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# Analysis, monitoring, and mitigation of power quality disturbances in a distributed generation system

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Despite the numerous benefits of distributed generation (DG), such as reliable energy supply and environmental friendliness, there are a number of challenges associated with integrating DG with the grid. In the field of DG, the complication of power quality (PQ) is a major technical challenge. Custom power devices (CPDs) are used in the distribution system to solve complications. This study presents different PQ disturbances (PQDs), monitoring techniques, and fundamental standards. Furthermore, with the widespread literature, the study critically reviews different PQ mitigation techniques such as distribution static compensator (DSTATCOM), dynamic voltage restorer (DVR), unified power quality conditioner (UPQC), and uninterruptible power supply (UPS). The present research work is not only limited to surveying the existing techniques but also analyzing the performance of UPQC using the ANFIS controller. Overall, this study is intended to provide researchers working on improving PQ in the distribution system with a valuable resource that will aid them in enriching their research.

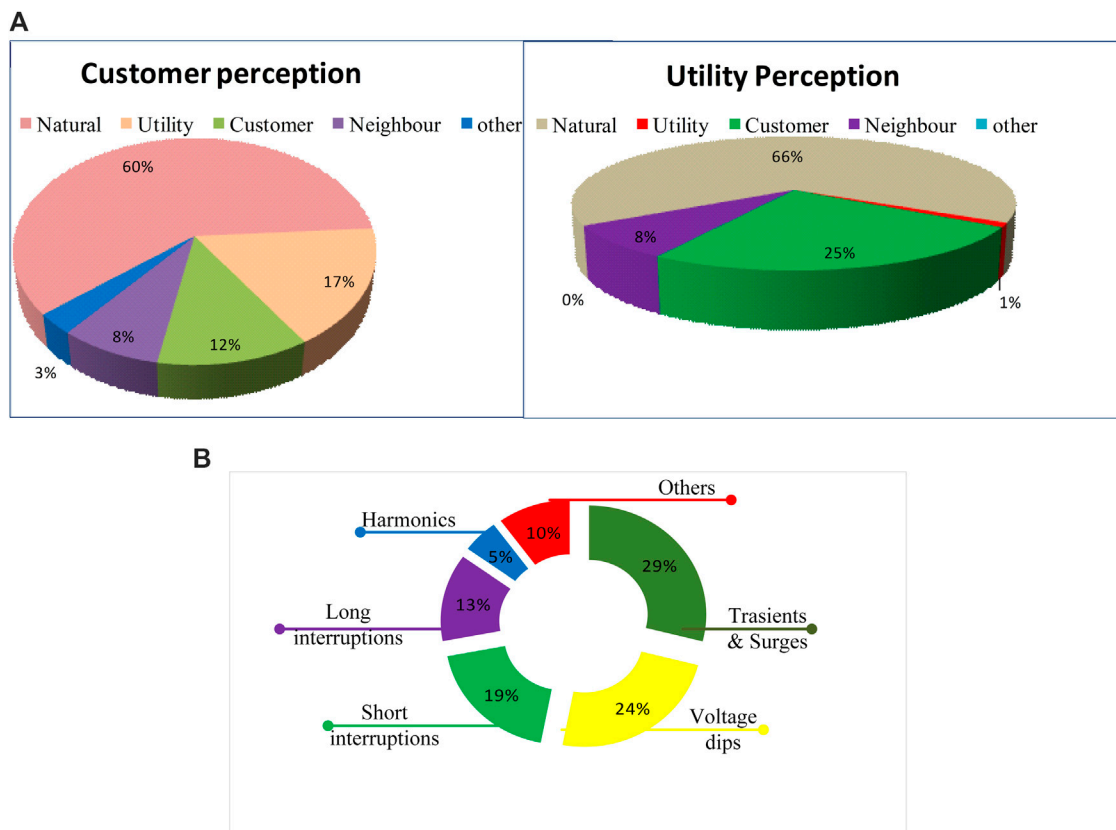
## KEYWORDS

power quality, distributed generation, custom power devices, unified power quality conditioner, ANFIS

## 1 Introduction

### 1.1 Background and motivation

Conventional electricity generation plants, such as coal-fired, nuclear, and hydroelectric power plants, experience various problems, including scarcity of fossil fuels, significant greenhouse gas emissions, and transmission line power loss. Distributed generation has the potential to address these issues while also assisting in meeting the ever-increasing load demand (Pepermans et al., 2005). Uncertainty is a significant issue with distributed energy resources (DER), causing a number of problems in the distribution systems. 1) It exacerbates the strain on the transmission network. 2) It establishes complicated supply–demand relationships. 3) This could result in the reversal of power flow from the distribution system to the transmission system (De Carne et al., 2018; Zhang et al., 2020).



