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Modelling, Simulation and Ann Recognition of Power Quality Disturbances in Photovoltaic Grid Connected System

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Abstract- In achieving global decarbonization goals through renewable energy resources (RES), there is an increase concern over the quality of electric power emanating from these non- conventional resources that cause electric power quality disturbances (PQD) notably: grid synchronization instability, outages, islanding, voltage sag, voltage swell, harmonics etc. To conceptualize related issues accentuated, the grid- side of a grid-connected Photovoltaic (PV) system is designed, modelled and simulated using MATLAB/Simulink environment. The developed model implements all components for synchronizing the PV system with the grid which includes: a three-phase Voltage Source Inverter (VSI), a grid filter, grid synchronization and VSI controller and each component of the system is modelled, simulated and validated over certain operating scenarios of the PV system controller under specific grid and weather conditions. The model developed has been validated with IEEE P1547 standard that covers the interconnectivity of distributed generation renewable energy resources. It is envisioned to bring about effective mitigation of the disturbances in the systems through compensation techniques. The simulation results show that, the model is simple, reliable, stable and suitable for implementation of the grid- connected PV system.

Keywords- ANN, power quality disturbances, grid instability, grid tied, renewable energy resources

I. INTRODUCTION

Due to rapid development in the use of renewable energy (RE) sources to satisfy high needs and decarbonization agenda in the society, the accessibility to ac energy has significantly increased. According to Energy Institute (2023), in 2020, the world primary energy consumption was 71.4GJ per person (i.e. 58 kWh per day per person) for a world population of 7.7 Billion people. Based on this trend, if the world population should increase to 10Billion and energy prosperity in all countries match the present high industrial nations like US, Germany and China, the world energy demand will increase in fivefold. Fossil fuel- and hydro-based power plants are no longer able to sustainably provide the rising demand for electricity, due to the rise in fuel prices. Consequently, one potential remedy is to explore renewable energy (RE) sources. Grid connected Photovoltaic (PV) systems have increased dramatically in the past few years primarily to cope with the growth in energy demand. Using PV renewable energy sources with fluctuating outputs and integrating converters, there are numerous instabilities in the quality of the electric power. Given this, it is imperative to recognize and eliminate PQ hindrances in order to provide consumers with clean energy. In particular, power quality issues are found in the supply voltage, linked loads, and therefore sinusoidal quantities vary as a result of PQDs. With regard to the primary effects on pure power supply in the presence of power quality instabilities, there are concern on harmonic distortion, voltage swell, dip, spikes, fluctuations, voltage imbalance, high-voltage, low-voltage, variations in frequency, and short and long disruptions. To address the quality issues, numerous experimental studies on power quality events have been conducted. Connecting renewable energy output to utility busbar, however, would exacerbate the output of an undistorted sinusoidal alternating current source, as the nature of renewable energy sources cannot be predicted. Therefore, the outline power quality disturbances (PQDs) associated with the source functional requirements, such as grid connection, outages, islanding, differences in solar irradiations, and irregular wind speed, will have an impact on the integration of renewable energy into the current utility grid system.

The incorporation of solar and wind energy into the grid utility system are the main causes of power quality disturbances (PQDs) such as voltage sags and voltage dips. Voltage dips, or abrupt drops in voltage, occur during the synchronization of the two sources together. According to Shaiket et al. (2018), the voltage sag value (limiting dip) should be less than 3%. In the case of solar source integration, voltage swell is brought on by input surge. This input surge is sometimes referred to as inflow current produced as a result of little differences between the connected produced solar voltage and the grid voltage. Voltage dips are caused by the reactive power drawn by the double fed induction generator (DFIG) when using wind energy (WE). Voltage swell and voltage sag combine to voltage stability for hybrid renewable energy sources in such as way that the phase angle, line impedances, and X-R ratios increased along with the voltage as the load breakers tripped in the case wind power. In contrast to wind, solar frequency variation is lower as renewable energy sources become more prevalent.

Voltage changes in form of swell and sag are associated with interruptions in renewable energy sources. Solar PV plants do not cause a flicker even though it has impulsive transient and associated frequency variations. Wind and hybrid RES are both affected by similar interruptions. The frequency dip varies in direct proportion to the degree of source penetration. This degree of penetration is attracting research interest in recent times and can popularly be determined by computation of Hosting Capacity (HC), (Zain ulAbideen et al., 2020; Caballero-Peña et al, 2022; Kumari et al, 2023). As a result, when a significant outage takes place, frequency fluctuations are simple to spot. Additionally, compared to solar energy, wind energy source has less frequency variation. For all varieties of renewable energy sources, low-level oscillatory transients have also been observed. For PV power, voltage sag is brought on by a decrease in solar insolation, which also causes a drop in voltage. The voltage swings with variations in the voltage magnitude leading to low-level voltage drops and changes. Frequency irregularities occur when there is an unanticipated change in solar insolation. Generally, there will be an increase in the amount of current and voltage harmonics with a greater penetration of solar photovoltaic sources.

With global concerns over renewable energy, energy security, and the environment, power quality (PQ) has emerged as the main topic of interest. Power flow fluctuations cause non-stationary PQ disturbances by altering the signal's capacity. PQ disturbances can be brought on by abrupt changes in frequency, voltage or current magnitude, and phase angle (Yue, Muhammad, Hui, &Fida, 2019). Power quality problems are brought on by the hike in nonlinear loads, such as solid-state switching equipment, electronically switched devices, industrial rectifiers, and inverters. (Sihan and colleagues 2022). We used MATLAB/Simulink o simulate a PV model integrated with a grid system. According to Blaabjerg (2014) cross referenced in Motan (2018), hardware structure of the grid-connected PV system, used to transfer and control the generated power from the PV system, is based mainly on power electronic converters (DC-DC chopper and inverter) classified as: (a) Module

Inverter (~300 W), (b) String Inverter (1 -10 kW), (c) Multi-String Inverter (10-30 kW), and (d) Central Inverter (≥30 kW). This work will adopt the MATLAB/Simulink 250 kW PV model to study and classify distinct PQ disturbances generated on the complete system using Artificial Neural Network (ANN).

We were able to generate major and minor disruptions and show that the inclusion of power electronic regulators and devices, an electric power system can continuously transmit sinusoidal voltage and current at its rated frequency to end users without any interruptions or inaccuracies. Our simulation also considered the effect of weather on electrical grids and show ha algorithms like ANN can greatly improve system reliability and stability.

