 kv through 38 kv. *IEEE Std 1409-2012*, pages 1–90, 2012.

[15] Ieee recommended practice for powering and grounding electronic equipment - redline. *IEEE Std 1100-2005 (Revision of IEEE Std 1100-1999) - Redline*, pages 1–703, 2006.

[16] Saifullah Khalid and Bharti Dwivedi. Power quality issues, problems, standards & their effects in industry with corrective means. *International Journal of Advances in Engineering & Technology*, 1(2):1–11, 2011.

[17] A. Kannan, Vipul Kumar, T. Chandrasekar, and B. Justus Rabi. A review of power quality standards, electrical software tools, issues and solutions. In *2013 International Conference on Renewable Energy and Sustainable Energy (ICRESE)*, page 91–97. IEEE, December 2013.

[18] Tanvi Upadhyay and Jitendra G. Jamnani. Grid integration of large scale renewable energy sources: Challenges,issues and mitigation technique. In *2021 Asian Conference on Innovation in Technology (ASIANCON)*, page 1–6. IEEE, August 2021.

[19] Sarah Rönnberg and Math Bollen. Power quality issues in the electric power system of the future. *The Electricity Journal*, 29(10):49–61, December 2016.

[20] Xiaodong Liang. Emerging power quality challenges due to integration of renewable energy sources. *IEEE Transactions on Industry Applications*, 53(2):855–866, March 2017.

[21] Xuan Hieu Nguyen and Minh Phuong Nguyen. Mathematical modeling of photovoltaic cell/module/arrays with tags in matlab/simulink. *Environmental Systems Research*, 4(1), December 2015.

[22] Zulfiqar Ali, Syed Abbas, Anzar Mahmood, Syed Ali, Syed Javed, and Chun-Lien Su. A study of a generalized photovoltaic system with mppt using perturb and observer algorithms under varying conditions. *Energies*, 16(9):3638, April 2023.

[23] Yue Xia, Ying Chen, Yankan Song, and Kai Strunz. Multi-scale modeling and simulation of dfig-based wind energy conversion system. *IEEE Transactions on Energy Conversion*, 35(1):560–572, March 2020.

[24] Pooyan Alinaghi Hosseinabadi, Hemanshu Pota, Saad Mekhilef, and Howard Schwartz. Fixed-time observer-based control of dfig-based wind energy conversion systems for maximum power extraction. *International Journal of Electrical Power amp; Energy Systems*, 146:108741, March 2023.

[25] Alessio Castorrini, Sabrina Gentile, Edoardo Geraldi, and Aldo Bonfiglioli. Investigations on offshore wind turbine inflow modelling using numerical weather prediction coupled with local-scale computational fluid dynamics. *Renewable and Sustainable Energy Reviews*, 171:113008, January 2023.

[26] Rudresh B Magadum and D. B. Kulkarni. Optimal placement and sizing of multiple distributed generators using fuzzy logic. In *2019 Fifth International Conference on Electrical Energy Systems (ICEES)*, page 1–6. IEEE, February 2019.

[27] Suhad Qasim G. Haddad and Hanan A. R. Akkar. Intelligent swarm algorithms for optimizing nonlinear sliding mode controller for robot manipulator. *International Journal of Electrical and Computer Engineering (IJECE)*, 11(5):3943, October 2021.

[28] Wajahat Ullah Khan Tareen, Muhammad Aamir, Saad Mekhilef, Mutsuo Nakaoka, Mehdi Seyedmahmoudian, Ben Horan, Mudasir Ahmed Memon, and Nauman Anwar Baig. Mitigation of power quality issues due to high penetration of renewable energy sources in electric grid systems using three-phase apf/statcom technologies: A review. *Energies*, 11(6):1491, June 2018.

[29] Lakshman Popavath and Palanisamy Kaliannan. Photovoltaic-statcom with low voltage ride through strategy and power quality enhancement in a grid integrated wind-pv system. *Electronics*, 7(4):51, April 2018.

[30] Ahmed Alhattab, Ahmed Nasser Alsammak, and Hasan Mohammed. A review on d-statcom for power quality enhancement. *Al-Rafidain Engineering Journal (AREJ)*, 28(1):207–218, March 2023.

[31] MHJ Bollen. Understanding power quality problems: Voltage sags and interruptions, piscataway, nj, 2000. *IEEE Power Engineering Series*.