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Feed Forward Neural Network Based DSTATCOM for Compensating Load Demand and Mitigate Harmonics in Distributed System

A. Kasim Vali[1], P. Srinivasa Varma[1], Ch. Rami Reddy[2,3]*, A. Giri Prasad[2], D. Raja Reddy[4], Joon-Ho Choi[5]

[1] *Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation, Guntur, INDIA*
[2] *Department of Electrical and Electronics Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, INDIA*
[3] *Applied Science Research Center, Applied Science Private University, Amman, 11937, JORDAN*
[4] *Department of Electrical and Electronics Engineering, Malla Reddy Deemed to be University, Secunderabad, INDIA*
[5] *Department of Electrical Engineering, Chonnam National University, Gwangju, SOUTH KOREA*

*Corresponding Author: crreddy229@gmail.com, joono@chonnam.ac.kr
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Abstract

Power Quality (PQ) has become a critical requirement in modern power systems due to its impact on industrial automation, computer-based technologies, and controlled electrical systems. Accurate identification and mitigation of electrical disturbances are essential for improving system reliability and efficient power delivery. However, conventional approaches often face limitations in optimizing power flow at the end-user level. In this paper, a superior controller to a Distributed Static Compensator (DSTATCOM) was developed with intentions of optimizing power quality in a traditional bus system. A baseline DSTATCOM model of a basic bus setup had first been set up, followed by gathering real-time data over a range of disturbance conditions to power quality. This dataset was then trained in a Feed Forward Neural Network (FFNN) controller, creating a DSTATCOM pulse signal to be created in the analysis of bus voltage measurements. The proposed controller efficiency was estimated using case studies based on IEEE 33 and 13 bus systems. Performance validation was conducted at a number of disturbances such as interruption, swell, harmonic content, and sag. In the case of the IEEE 13-bus system, the model proposed meets the total harmonic distortion (THD) of 2.93, 1.81, and 0.02, under sag, swell, and interruption conditions, respectively. In the same manner, in the case of the IEEE 33-bus system, the THD of sag, swell and interruption are 0.58% 0.26% and 0.33%. The results confirm that the proposed FFNN-based DSTATCOM controller effectively mitigates a wide range of power quality disturbances while enhancing system stability and reliability.

1. Introduction

Maintenance of observed frequency and voltage of AC bus sinusoidal waveform is known as PQ in a power distribution system [1]. The waveforms of current and voltage must be completely sinusoidal and free of interruptions. But the waveform may be distorted and voltage instability may result from grid transients and imbalanced loads [2]. These distortions might spread throughout the entire power distribution network. The problems of power quality (PQ) include a set of transients of the grid, such as voltage unbalance, voltage sag and swell, voltage spikes, distortion of voltage and current waveforms, harmonics, flicker and electrical noise [3].

These may begin the apparatus operating abnormally or undoubtedly trip the protection components. FACTS devices are used in the power system sectors to dampen the amplification of PQ problems [4]. A FACTS device called DSTATCOM operates by injecting VAR into power system networks, where it has been demonstrated to be reliable [5]. DSTATCOM offers a relatively inexpensive reactive power compensation and unbalanced load control solution to a distribution system [6]. It is considered to be among the established custom power devices, together with the unified power quality conditioner and the dynamic voltage restorer [7]. The first step to ensuring that customers are satisfied with their electrical power framework is to address the PQ issue [8]. Control quality problems are anticipated to get worse as control gadgets and nonlinear loads proliferate. FACTS can offer a logical solution to this problem [9]. To keep the compensators operating properly, certain technologies with quick and trustworthy control over transmission parameters are required [10]. A number of control measures have been suggested in order to overcome these problems. The more traditional controllers are using proportional-integral (PI) and proportional-integral-derivative (PID) methods in conventional compensator controllers [11], but fuzzy logic controllers have also been used to alleviate PQ issues [12]. However, it is still a challenging task to select the best parameters to use on such controllers. In order to eliminate this problem, the best control strategies have been provided [13]. Regardless of these attempts, these types of models tend to be unstable when subjected to different operating conditions and do not provide a stable and reliable work [14]. Later on, model-generating strategies involving artificial intelligence (AI) have been created to make sure that compensator behaviour is effective at any operational condition [15]. AI's capacity to operate continuously, without pause or downtime, and to react more swiftly and precisely in any circumstance is a benefit of using it [16]. This circumstance inspired us to develop an intelligent learning-based controller to enhance the compensator's performance by minimizing PQ difficulties. To control the voltage deviation caused by PQ difficulties, the DSTATCOM compensator is connected to the system. The performance of the compensator will always be regulated by a Machine Learning (ML) based controller.

Several models are used for improved power quality some of them listed below. PQ problems in the system can emerge as a result of operator error or mechanical problems. Many strategies were developed to mitigate power quality issues; some of these strategies are summarized here. Rodríguez-Pajarón et al. [17] suggested a probabilistic technique to evaluate the effects of voltage unbalance and harmonics levels in low voltage networks when nonlinear loads and electric vehicles are integrated more concurrently. The EN50160 standard limitations were used as the benchmark for low voltage PQ, and the IEEE European Low Voltage network and a bigger 471-bus residential network were both subjected to the methods. Yet the model only considers harmonic mitigation of a bus system other PQ issues are considered. Bajaj and Singh [18] developed the application of the analytical hierarchy approach, the PQ indexes were integrated into a PQ evaluation of the same that was much simplified. A centralized Global Power Quality Index (GPQI) of load, utility and distributed generation (DG) buses and of the entire system is achieved due to the formulation process. But, this model was not applied to an IEEE bus system and thus could not achieve good results. Mahela et al. [19] suggested the enhancement of power quality through the use of a distribution static compensator that was connected to a distribution network with PV energy integration and equipped with a battery energy storage system. This controller's changeable switching frequency, which causes varied ripple frequency to be generated, is negative. Abbas et al. [20] developed a technique for harmonic mitigation that could help distribution networks with their power quality issues. Two case studies have been performed to assess how distributed generation (DG) harmonic spectra affect the overall system distortion and filter design. The IEEE 69-bus distribution system was used to analyze the suggested technique. However, because of its high cost, it is regarded as an uneconomic method. Ahsan et al. [21] have examined low-voltage (LV) power quality problems that can be brought about by large nonlinear loads at the point of common coupling (PCC).