II. REVIEW OF RELATED WORK

Power system faults and operating circumstances associated with renewable energy sources need to be quickly identified and corrected else it could result in malfunction of end-user equipment or power system resources. IEEE has produced guidelines in response to the PQ distortions in the power grid brought on by the usage of renewable energy sources. The management of synchronization of renewable energy sources with utility grid is implemented because operational conditions with the performance of renewable energy sources result in voltage and frequency instability at the point of interconnections (POI).

Saxena et al. (2010) offered summary and main points of Power quality incidents. For the past decade years, power engineers' attention has been focused on power quality (PQ) problems because of the widespread usage of nonlinear and microchip established monitored loads. However, these devices cause poor power quality and malfunction as a result of the issues they generate with poor power quality. PQ difficulties and interruptions occur over a large frequency range with noticeably varied levels of change and might be non-stationary, therefore precise processes are required to identify and classify them. The study provides a complete overview of the various PQ systems used, particularly the numerous artificial intelligence techniques employed to PQ evaluations.

The various studies conducted and pertinent inquiries on how efficient the power is supplied as it relates to power quality. There are numerous solar power options, including grid-connected, stand-alone, and integrated building PV systems. Chayawatto et al. (2018) investigated the impact of islanding brought on by the grid's voltage types splitting. The analysis strategy involved looking at a 1.4 kW grid system. To evaluate PQD, mostly reactance and resistive loads were used. Four (4) portions of a sinusoidal waveform: First (0-900 sec), second (91-1890 sec), third (181- 2700 sec), and fourth (271-3600 sec) places are in order. From the beginning of the grid system until the inverter went down, the islanding test's results and disconnecting time were recorded. According to the results, resistive loads have the quickest disconnect times when compared to other types of loads.

Mohan et al. (2011) created artificial neural network-based models for simulating spring emission. The study describes how artificial neural networks (ANNs) are used to forecast the weekly spring flow. The study area was situated in the Uttarakhand region of India. With the use of five models that were created to predict utilizing rainfall, evaporation, and temperature with a specific delay period, spring discharge based on a weekly interval was accomplished. One and two hidden layers were used to create the models. Each model was created through a series of trials using various network designs and hidden neuron densities.

Using weekly data between 1999 and 2005, Out of the three methods submitted, the best model for the simulation was selected using statistical parameters such the correlation coefficient (R), determination coefficient, or Nash Sutcliff's efficiency (DC). For the best model, increased numbers of neurons were used. The models' ability to predict the weekly spring discharge was demonstrated by the preparation and analysis findings.

Because of the growing usage of renewable energy sources and distributed generation to fulfill our daily power consumption, Saini et al. (2012) demonstrate that PQ problems evaluation can be improved in the future and can be crucial in smart grid sub distribution stations. This inspires the notion of using intelligent signal processing and optimization approaches in PQ analysis.

Bishal et al. (2018) examined the efficiency and power quality of a grid-synchronized solar power system. A 12.5 kW PV system with 7 kW functioning on its own and 5.5 kW connected to the grid was used in the example study. The study looked at the efficiency, power quality, current, voltage harmonics, and frequency deviation of the connected grid. The voltage profile shows a very good voltage profile since, during the course of the day, no swells or dips were seen. Furthermore, studies of frequency variation were conducted with and without the solar system. Regarding distortions, the influence of current harmonics on voltage waveforms depends on the distance between the load producing the harmonics and the power system.

The power quality parameters have been typically evaluated using a variety of criteria. Vijay et al. (2019) and Paula et al. (2019), carefully selected the following power quality disturbance factors under one PQ issue with two combinatory circumstances:

- Sag
- Swell
- Flicker
- Sag plus flicker
- Harmonics plus Swell
- Harmonics
- Notch and swell
- Notch + interruption
- Notch
- Spike
- Transient
- Interruption

A real or synthetic signal can be identified as signal source. The logical tools used to establish above disturbances were adopted from over 100 articles under the following techniques:

- Artificial intelligence.
- Wavelet transforms.
- High-order statistics.

However, the analysis should have considered the possibility of grouping more than two PQ issues. Poongothai et al. (2020) analysed the improvement in power quality when solar electricity is connected to the grid using the Unified Power Quality Conditioner (UPQC). A DC-DC converter that tracked the phase-modified control of the non-controlled DC input and DC output served as the UPQC's termination point. Pulse width modulation (PWM) is used to convert photovoltaic Direct Current (DC) voltage to Alternating Current (AC) voltage at the same line frequency. When a DC-DC enhancement converter is used to implement the various MPPT control strategies between the solar and inverters, it has been discovered that a consistent input voltage with fewer ripples ensures a high-quality inverter output. More effort is being put into developing a hysteresis controller that uses the P & Q algorithm to assure MPPT functionality. The proposed grid configuration with solar systems and a single-phase unified power quality conditioner was found to have Total Harmonic Distortions (THDs) that were within the IEEE519-2014 standard for a THD that is typically set within 5%.

To increase the systems' dependability and lower their costs, batteries are typically connected to standard diesel generators. According to Pourbehzadi et al. (2019), batteries are employed far more frequently than super-capacitors and flywheel storages. When the generation of the renewable energy system is insufficient to provide the client with the required amount of power, they typically come on. Batteries play a big part in the project's overall electricity cost because they need to be replaced regularly every six to eight years. How batteries are maintained as well as environmental elements like temperature and sanitization level have an impact on how long they survive. However, due to the switch from sodium-sulfur to lead-acid batteries because of their dependability and cost, the battery storage industry has made great strides recently. Figure 1 shows the typical hybrid system.

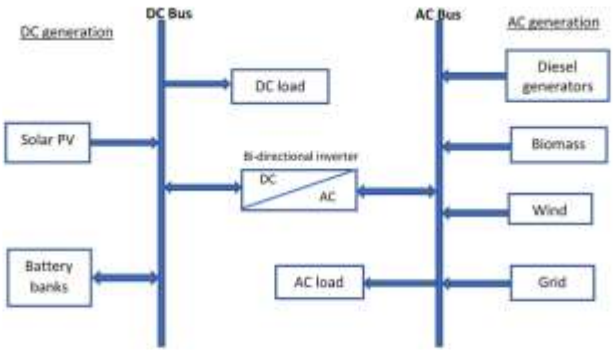

Figure 1: A Typical schematic of HRES

In monitoring existing systems, Ashwin et al. (2017) reported an experimental investigation of power quality (PQ) disturbances related to grid integrated wind energy system. Under various types of loads, PQ disruptions associated with grid synchronization with wind energy production systems and outages of doubly fed induction generators (DFIG) have been noted. The voltage signal at the point of common coupling (PCC) was recorded using a laptop, a power quality tester, and WT viewer software. The PQ abnormalities were found after MATLAB software was used to evaluate the voltage signal. According to the study, voltage fluctuations, flicker, voltage sag, voltage swell, and harmonics are all PQ disruptions that have been connected to the grid harmonization and outage of the DFIG-based wind energy transfer technology.