**FIGURE 1** (A) Results of a survey on the causes of PQ problems conducted by Georgia Power company. (B) Major PQ issues study conducted by GreenTree Global team.

Distributed generation (DG) or shunt reactive compensators are common compensatory methods (SRCs). Four types of DG units exist: Type 1, which involves injecting only active power into the network, such as PV and fuel cells; Type 2, which offers just reactive power, such as no-load synchronous motors; Type 3, which produces both active and reactive power, such as a synchronous generator or microturbine, and Type 4, which provides active power but consumes reactive power, such as an induction generator-based wind energy system. SRCs inject reactive power into distribution networks. SRCs are shunt capacitor banks, static VAR compensators, or distribution static compensators (DSTATCOM). The DSTATCOM is the most costly and sophisticatedly regulated device utilized in higher power applications. Size, cost, and control place the static VAR compensator (SVC) between the shunt capacitor (SC) and DSTATCOM.

The term “power quality” refers to an electric power system ability to maintain the rated amplitude and frequency of noise-free sinusoidal voltage and current. The

primary sources of PQ issues are switching operations, faults, and lightning on the utility side, whereas nonlinear loads, inadequate grounding, electromagnetic interference, and static electricity on the end-user side present a variety of technical challenges. Power quality is a significant issue that affects almost all industrial, commercial, and residential customers. Figure 1 shows the results of a survey on the causes of PQ problems conducted by Georgia Power Company from the perspective of utility and customers (Bhadane et al., 2012). Various PQ issues that the grid encounters include voltage sags, swells, harmonics, load shedding, and so on. Some PQ issues have a detrimental effect on the protection system, resulting in malfunctioning protective devices. These factors also have an effect on the various measurement instruments and monitoring systems.

Voltage disturbances are a significant PQ issue that requires regulation. Regulation of voltage is dependent on the generator excitation system and reactive power compensation (Muljadi and McKenna, 2001). CPDs are primarily used in DS to reduce PQDs

and improve PQ (Ghosh and Ledwich, 2002). Figure 1B illustrates a market research and an analysis study conducted by the GreenTree Global team on major issues affecting PQ, market sizing, and trends for 2018–21 (Power Quality Monitoring: Market Landscape Assessment, 2022). According to this, over 50% of the causes of PQ degradation are voltage dips, transients, and spikes.

## 1.2 Literature review

Since the early 1990s, researchers have integrated DG or SRC units into distribution networks for various purposes. These objectives were to reduce power loss by mitigating line currents, maximizing voltage stability, and improving power quality. The researchers used several methodologies and methods to allocate DG or SRC units in distribution systems. Reactive power injection reduces source's reactive current and the feeder current. Power loss and voltage profile improve. The shunt capacitor is the simplest device to inject reactive power. Shunt capacitor (SC) core issues are fixed reactive power and bus voltage dependence.