To examine seasonal variations and overall harmonic distortion in the voltage and current at PCC, many PV penetration samples (0 to 100%) were confirmed at radial modified IEEE-34 bus and assessed for useful feeder data in a poor grid setting. However, the method only mitigates THD in a system, other issues are not considered so it is not fit for real-time implementation. Dheeban and Muthu [22] constructed a photovoltaic (PV) based-integrated UPQC with bidirectional series and shunt converters which are regulated with the hybrid mode of p-q theory and Unit Vector Template method. An adaptive neuro-fuzzy controller that assists with the reference current generation and enhances system performance by inferring system parameters from language rules had been utilized to analyse this system. However, the model is curse of dimensionality and computational expense. Teferra and Ngoo [23] suggested the Newton Raphson technique of modelling three FACTS controllers in the IEEE

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5-bus standard system. NEPLAN simulation software was used to determine the effects of these controllers on transmission line capacity and improvement of voltage profile. The method's low FACTS controller controlling performance makes it unsuitable for real-time use. Alanazi and Alanazi [24] developed an artificial electric field algorithm (AEFA) is improved by the PS algorithm on an imbalanced IEEE standard 33-bus network and a real imbalanced 13-bus network. The choice variables are identified as open switches of the networks using AEFAPS, which takes into consideration the operational constraints and the desired value. However, the model is time consuming and does not provide sufficient outcomes in mitigating PQ problems. Tariq et al. [25] suggested an approach to lessen PQ issues, a Static Synchronous Compensator (STATCOM) based on a Hysteresis Band Current Controller (HBCC) is modelled. The HBCC was created to reduce system THD inside the bounds set by IEEE 519-1992 STATCOM standards, hence improving PQ in a distribution system. However, due to the model's high switching frequency, undesired harmonics are produced. Nafeh et al. [26] developed a current-controller with Fuzzy-PID, Fuzzy-PI, and D-STATCOM. The power system's voltage stability, various power quality issues, and dynamic performance were all helped by D-STATCOM-based controllers. However, a relatively significant impact on dynamic system performance and voltage stability due to a change in the parameters of controllers. The studies mentioned above are the latest attempts to improve PQ in distribution systems. These models are providing a better performance based on its developed scope. Yet those have some drawbacks as per the concept of real-time simulations like cannot consider all PQ issues [17], not analysed the performance in IEEE bus system [18], variable switching frequency [19, 25], high cost and poor mitigation performance [22]. While these approaches have shown improvements in specific areas like harmonic mitigation, THD reduction, or voltage stability, they often address only a subset of PQ disturbances, are computationally intensive, costly, or lack real-time adaptability. Many methods have also not been validated on standard IEEE bus systems, limiting their general applicability. These gaps highlight the need for an intelligent, adaptive solution capable of mitigating multiple PQ issues simultaneously in real time. To address this, a machine learning-based DSTATCOM controller is proposed, which analyzes bus voltages to generate appropriate compensator signals, providing robust, cost-effective, and dynamic mitigation across a variety of PQ disturbances in standard distribution networks (IEEE 13 and 33 bus systems). The main objectives of the proposed model PQ issues compensation is stated as follows;

- An enhanced traditional IEEE 13 and 33 bus network was developed with a DSTATCOM based on machine learning to achieve a wide range of PQ concerns.
- One of the generators is selected at the grid system which bus is considered as PCC. DSTATCOM is fixed at any place in the bus system.
- Proposed a unified control framework capable of mitigating multiple PQ disturbances such as voltage sag, swell, interruption, and harmonic distortion.
- The FFNN controller is designed based on the resulting dataset and the trained network is synchronized with the compensator.
- The designed ML controller analyses the bus voltages at every second and generate the appropriate PWM of compensator to manage load demand.

The manuscript is organized as follows: Section 2 presents recent control techniques used to improve power quality in systems employing compensators. Section 3 describes the operating principle and numerical modelling of the ML-based FFNN controller for PQ enhancement. The performance analysis and related discussions are provided in Section 4, while the conclusions of the proposed work are summarized in Section 5.

2. Proposed Methodology

Developments in digital control and power electronics have also made active control of the DG systems possible, enhancing the overall system operation and PQ at the PCC. The high utilization of power-electronics equipment and nonlinear loads at the PCC however, causes harmonic currents that may adversely affect the quality of the supplied power. A ML-based parallel DSTATCOM model is developed with the goal of reducing the aforementioned difficulties and improving PQ in a distribution system. The controlling system of DSTATCOM is done through the use of ML, because ML can handle varieties of multi-dimensional and multi-variety data. Figure 1 demonstrates the ML-based DSTATCOM model's architecture. In an IEEE bus system, voltage data of each bus is recorded and stored to analyse and prevent PQ disturbances. In addition, various PQ issues conditions are created in the system and sense the voltage of each buses to store it. Afterward, the DSTATCOM compensator is linked into the system at a parallel combination. Based on the sensed value, the ML controller is designed. The designed net model of the designed controller is fixed into the standard bus system model. In each seconds, the voltages are sensed and given to the input of the ML controller. This data is processed by the controller and a pulse-width modulation signal, which is created in order to stabilize load voltage. The compensator feeds power into the load to counter the load taking into consideration the generated pulses. It is then followed by a discussion of the mathematical model of the proposed method.

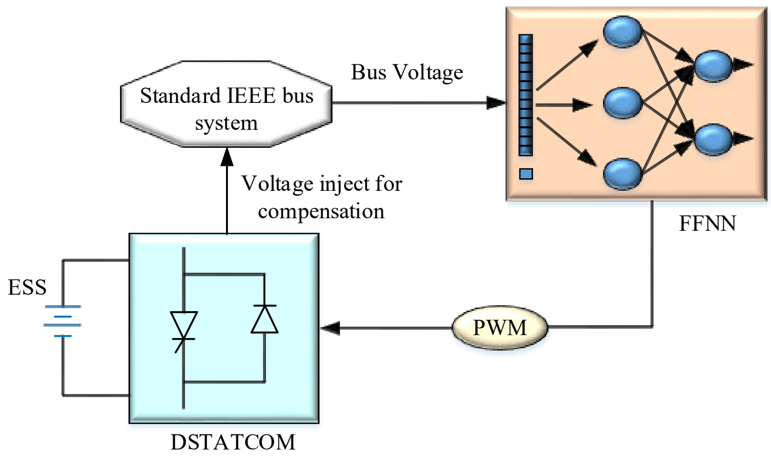


Fig. 1 *Framework of the designed ML-based DSTATCOM model*

2.1 Standard IEEE Bus System

The IEEE standards network includes a number of load points, generators, synchronous condensers, and certain components with both long and short line parameters. The network has been constructed in accordance with IEEE standards. The bus types for each test system are defined as follows: Type 1 – Slack bus, Type 2 – Generator or DG bus, and Type 3 – Load bus. The generators are enough to supply power for load activation, but during PQ issues the system voltage was collapsed to damage the consumer loads. Thus, an IEEE bus system is taken into consideration for the PQ mitigation process in the suggested model. In the system, DSTATCOM compensation is used to inject power during PQ disturbances which corrects the load power.