Gajendra et al. (2020) studied utility grid synchronization with Renewable Energy sources. The concern over power quality as a whole is growing as more renewable energy (RE) sources are being used to meet energy needs and reduce carbon emission goals. Due to their erratic outputs and interface converters, PQDs are typically noticeable when using renewable energy sources.

1. Artificial Neural Network (ANN)

Artificial neural networks (ANNs) are a relatively new class of statistical prediction tools that are particularly Predicting technique survival in peritoneal dialysis patients, ANNs are mathematical models that can be employed in the modelling of complex systems. It consists of three layers, namely, the input layer, the middle layer and the output layer.

The ANN method is speedier in contrasted to its conventional techniques, robust in noisy environments, and can also solve a wide-ranging of complications. These advantages of ANNs have been used in several real-time presentations. Neural networks in hydrology has three layer as follows, input layer through which data is fed into the network, hidden layer(s) this is a particular place where data is processed and output layer is where the result is obtained or presented as in Figure 2.

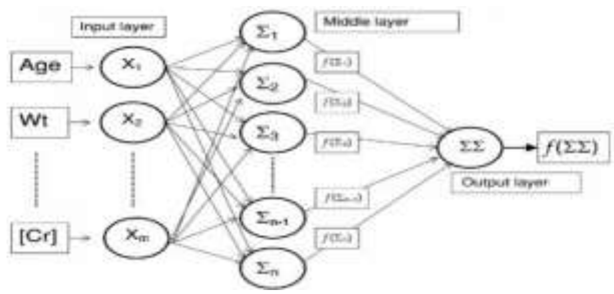

Figure 2: A typical ANN architecture. (Navdeep et al., (2008))

Neurons or nodes are the processing elements in each layer. The order of data processing in the network; it begins from the input layer to the hidden layer and then output layer. The number of neurons and hidden layers in the network cannot be determined except with the nature of the problem or is decided by the trial-and-error method. A weight is designated to each connection to ip. The represent the relative connection strength of each nodes at both ends in forecasting the input output relationship output, y j of any node j, is given as;

$$y_i = f(\sum_{i=1}^{m} W_i X_l + b_i), \qquad \ldots (1)$$

Where X_i is the input received at node *j*, W_i is the input connection pathway weight, *m* is the total number inputs to node *j*, and b_i is the node threshold. Function *f* is known as activation function which defines the response of a node to the total input signal that is received. The activation function is sigmoid transfer function and is given by.

$$f(x) = \frac{1}{1 - e^{-x}} \qquad \ldots (2)$$

Sigmoid function is continuous and differentiable everywhere, and a nonlinear process can be mapped with it. Back-propagation algorithm is mostly used in training of the feed-forward neural networks. In this algorithm, each input pattern of the training dataset is passed through network from the input layer to the output layer.

New and modern control strategies continued to be evolved to improve the efficiency, reliability, and stability of grid-connected PV systems. However, the wide variety of the PV system components and control algorithms with susceptibility of the system destructive testing under different types of scenarios and faults, make the practical testing of the PV system very difficult, very expensive, and impossible in many cases. To eliminate all these risks and to reduce the expenses of testing, the whole grid- connected PV system is modelled and simulated under various weather and grid conditions. The hardware structure of the grid-connected PV system, used to transfer and control the generated power from the PV system, studied are mainly centered on module Inverter (~300 W), and String Inverter (1 -10 kW) but rarely go beyond the Multi-String Inverter (10-30 kW). The work will categorize distinct PQ disturbances generated on the complete 250 kW PV system using ANN.

III. METHODOLOGY

1. Mathematical Representation of PV System the PV Array

As shown in Figure 4(a) and (b) for solar cell and PV module respectively.

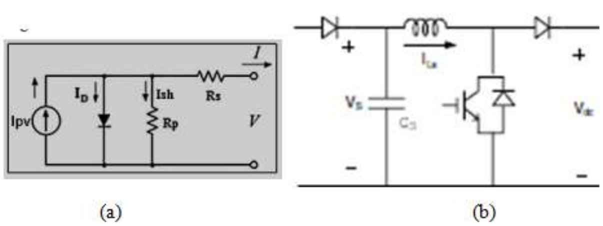

Figure3: Equivalent circuit: (a) Solar Cell (b) PV module

At the cellular level, the relevant model equations are given in Eqns. (3.1) to (3.7).

$$I = I_{pv\_cell} - I_{0\_cell}\left[exp\left(\frac{qV + iR_s}{nkT}\right)\right] - 1 - \frac{V + iR_s}{R_p} \quad \text{... (3}$$

Table 1: Parameters of PV Panel

Parameter	Value
Solar module type	SPR-415E-WHT-D
Maximum power (Pmax)	414.801W
Open-circuit voltage (Voc)	85.3V
Short-circuit current (Isc)	96.09A
Voltage at Pmax (Vmp)	72.9V
Current at Pmax (Imp)	5.69A
Temperature Coefficient of Voc (%/deg.°C	-0.22

The incidence photocurrent is calculated by the Temperatures T_1 and T_2 as in Eqn. (3.2)

$$I_{pv\_cell} = I_{0_{pv_{cell}}} + (T_2 - T_1) \quad \text{... (3.2)}$$

$$I_L = I_{SC_{T1}}\left(\frac{G}{G_{nom}}\right) \quad \text{... (3.3)}$$

$$K_0 = \frac{\left(I_{SC_{T1}} - I_{SC_{T2}}\right)}{(T_2 - T_1)} \quad \text{... (3.4)}$$

The reference solar radiation and current represented by G

During the dark, the cell is inactive and behaves like diode. The shunt resistance and internal resistance of the solar cell is denoted by R_p and R_s respectively. The maximum power fora given resistive load) is given by

$$P_{max} = V_{max} \times I_{max} \quad \text{... 3.5}$$

Solar cell's efficiency can be defined by-

$$\eta = \frac{P_{max}}{P_{min}} = \frac{V_{max} \times I_{max}}{A \cdot G} \quad \dots 3.6$$

where: A represents area of the cell and G is the radiation of the cell.