In the conventional distribution system, power filters (PFs) have been used to mitigate PQDs. Passive power filters (PPFs) are used to reduce harmonics in traditional power systems due to their low cost and simplicity. However, PPFs are extremely sensitive to parallel resonance due to the capacitors low rating (Kashif et al., 2020). However, disadvantages such as large size, fixed compensation, and susceptibility to resonance can be avoided by utilizing equipment referred to as an active power filter (APF). Additionally, APFs filter out both higher- and lower-order harmonics (He et al., 2017). Shunt APFs and series APFs are two forms of APFs. Both the series and shunt APFs are designed to lower total harmonic distortion (THD) in the voltage and current, respectively. The UPQC is a hybrid of series and shunt APFs that is designed to simultaneously suppress multiple PQ problems (Nabavi-Niaki and Iravani, 1996; El-Habrouk et al., 2000). An UPS can also be used to mitigate PQ problems. It provides emergency power to critical loads in the event of a power outage. Generally, UPSs are used to safeguard hardware such as computers, telecommunications, and data center equipment (Yeh and Manjrekar, 2007; Aamir et al., 2016). Any power electronics-based system relies heavily on its control strategy. The control strategy of a system determines its behavior and desired operation. The control approach validates the reference current and voltage signals and, thus, elects the converter switching moments to achieve the desired performance. The term “flexible alternating current transmission system” (FACTS) is a commonly used term in AC transmission. One or many system parameters can be adjusted to enhance the systems controllability while simultaneously increasing system's capacity for power transmission (Edris et al., 1997). The STATCOM is a member of the FACTS family that provides

reactive power at low voltages, improving the voltage profile. Additionally, due to the DC capacitor, it has a very low active power capability. Moreover, it has a faster switching time than a static VAR compensator (SVC) because of the IGBTs used in voltage source converter (VSC)-based STATCOM (Singh et al., 2009; Al-Nimma et al., 2011). Agarwal et al. (2017) developed a leaky least mean fourth (LLMF) control method for a three-phase single-stage grid integrated solar photovoltaic distributed static compensator (SPV-DSTATCOM). For the extraction of fundamental active and reactive loss components and load currents, feed-forward SPV power, extraction of in-phase, and quadrature unit templates are used to produce the grid's reference currents. To determine the terminal voltage amplitude, the LLMF method is necessary.

## 1.3 Contributions

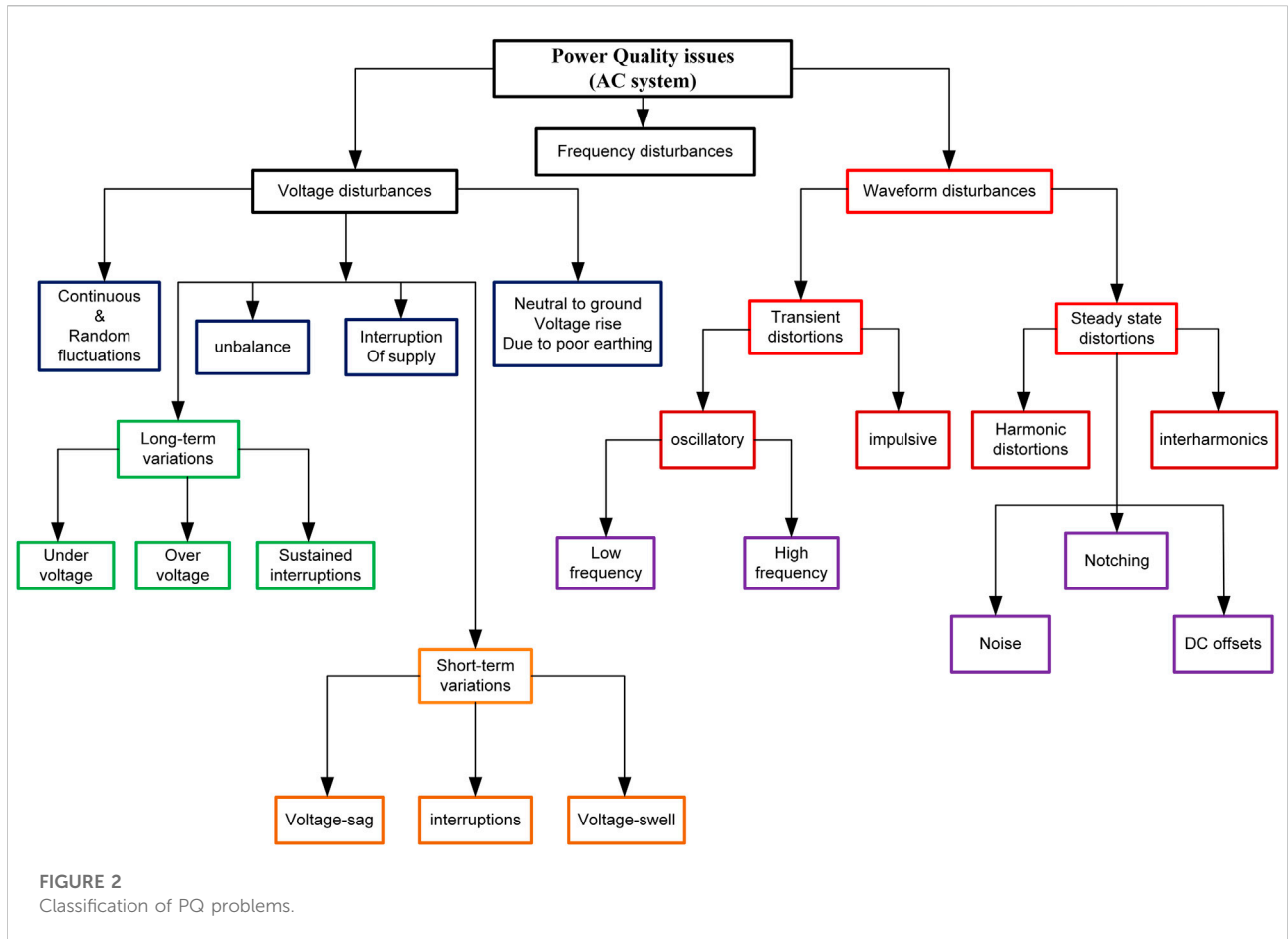
The primary purpose of the study is to give a comprehensive analysis of power quality problems and provide possible solutions to these problems. This study covers a detailed examination of the power quality in power systems, including those with DC and renewable sources, and the standards that describe these concerns. The analysis was carried out by the authors of this study. Methods for evaluating the power quality and possible improvements to the power quality of power systems are both being thoroughly researched. In summary, a comprehensive analysis of power quality problems together with their monitoring, mitigation, and control techniques of CPDs as a whole is presented in a single body of work.