2.2 Design of DSTATCOM

DSTATCOM is a conservative power compensation, which employs an Insulated Gate Bipolar Transistor (IGBT) as a dependable and high-speed switching component with a pulse-width modulation (PWM) to produce or yield reactive power. The equation (1) illustrates the DSTATCOM terminal,

$$\bar{V} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}; \overline{V_{sh}} = \begin{bmatrix} V_{a\,sh} \\ V_{b\,sh} \\ V_{c\,sh} \end{bmatrix}; \overline{I_{sh}} = \begin{bmatrix} I_{sh\,a} \\ I_{sh\,b} \\ I_{sh\,c} \end{bmatrix} \tag{1}$$

where, V_{sh} and I_{sh} represents the voltage across the shunt and shunt current. The equation (2) expresses the reactive and active power exchanged over the system,

$$\begin{cases} P = \frac{V_s V_{sh}}{X_t} \sin \delta_{sh} \\ Q = \frac{V_s^2}{X_t} - \frac{V_s V_{sh}}{X_t} \cos \delta_{sh} \end{cases} \tag{2}$$

the reference compensator currents are expressed as equation (3),

$$\left.\begin{matrix} i_{fa}^* = i_{la} - \frac{v_{ta} - v_0}{\Delta} p_{lav} \\ i_{fb}^* = i_{lb} - \frac{v_{tb} - v_0}{\Delta} p_{lav} \\ i_{fc}^* = i_{lc} - \frac{v_{tc} - v_0}{\Delta} p_{lav} \end{matrix}\right\} \tag{3}$$

$$\bar{S} = \bar{V_t} * \overline{I_{sh}} = \frac{\bar{V_t}(\overline{V_{sh}^*} - \overline{V_t^*})}{-jX_t} = \frac{\bar{V_t}.\overline{V_{sh}^*} - \overline{V_t^2}}{-jX_t} \tag{4}$$

where, $\Delta = \left[\sum_{\gamma=a,b,c} v_{t\gamma}^2\right] - v_0^2$ and $v_0 = (1/3)\sum_{\gamma=a,b,c} v_{t\gamma}$, p_{lav} signifies the average load power. The power injected into the bus bar is given equation (4),

2.3 DC Link Capacitor

The DC-link capacitor, C_{dc} is a capacitor that is linked to the DC side of the voltage-source converter (VSC). The design of this capacitor depends on the capability of the VSC to control the voltage in the transient. The DC-link capacitor can be used in transient conditions to supply or demand active power depending on the transient condition. The lowest and maximum battery voltages as well as the immediate amount of energy the DSTATCOM has access to throughout transients determine this capacitor's value. To calculate the DC link capacitor use Equation (5).

$$\frac{1}{2}C_{dc}[V_{dc}^2 - V_{dc\,1}^2] = 3VIt \tag{5}$$

Where V is the phase voltage; $V_{dc\,1}$ is the lowest value of the DC bus voltage; I is the current in the phase; and t is the period it takes the DC-bus voltage to recuperate. Tracking the system's power and producing the right trigger pulses to operate the Voltage Source Converter (VSC) are essential for the efficient operation of DSTATCOM. A ML controller is created in the suggested model to govern the compensator effectiveness.

2.4 Machine Learning Controller for PWM Generation

In this section, the control system based on machine-learning which is used in the compensator is further detailed. In artificial intelligence, machine learning allows computational systems to learn (in the same manner that humans can learn) through example. A computer by virtue of layered learning can create complex ideas using simple components. Within the framework suggested, a Feed-Forward Neural Network (FFNN) based control architecture of a DSTATCOM is created with the aim to improve the quality of powers in the distribution network. The mathematical description of the proposed controller is as given in the next sub section.

2.5 Working Process of FFNN

A type of artificial neural network without looping interconnections among its nodes, known as a FFNN. The FFNN was the very first and most fundamental architecture of an artificial neural network. In this network, data can only move via concealed nodes from the input nodes to the output nodes. The overall figure of the proposed FFNN was presented in Figure 2. It shows the FFNN is made up of the following:

Input layer: The neurons of this first layer have the responsibility to accept input signals and transfer them to other layers. A comparable amount of neurons in the data entry layer ought to represent each of the parameters or characteristics in the dataset.

Hidden layer: There may be layers that are concealed among the input and output layers, based on the model. Before inputs are sent on, several neurons in buried layers are used to modify them. As the network is trained, the weights are adjusted to make them more accurate.

Neuron weights: A weight is the magnitude or strength of the link among two neurons. And if they are conversant with linear regression, compare weights on inputs such as coefficients. Often, weights begin with tiny, random values, like those between 0 and 1.

Output layer: The anticipated feature, or output layer, is contingent upon the model architecture type.

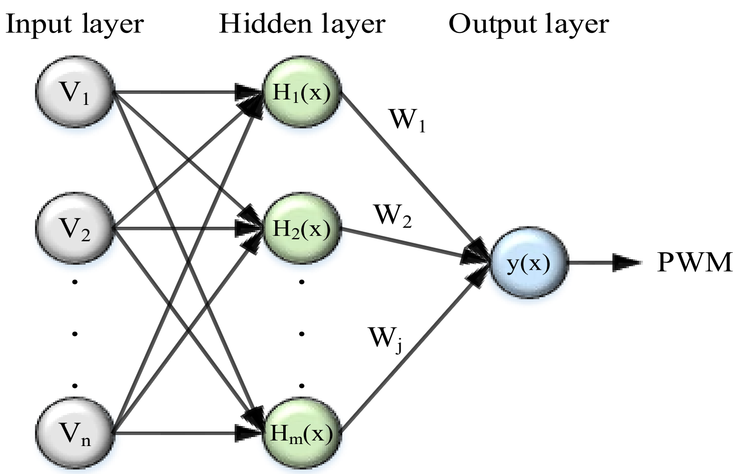


Fig. 2 *Architecture of proposed FFNN*

The training labels are M-dimensional binary vectors with the format $y_t = [y_t^1, \dots, y_t^M]$, where FFNN training labels are represented in Equation (6).

$$y_t^m \begin{cases} 1, m = m_{true}, \\ 0, m \neq m_{true}, \end{cases} m = 1, \dots, M \tag{6}$$

From equation (6), class m_{true} true as an input. A likelihood-like distribution M classes, and a t time of $\hat{y}_t = [y_t^1, \dots, y_t^M]$, is the result of the FNN is formulated in Equation (7).

$$\hat{y}_t^m = f(\sum_{i=1}^{D} w^{i,m} x^i) = f(w^{mT} x_t), m = 1, \dots, M \tag{7}$$