To measure the quality of the solar cell, we use Fill Factor (FF). The FF should be more than 0.7. It is inversely proportional to the cell temperature.

$$FF = \frac{I_{Sc} \times V_{oc}}{V_{max} \times I_{max}} \quad \dots 3.7$$

2. Chopper

Choppers serve to step up the voltage to the level of the allowable maximum line voltage and to stabilize the required DC level without the use of storage facilities like batteries. The chopper is controlled to track the maximum power point of the PV array. Figure 4 depicts the booster converter schematic and circuit diagram respectively.

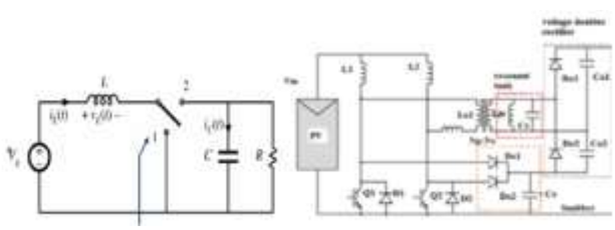

Figure 4: Boost converter (a) schematic diagram (b) Circuit Diagram

The static gain (K) of boost converter can be calculated where D represents the duty cycle of each switch and must be higher than 50% to guarantee the necessary overlapping for the correct operation of the Two Inductor Boost Converter (MathWorks, 2013).

$$\frac{V_{out}}{V_{in}} = K = \frac{1}{(1-D)} \times \left(\frac{2N_s}{N_p} + 1\right) \quad \dots 3.8$$

where:
K-Static gain
D-Duty cycle
Ns-Secondary turns ratio of transformer
Np-Primary turns ratio of transformer

3. Inverter

Inverters make use of converters in order to change from DC power to AC power. There are two types of inverters namely single-stage inverter and multi-stage inverter. The single-stage inverters have advantages like high efficiency, lower cost, robust performance, simple structure and high reliability. The multi-stage inverter accepts a wide range of input variations. Their structure is more complicated, they have high cost and low efficiency. Figure 5 shows a single-input inverter.

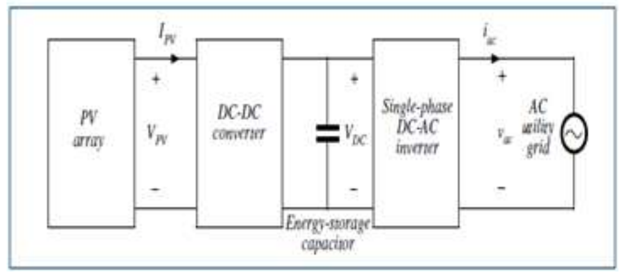

Figure 5: Single-stage inverter

4. Complete PV Grid Connected System

The grid network supply is obtained from a dedicated 132/11 kV substation transformer and has been modeled into the MATLAB Simulink for system performance analysis.

The customer is expected to have a plan to connect its PV plant rated 250 kW ready for grid connectivity. The customer was equipped with 1800 KVAR of shunt power factor correction capacitors. The complete PV grid connected system one-line diagram is shown in Figure 6.

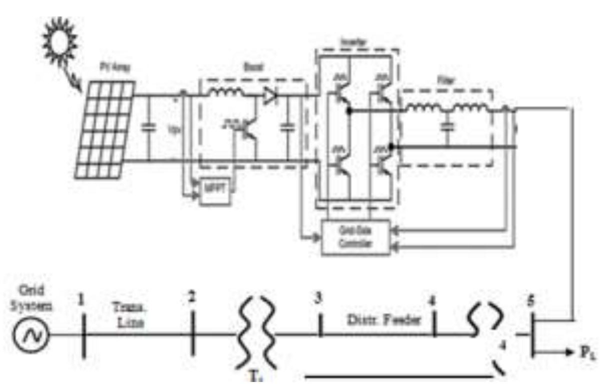

Figure 6: One line diagram of 132/11 kV PV Grid Connected 4-Bus Network

5. PV Connection

The photo-voltaic system is a single-phase system. The PV modules are responsible for capturing energy stored in the sun (irradiance + temperature) and converting it into electric signals. The PV modules are connected to the booster. The booster helps to step up DC signals at a lower level (voltage) to DC signals at another level. The pulse generator is used to adjust the booster to required conditions. The inverter control mask Simulink block was invoked to trigger three level bridge Insulated Gates Bipolar Transistor (IGBT) that inverts PV/DC-DC boost converter output to AC power. Noticed that inverter control unit implement 5 different operational control that would have been performed by discrete component in lower MATLAB versions PLL and measurement, maximum power point tracker MPPT system that uses perturbation and observation algorism, DC voltage regulator, current regulator and Pulse with modulation unit. : The parameter of these 5 unit are specified in Appendix one, for instance the nominal power and frequency, power 250Kw and frequency 50Hz. MPPT is the incremental type with output limit upper and lower limit583 and 357 respectively, with nominal DC voltage of 480V, Figure 7 shows the PV connection as developed in MATLAB/Simulink platform.

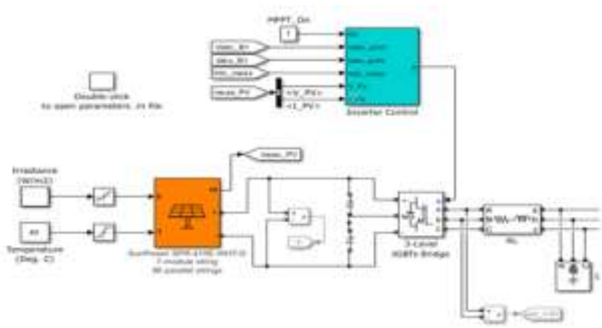

Figure 7: Model of PV system for Grid Connection

6. Grid Connection

A three-phase AC load was connected at the consumer side without PV connection to verify its impact on the overall performance of the grid. The complete schematic of the grid network modelled is shown Figure 8.