Where w^m a vector of weights and f (.) is any function and w^m a weight vector. Through reducing a cost function J, $t = 1, \dots, T$ specifies the input data, weights $w^m m = 1, \dots, M$, assessed by inversion and reducing a cost function, J, over $t = 1, \dots, T$ input samples. The optimal FFNN weights are obtained by minimizing the cost function in Equation (8).

$$\widehat{\mathrm{w}}^m = \arg_{\mathrm{w}^m} \min \left\{ -\sum_{t=1}^{T} \left(\mathrm{J}\left(y_t, \hat{y}_t(w^m, x_t)\right) \right) \right\} \tag{8}$$

The FFNN at a single weight set, w^m, and using a linear activation function $f(z)$, (e.g., $f(z) = z$) is a linear regression. The linear activation-based FFNN output is expressed in Equation (9).

$$\hat{y}_t = \mathrm{w}^{mT} \mathrm{x}_t, m = 1, \dots, M \tag{9}$$

The cost function of the FFNN is represented in Equation (10),

$$\mathrm{J}\left(y_t, \hat{y}_t(x_t)\right) = y_t^T \hat{y}_t(\mathrm{w}^m, \mathrm{x}_t) \tag{10}$$

Putting a weight matrix constraint in place, $\mathrm{W}^M = [\mathrm{w}^1, \dots, \mathrm{w}^M]^T$, a solution at mth Weight class is shown in equation (11),

$$\widehat{\mathrm{w}}^m = \arg_{\mathrm{w}^m} \min \left\{ -\sum_{t=1}^{T} \mathrm{w}^{mT} \mathrm{x}_t + \frac{\mu}{M} \|W^M\|_F^2 \right\} \tag{11}$$

Assuming that an FNN can be trained using one sample per class so that m relates to t, $m \mathrel{\widehat{=}} t$ and $\mathrm{w}^m = \mathrm{w}^t$. Making distinctions based on the mth weight,

$$\frac{\partial}{\partial \mathrm{w}^m} \left(-\sum_{t=1}^{T} \mathrm{w}^{t\mathrm{T}} \mathrm{x}_t + \|\mathrm{W}^T\|_F^2 \right) = -\mathrm{x}_m + \frac{2\mu}{M} \mathrm{w}^m, \widehat{\mathrm{w}}^m = \frac{M}{2\mu} \mathrm{x}_m, \tag{12}$$

Where regularization is controlled by μ. Therefore, $\mathrm{x}_t = \mathrm{x}_m$, which provides the optimum FFNN weights in each equation (12).

3. Result and Discussion

The DSTATCOM model created with FFNN is supposed to improve the performance of PQ in an IEEE bus system. The proposed model is simulated in MATLAB/Simulink 2021b and tested in terms of performance. The ensuing sections contain an analysis of each situation separately as well as the observed values under various settings such as swell, interruption, sag and THD. The parameters used for the proposed and present controller design is presented in Table 1.

Table 1 *Simulation parameters of proposed*

Parameter	Method	Ranges
Epoch	FFNN	100
Gradient		6.8e-05
μ		1e-07
Training algorithm		Levenberg-Marquardt

Table 2 *Test system modelling parameters of IEEE 13-bus and IEEE 33-bus distribution systems*

Component	Parameter	IEEE 13-Bus	IEEE 33-Bus
Generator (Bus)	Slack bus voltage	1.0 p.u.	1.0 p.u.
	Frequency	50 Hz	50 Hz
	Base power	5 MVA	10 MVA
Transmission Line / Transformer (Branch)	Line resistance (R)	0.05 p.u.	0.0575 p.u.
	Line reactance (X)	0.11 p.u.	0.029 p.u.
	Transformer rating	4.16/0.48 kV	12.66/0.4 kV
Load (Bus)	Load power factor	0.92 lagging	0.95 lagging
	Total load demand	3.5 MVA	3.72 MVA
	Load type	Constant PQ / ZIP mix	Constant PQ load

3.1 Dataset Generation

The datasets creation is the initial stage of the proposed model that is a strategic procedure to mitigating power quality successfully. An IEEE representative bus system is modeled with a DSTATCOM and voltage at each bus is measured at the nominal operating conditions with no parameter adjustments, providing baseline data. Flaws are then created to create voltage sags and similar swell and interruption conditions are then simulated to record the relevant data. Any datasets obtained will be placed in an Excel sheet with the proper labeling used to be used in future. The FFNN controller employs the real-time data in order to design it so that it produces the IGBT pulse signals to the DSTATCOM. The offered controller constantly keeps track of the bus-system voltage per second and sends the device the necessary switching impulses. In this way, each bus systems dataset are created and analysed the PQ mitigation performance of the proposed controller.

3.2 Efficiency of Power-Quality Mitigation in IEEE 13 Bus System

For this case, an IEEE 13-bus system is employed and proposed FFNN-based controller leads to the installation of the DSTATCOM, which is estimated under sag, swell, and interruption conditions. Also THD is tested prior to and following compensation. The IEEE 13-bus test feeder is used to conduct simulations to determine how the DSTATCOM impacts PQ problems in distribution networks. The feeder consists of one generation unit, a three-unit voltage regulator (wye-aligned) with a primary 115/4.16kV (D) transformer, an in-line Y-transformer (4.16/0.480kV), two shunt capacitor banks and two imbalanced hotspot and distributed loads. The ten lines of buses connecting thirteen buses consist of overhead and underground lines with different phasing arrangements [27]. The evaluation of THD voltage sag, swell, interruptions are carried out using this network as explained in the next section. The proposed system Simulink model (Figure 3) is connected by connecting the STATCOM compensator to bus 6 and a fault to bus 4.

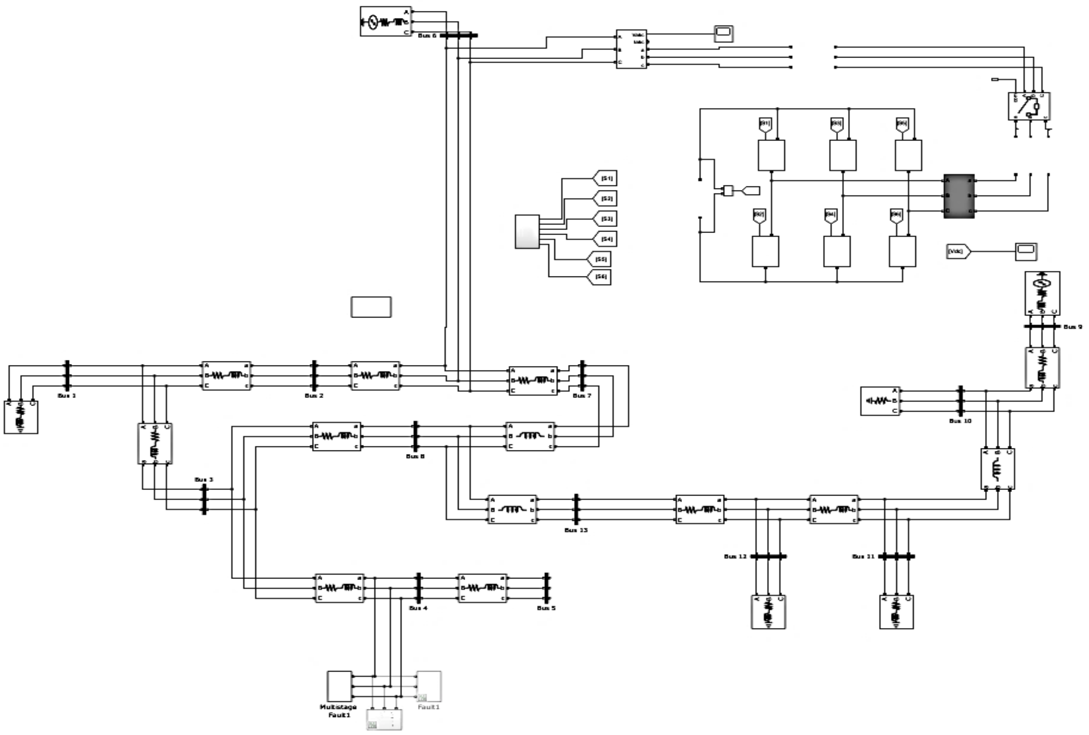
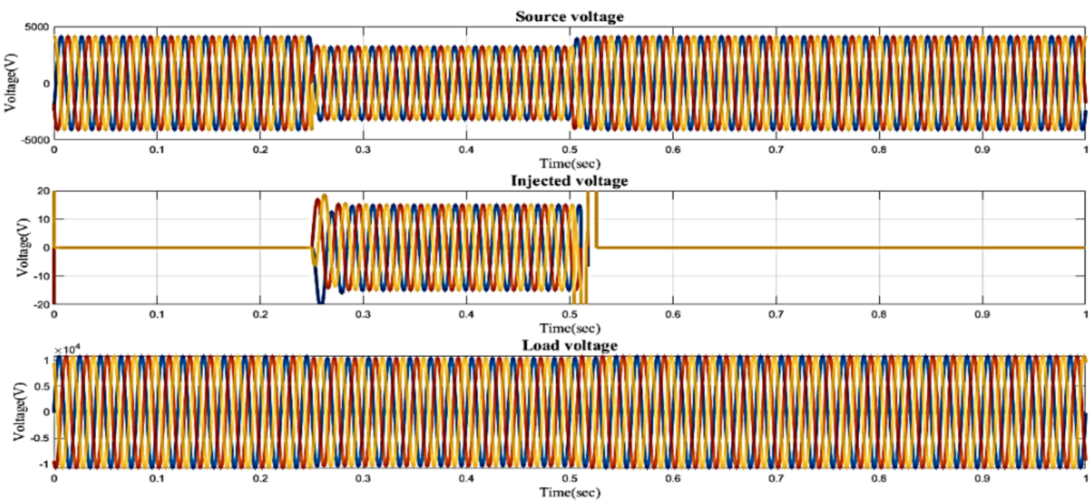


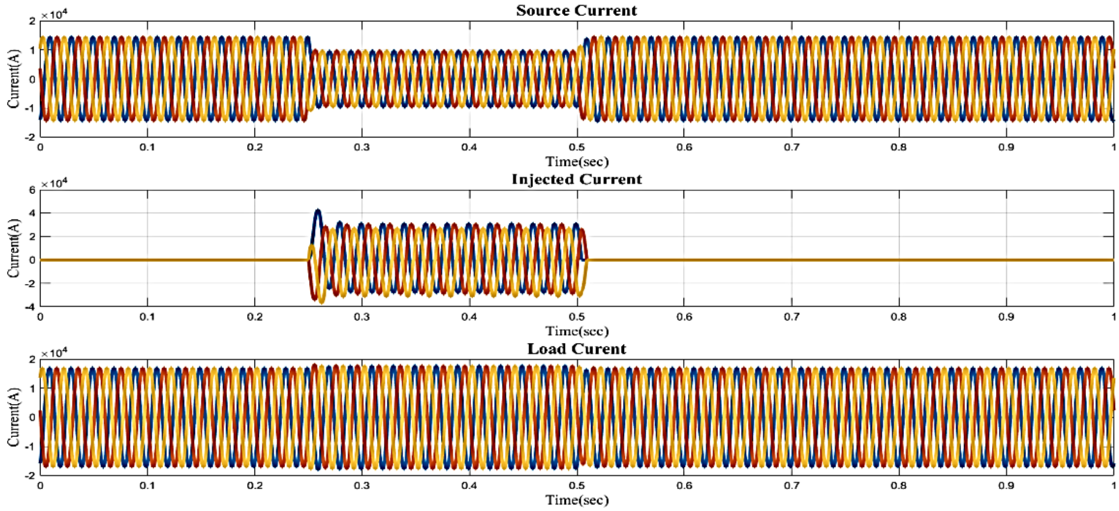
Fig. 3 *Simulink design of proposed controller (IEEE 13 bus)*

3.2.1 Sag Issues

The waveforms reduce temporarily at this period leading to the dip of the voltage to 10% of the nominal value. The voltages at both buses are inputted into the proposed controller and 39 attributes in each bus voltage are evaluated and appropriate DSTATCOM switching pulses produced. At bus 4, the sag fault is added, resulting in a short-term reduction of voltage. The sag fault causes power to be injected into the load by the compensator to recover the voltage of the load. Figure 4 shows the voltage waveforms of the proposed model during the sag event, which happens between 0.25 and 0.5s. The DSTATCOM at this time injects voltage to maintain constant power flow by correcting the dip. In addition, the THD across the load side is analyzed and shown in Figure 5. The THD measures the distortion of a signal by measuring the energy of the harmonic components. The findings show that THD load-side voltage and current after compensation are 2.93% and 0.06% respectively. The reactive and real power of STATCOM is analysed and plotted in Figure 6. It demonstrates the reactive power of the compensator is 0.1*105 kVAr and the real power of the compensator is 6.5*105 W.