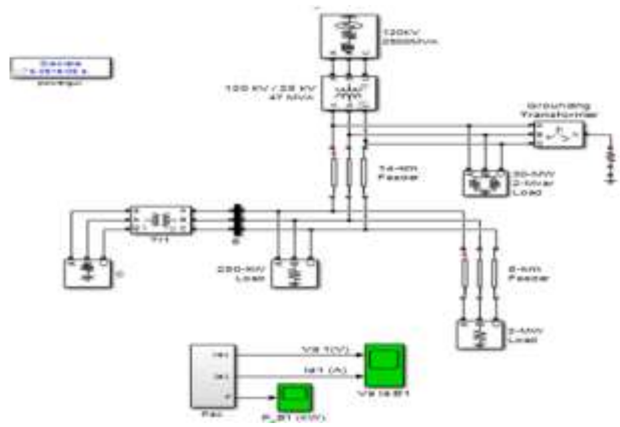

Figure 8: Grid Connection Stage without PV system

7. Analysis

The parameters being varied were the temperature and solar irradiance for the PV subsystems while the disturbances such as sag, swell, interruption and harmonics were introduced at the point-of-common coupling. The FFT algorithm was used to THD of the respective results obtained while other Simulink scopes were explored to study the output responses of the reference ports. Different frequencies were applied and their impact on the grid analysed. The grid was also analysed in the presence and absence of the PV system.

IV. RESULT

The PV model interconnected with grid network has been studied with MATLAB Simulink toolbox. The simulation model was run and resulting signals on the various scopes were observed as presented hereunder. Herein, the model of the PV module, I-V characteristic plots, solar irradiance with panel output, and simulated output characteristics of PV are described.

1. Impact of Weather Condition on Performance of PV System

The initial input irradiance to the PV array model was1000 W/m2, the operating temperature was 45 degrees C and the total time for the simulation was 1.5 sec.

When the simulation runs reached 0.3 sec, the solar irradiance was changed from 1000 W/m2 to 200 W/m2and then increased back to its initial stage at

1.15 sec. Figure 9 shows the PV panel and monitoring ports in MATLAB/Simulink environment. Figures 10 and 11 show the I-V characteristics curve of the solar panel at temperature 40^{0}C and 45^{0}C in comparison with 25^{0}C. Figure 9 shows the PV module output recursion between the entire simulation period of 1.5 sec while Figures14 to 15 reveal the impact of solar irradiance variation on the panel output during simulation runs.

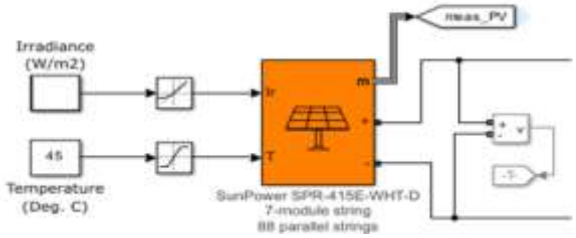

Figure 9: Simulink model of the PV module

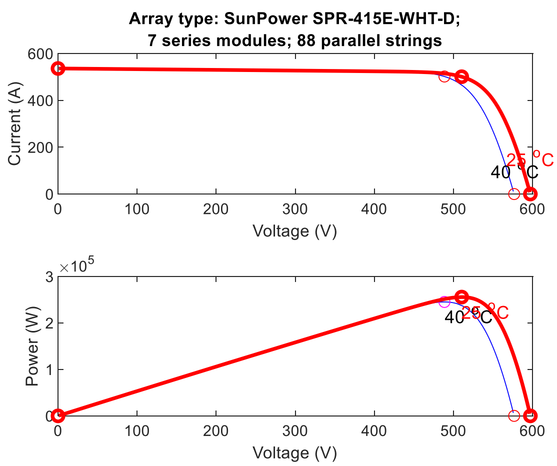

Figure 10: I-V characteristic plots at 40^{0}C

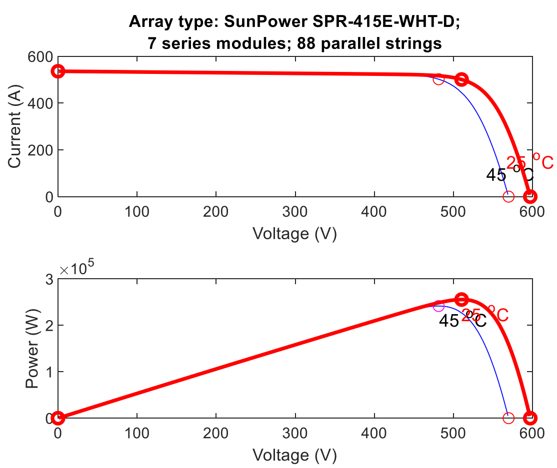

Figure 11: I-V characteristic plots at 45^{0}C

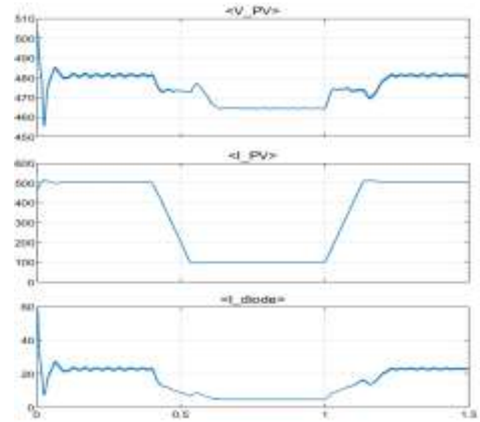

Figure 12: Module Output characteristics

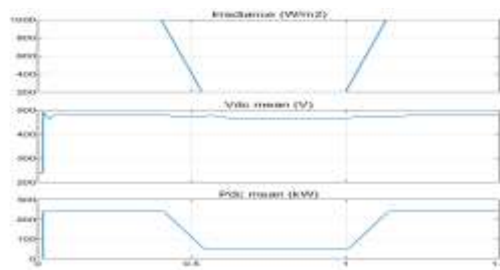

Figure 13: Panel Output Power for Maximum Solar irradiance of 1000 W/m2 and 200 W/m2 Minimum

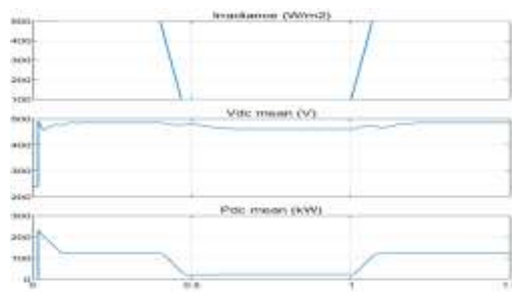

Figure 14: Panel Output Power for Maximum Solar Irradiance at 500 W/m2 and 100 W/m2Minimum