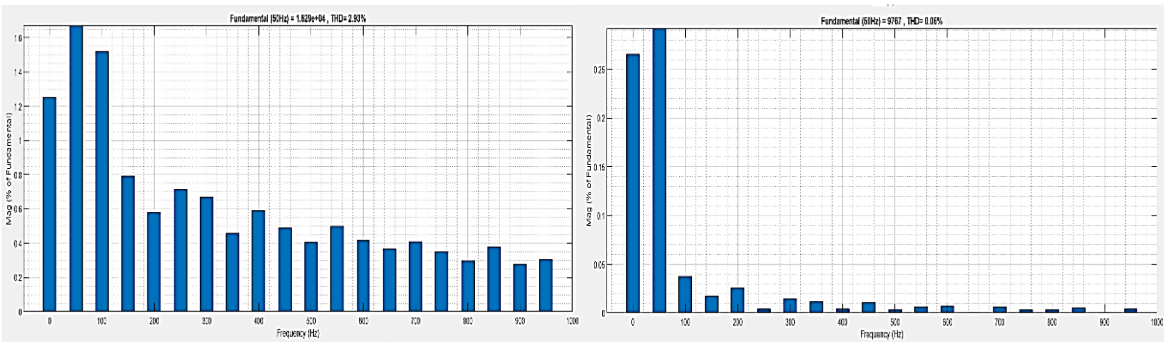


(a)



(b)

Fig. 4 *Evaluation of sag condition with (a) Voltage; and (b) Current waveforms*



(a) **(b)**

Fig. 5 *Evaluation of THD after sag compensation with Load for (a) Voltage; (b) Current*

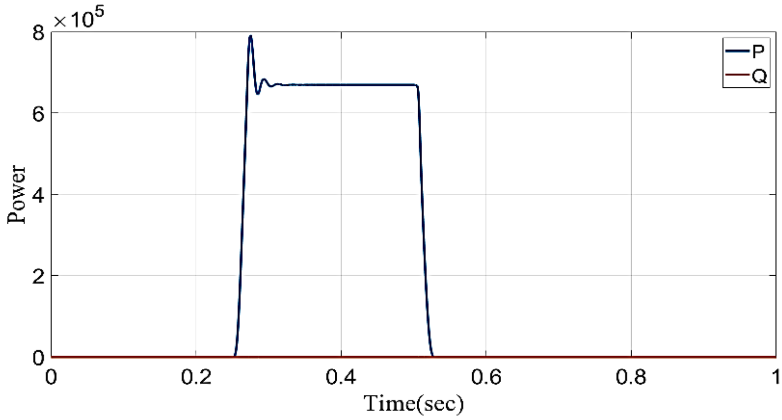
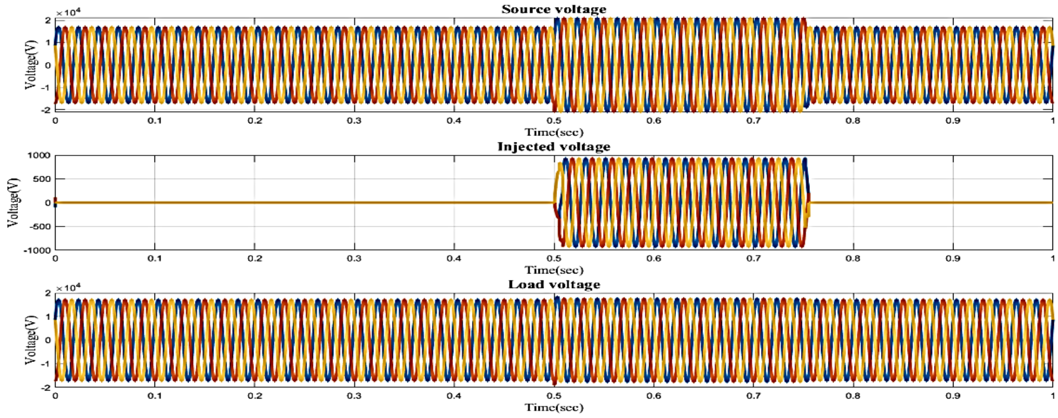


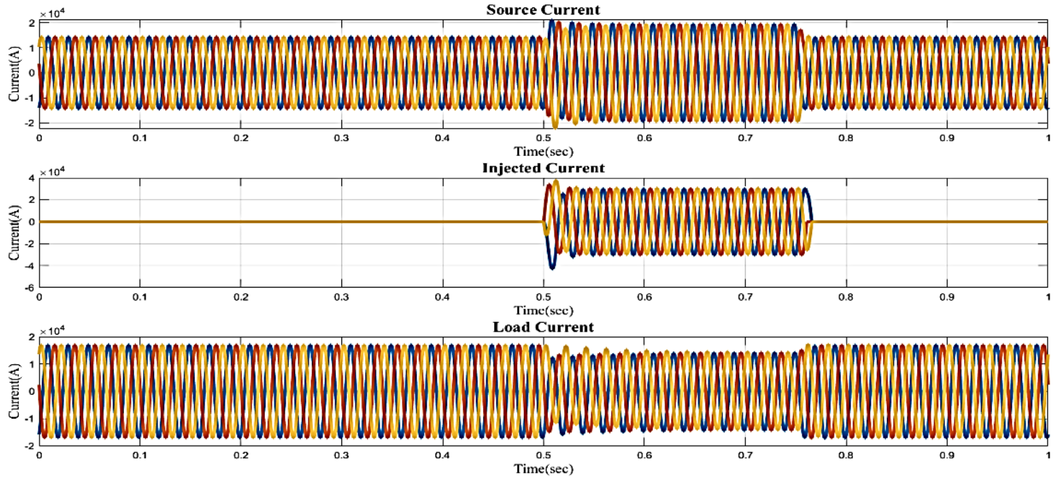
Fig. 6 *Evaluation of real and reactive power of STATCOM at sag issues*

3.2.2 Swell Issues

After the sag compensation, the system is tested on swell fault in order to check performance. At this occurrence, the voltage escalates to 10 percent higher than the nominal value. Each seconds the bus voltages are fed to the proposed controller that analyse and generates the pulse signal.



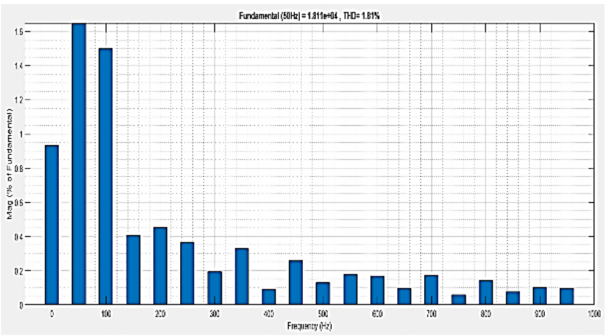
(a)



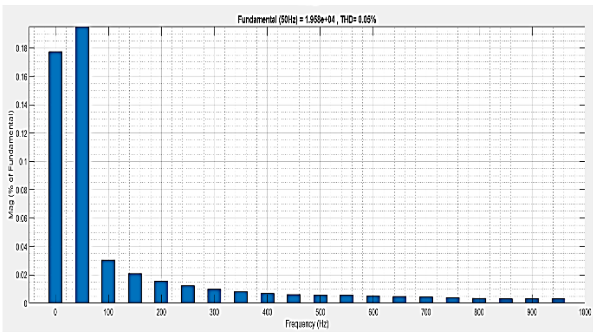
(b)

Fig. 7 *Evaluation of (a) Voltage; (b) Current waveforms at swell period*

The voltage and current waveforms at the source, injected and load-side during a swell event are analysed and represented in Figure 7 (a) and (b). The waveforms also means that the swell is within the range of 0.5 to 0.75s, and at this point the voltage is greater than the nominal one. The injected voltage shows that DSTATCOM balances during this phase and keeps the load voltage constant to guarantee constant power flow. The resulting values of THD are indicated in Figure 8. The THD cannot be compensated to equal the IEEE standard limits, but when THD is compensated, load-side voltages THD is 1.81% and current THD is 0.05%.



(a)



(b)

Fig. 8 *Evaluation of load (a) Voltage; (b) Current THD after swell compensation*

Reactive and real power of the compensator at the swell is analysed and sketched in Figure 8. The analysis shows the real power of the STATCOM injected period is 7*105 W, and the reactive period is 0.01*105 kVAr. The real and reactive power of compensator at swell issue are shown in Fig. 9.

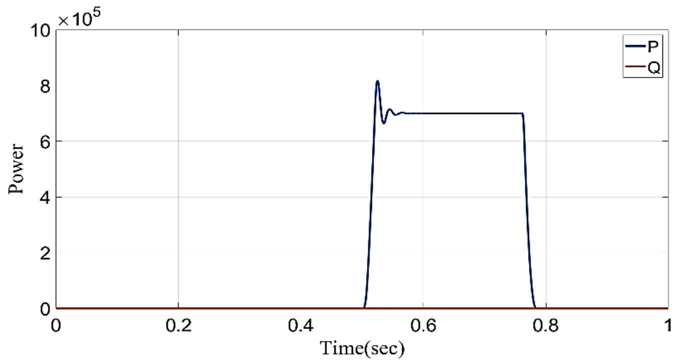
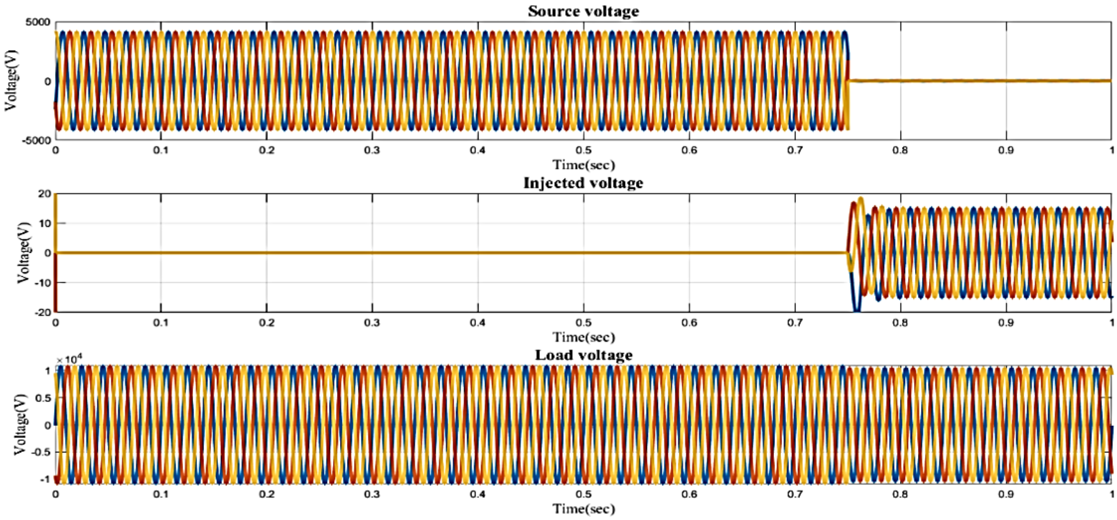


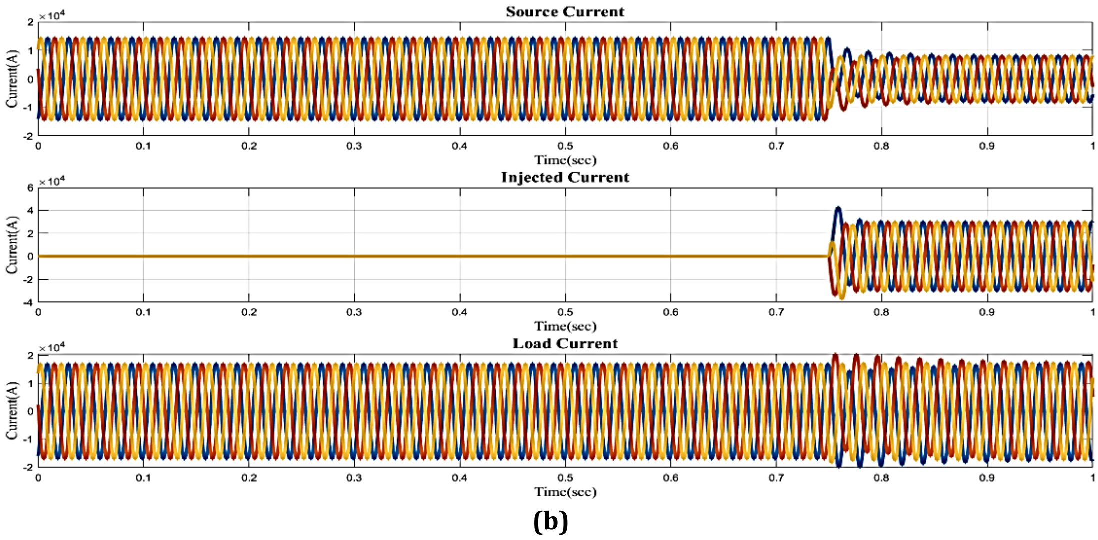
Fig. 9 *Real and reactive power of compensator at swell issue condition*

3.2.3 Interruption Issues

The compensation for interruption issues is analysed and the performance is observed. Interruption is arise by applying a fault in the bus no. 4. At this stage, the voltage is decreased to 0.1 per unit over a short period of time, which was less than one minute. The mitigation process of interruption using the proposed controller is provided in Figure 10.