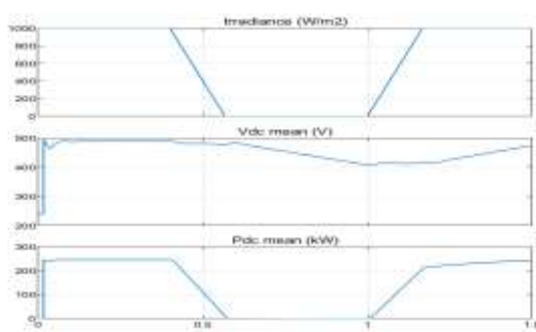

Figure 15: Panel Output Power for Maximum Solar Irradiance at 500 W/m2 and 100 W/m2Minimum.

Figures 11and 12show the output characteristic plots of the panel under two different operating temperature. For instance, a cursory look at the graph in Figure 12when the operating temperature of the PV module was 45^{0}Cdepicts that current, voltage and power at the maximum power point are 501 A, 481.318 V and 247,948 W respectively and the same PV panel returned higher power of 255,517 W and249,350 W 25^{0}C and 40^{0}C respectively. This implies that maintaining a lower temperature improves the PV module performance by 3%.

As shown in Figure 13 when steady state is reached (around t=0.15 sec.), PV voltage (Vdc_mean) of 481 V was obtained and the power extracted (Pdc_mean) from the array was 236 kW. These values correspond very well to the expected values from the PV module manufacturer specifications.

In Figure 14, at t=0.3 sec, solar irradiance is rapidly ramped down from 1000 W/m2 to 200 W/m2. Due to the MPPT operation, the control system reduces the VDC reference to 464 V in order to extract maximum power from the PV array (46 kW). This is apparently shown in Figure 11, V_PV sub plot. Figures 15 and 16 studied other operating status of the panel for 100 W/m2 and 0 W/m2 respectively.

2. PV Grid Synchronization

In order to implement synchronization of the PV system with the grid, the results are rippled through the entire model and stage-by-stage of all components are monitored in the MATLAB workspace.

The components provided as Masked Simulink block in Plate II has been harnessed to achieve Phase Lock Loop (PLL), Maximum Power Point Tracker (MPPT), DC voltage & current regulation and Pulse Width Modulation (PWM)for the three-phase Voltage Source Inverter (VSI) and grid synchronization control. The controlled output of the VSI and the grid are shown in Figures 17to 18 for PV connection while Figure 19 and 20 explored the scenario without PV integration.

Figure 16: Masked Inverter Controller of 250 kW PV Grid Connected System

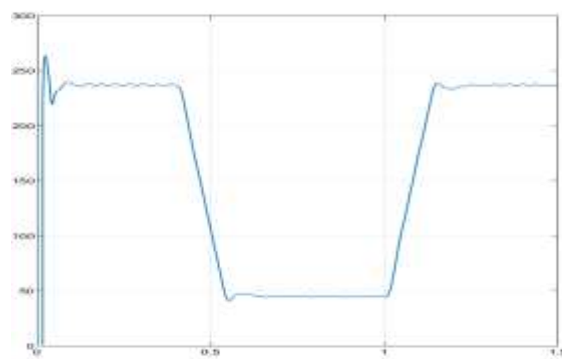

Figure 16: Inverter Power Output (kW)