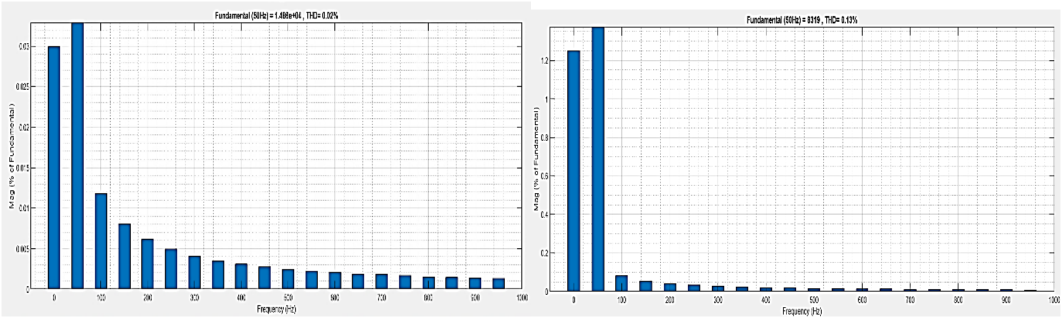
(a)



(b)

Fig. 10 *Analysis of (a) Voltage; (b) Current waveforms at interruption period*

When an interruption event occurs, the voltage does not only drop to 0.1 per unit in a one-second interval, it also generates considerable load-side disturbances. The proposed controller levels bus voltage by presenting the required pulse signals to compensator hence keeping load voltage constant. Figure 10 demonstrates the interruption strategy, which explains the affected source voltage due to the interruption fault at the period of 0.75 sec to 1 sec. At that period the proposed controller inject the voltage, so the load voltage is not much affected about the interruption.



(a) **(b)**

Fig. 11 *Analysis of load (a) Voltage; (b) Current THD after interruption compensation*

Finally, the proposed model THD value of the load side is analysed and shown in Figure 11. The interruption cause a reduction of nominal voltage for a few seconds. After compensating for the interruption using the proposed controller, the THD value also reduces to 0.02% for voltage and 0.13% for current. The observed data demonstrate that the suggested approach yields superior results in every circumstance.

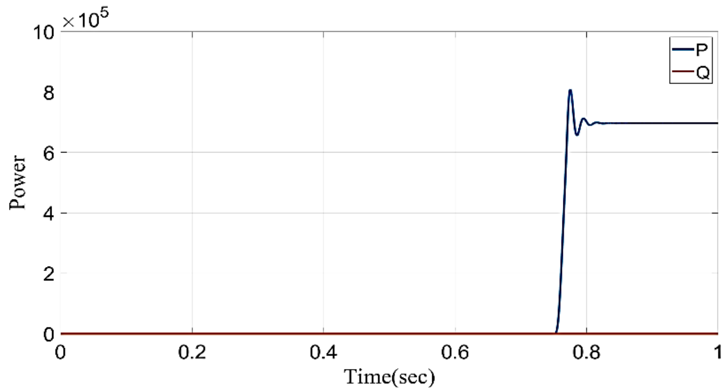


Fig. 12 *Analysis of real and reactive power at the interruption period*

During the interruption period, the reactive and active power of STATCOM is analysed and provided in Figure 12. The real power of the compensator is 7*105 W and the reactive power of the compensator is 0.01*105 kVAr.

3.2.4 Performance Analysis of the Proposed Controller

The efficiency of the proposed controller is checked by comparing its performance measures with the measures of some of the alternative methods. The proposed FFNN controller is compared to NB and KNN. At first, the proposed model's confusion matrix was analysed and plotted in Figure 13. In the matrix, classes 0, 1, 2 and 3 are used to designate normal, sag and swell faults, and interruption faults, respectively. The suggested model successfully forecasts which class will be best for choosing a pulse generation. The comparison of proposed and traditional methods metrics are indicated in Table 3.

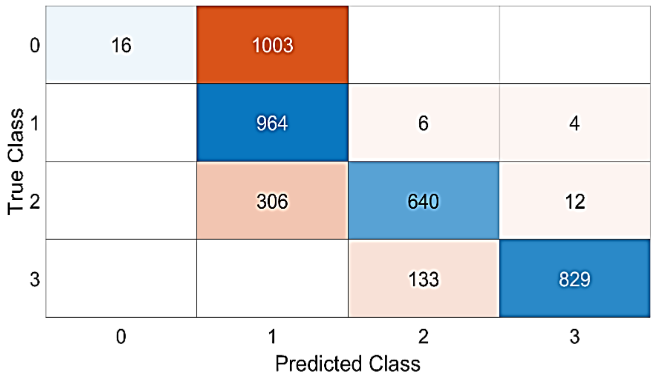


Fig. 13 *Confusion matrix of proposed FFNN at IEEE 13 bus system*

Table 3 *Proposed and existing approach performance metrics analysis*

Metrics	Proposed FFNN	NB	KNN
Accuracy (%)	94	79	69.5
Error (%)	6	21	35
F1_score (%)	94	78.5	69.9
False positive rate (%)	1.5	7	11
Kappa (%)	88	43	18
MCC (%)	94	71	61
Precision (%)	95	79	75
Sensitivity (%)	95	79	69
Specificity (%)	98	93	90

4. Conclusion

A machine-learning-controlled DSTATCOM controller was designed in this paper to test its effectiveness in typical IEEE bus environments with a variety of power quality (PQ) disturbances. Poor PQ does not only interfere with the operation of mechanical and electrical equipments but also increases the electricity expenses and has negative impacts on the wider economy. The DSTATCOM is known to be able to overcome these issues due to its inherent flexibility, simplicity in its implementation, and ability to handle dynamic loads. A conventional bus system that uses the DSTATCOM model was created first to get the nominal voltage profile of each branch. This was followed by recording of voltage measurements under different PQ disturbances in order to develop an extensive dataset. Based on this dataset, a machine-learning-based controller was designed, and it could observe bus voltage every one second and produce corresponding pulse signals to the compensator. Such pulses are then injected into the DSTATCOM to inject voltage, and harmonics are reduced, and power quality issues are eliminated. The proposed controller-based DSTATCOM has proved to be effective on the IEEE 33-bus system and IEEE 13-bus system. To assess its efficiency, the obtained data were compared to a number of modern strategies. In the IEEE 13 -bus system, the values of THD were 2.93%, 1.81%, and 0.02 % of sag, swell, and interruption conditions respectively, with a value of accuracy of 94, a false-positive rate of 1.5% and sensitivity of 95%. Future work can focus on developing deep learning or hybrid AI-based controllers to further improve compensation performance under dynamic operating conditions. In addition, integration with renewable energy-based smart grid systems can be explored for practical applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper equally.

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