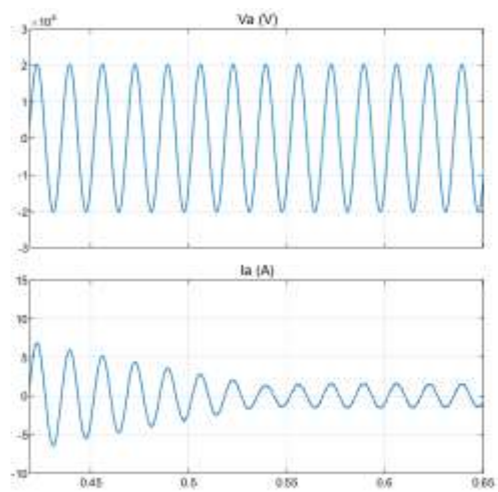

Figure 17: VSI Output Voltage and Current

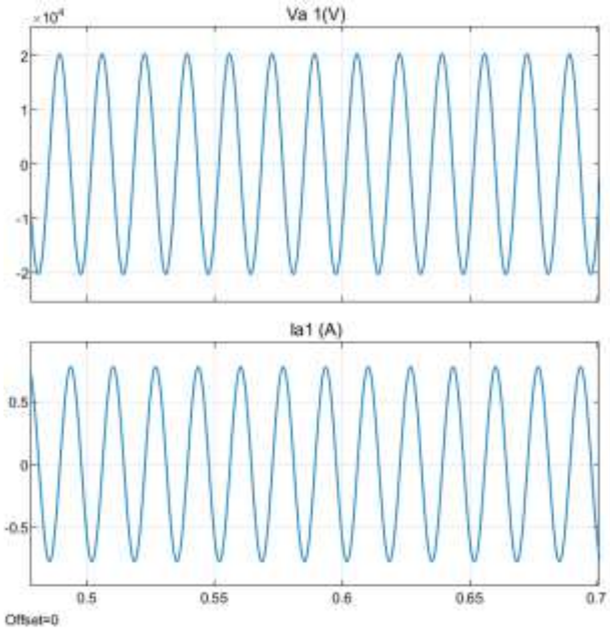

Figure 18: Grid Output Voltage and Current

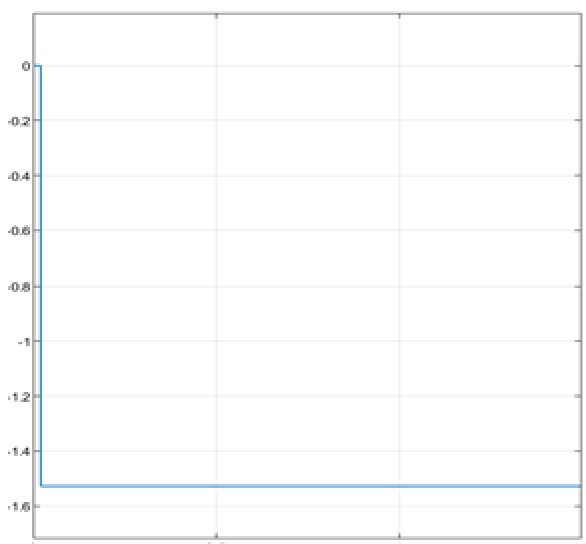

Figure 19: Power Output (kW) without PV Connection

3. PQ Disturbance of PV Grid-Connected System

FFT subroutine was run on the output voltage waveform for one cycle at the fundamental power frequency of 50 Hz applying Nyquist criterion and the maximum frequency of 1 kHz, the histogram plot is shown in Figure 21. The fundamental RMS returned 17 kV and 45.6% THD. Figure 22 shows a disturbance of sudden reduction of solar irradiance to 0 W/m2. In this condition, the voltage regulator and MPPT were able to sustain the status within the margin slightly lower than 400 V.

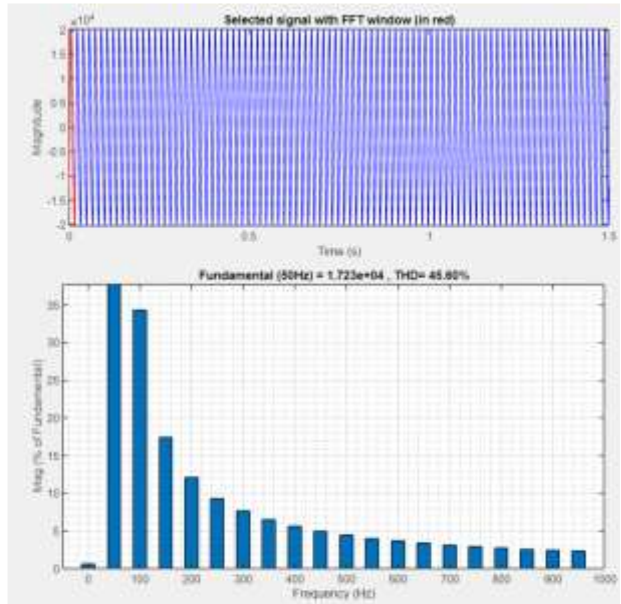

Figure 20: FFT Histogram Plot of the Distorted Waveform

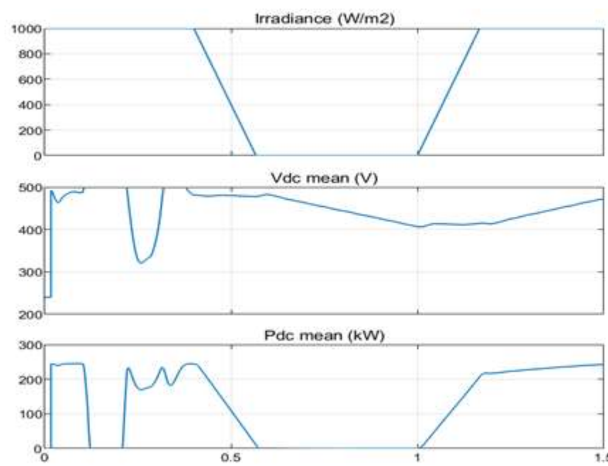

Figure 21: Panel Output Power under a PQ Disturbance for Maximum Solar Irradiance of 1000 W/m2

4. Classifying PQ Disturbances Generated in Grid Connected PV System

This section studies classify of PQ disturbances generated in 250 kW grid connected system. The PQ signature produced is used to train a Multilayer Neural Network with Multivalued Neuron (MLMVN) in agreement with the recently developed approach Iturrino et al., (2023).

Figures 23 to 26 show PQ events: Sag, swell and interruption, while Figure 27 was obtained as replica for typical fault disturbance using MATLAB workspace function.

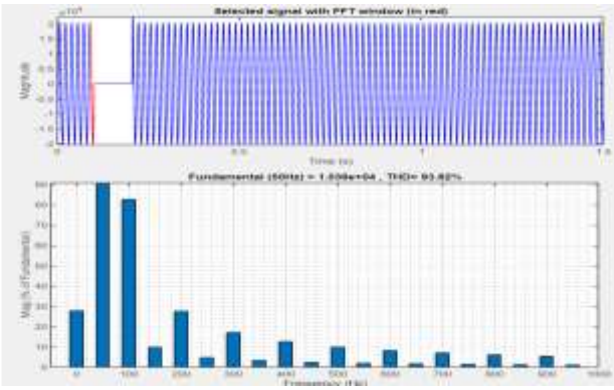

Figure 22: Simulated voltage Sag for heavy Fault Current

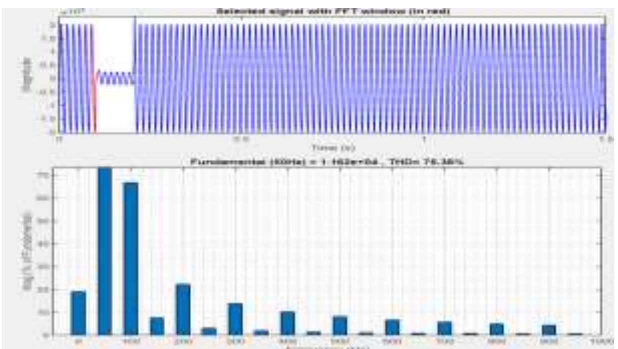

Figure 23: Simulated voltage Sag for light fault current

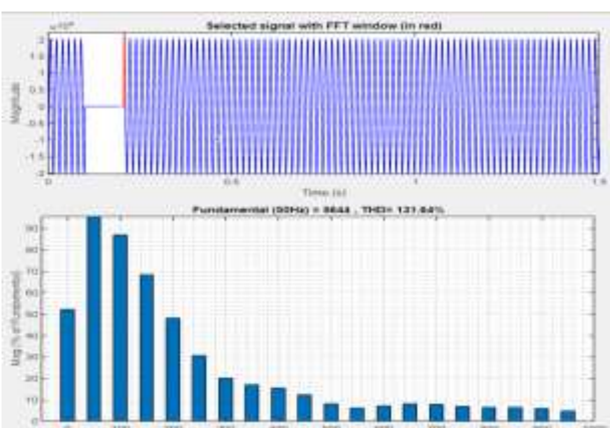

Figure 24: Simulated voltage Swell for heavy fault current

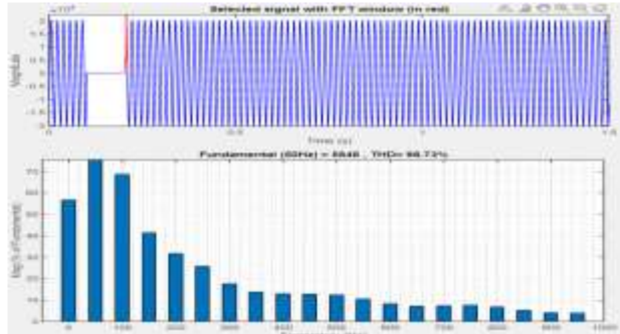

Figure 25: Simulated voltage Swell for light fault current.

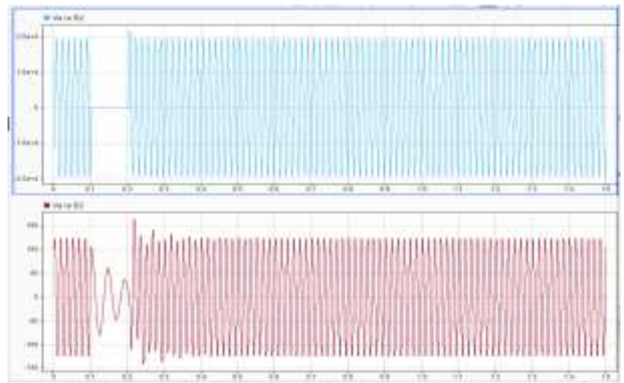

Figure 26: Simulated voltage sag due to fault with workspace function

5. Identification of PQ Disturbances Using Artificial Neural Network (ANN)

Based on PQ data formulated from IEEE 1159 standard, some distinct PQ disturbances were developed using pattern recognition technique of the ANN. The data was used to train ANN and thereafter used in the identification of PQ disturbance. The simulation engine of ANN is shown in Plate II for PQ disturbance using pattern recognition tool of MATLAB/Simulink software. Plate III shows the performance metric of the ANN technique in the identification of correct PQ disturbance pattern. The MSE obtained for training, validation and testing ANN operation were 10-3, 1.2025 x 10-7 and 10-16 respectively. The last performance index shows the lowest MSE which is an indication that the ANN will be able to identify independent and unfamiliar data within a tolerable level of error. The confusion matrices are another performance metrics to determine whether the classification of the PQ events: transient, harmonics, notch etc have been satisfactory achieved in a way that correct classification of PQ disturbances outperformed the false alert. In Plate IV, the diagonal element of the matrices has higher values than the off-diagonal elements which returned 32.3%, 44.4% and 25.9%, for PQ event 1, 38.7%, 37.0% and 25.9% for PQ event 2, 29%, 18.5% and 25.9% for PQ event 3 each for training, validation and testing MSE respectively while cumulative of 33.1%, 39.3 and 27.6% correct classifications have been correspondingly obtained.

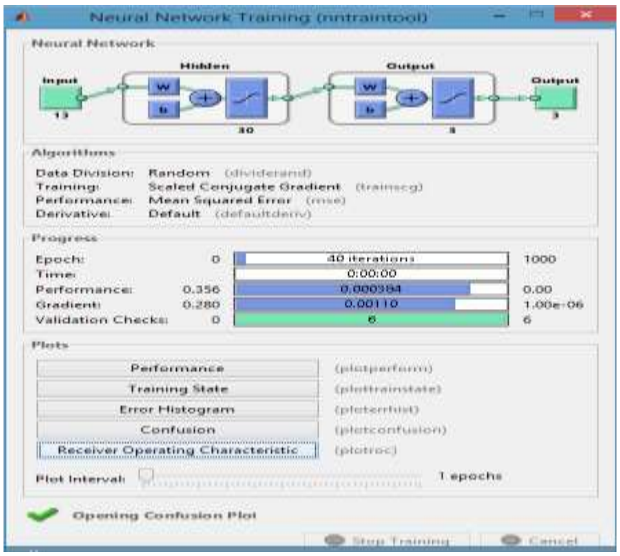

Figure 27: ANN Performance Metric of PQ Disturbance Identification

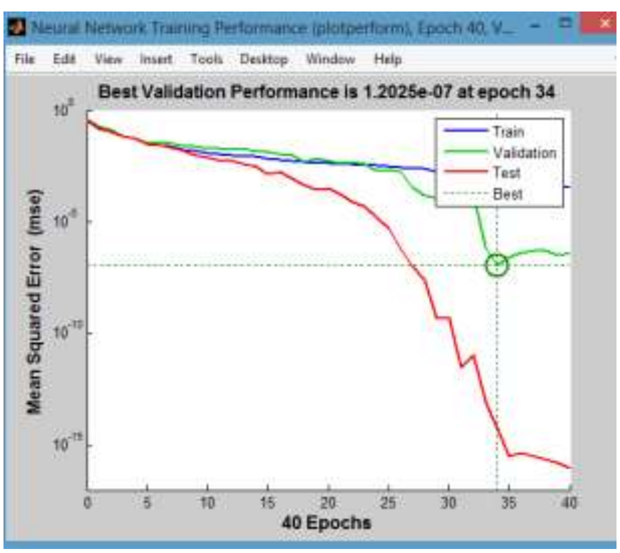

Figure 28: ANN Performance Metrics of PQ Disturbance Identification

Figure 29: ANN Confusion Matrix for PQ Disturbance Identification

V. CONCLUSION

The research modelled 250 kW PV grid connected system in MATLAB/Simulink software to study the impact of PQ disturbances on its performance in relation to weather and emergency operating conditions. At the end of this research, the findings therein have been summarized as follows:

- The model of the PV module, I-V characteristics, solar irradiance with panel output, and output characteristics of PV were successfully developed in MATLAB/Simulink software.
- PV grid-connected system is more prone to PQ disturbances adversely reducing the performance of the PV inverter output. Solar irradiation levels and panel temperature are two important environmental parameters that can decrease or increase the power wheeling capability of the solar PV plants to the grid systems.
- FFT subroutine has been used to study the PQ disturbances emanating from the PV inverter systems, producing high THD up to 45%.
- ANN pattern recognition tool has been harnessed to classify PQ disturbance of PV grid system with high level of accuracy measured by lower value of MSE in training performances.

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