## 1.4 Article organizations

This article focuses mostly on power quality disturbances. The following sections discuss various PQ issues that can occur in both alternating current (AC) and direct current (DC) systems. Section 2 discusses PQ monitoring systems and various PQ mitigation techniques (such as DSTATCOM, DVR, UPQC, and UPS), and the review on various controllers of CPDs are presented. PQ standards such as IEEE and IEC are presented in Section 3. A proposed PQ improvement technique has been described in Section 4. Section 5 contains overall review on PQ mitigation techniques, and Section 6 provides the conclusion.

## 1.5 Typical PQ issues

Various PQ issues that occur in the AC system are classified according to the IEEE 1159 standard and illustrated in Figure 2 using a tree diagram.



### 1.6 PQ issues in AC systems

To highlight the impact of PQDs, we might state that poor PQ results in significant energy and economic waste. It burdens both suppliers and consumers financially. Voltage and frequency fluctuations frequently disrupt the flow of electricity through transmission lines. “Voltage fluctuation” denotes variations in voltage amplitude. A transient is a short-lived energy surge (Rönnberg and Bollen, 2016). It is usually caused by a sudden change of state, such as surges. Voltage, current, or both may undergo an abrupt shift in their steady-state conditions. Voltage sag refers to the decrease in magnitude of the supplied voltage (Styvaktakis et al., 2000). The voltage swell phenomenon refers to a transient rise in voltage that exceeds standard tolerance thresholds. It normally lasts less than a few seconds and has duration of more than one cycle (Ma et al., 2021). Harmonics are voltage or current waveform distortions generated by nonlinear loads. “Long time voltage interruption” is another significant PQD (Sarangi, 2020). This issue refers to the interruption or reduction of the voltage or load current for durations

ranging from a few milliseconds to 1 or 2 s (Ma et al., 2021). This type of issue causes data processing devices to malfunction. Distortion of the waveform is a steady-state variation from an ideal sine wave of power frequency. DC offset harmonics, interharmonics, notching, and noise are the most common kinds of waveform distortion (Gupta et al., 2021). “Frequency variation” is the deviation of the fundamental frequency of a power system from its nominal value (50 Hz or 60 Hz). Figure 3 illustrates the major PQ disturbances with waveforms, and the summary of power quality disturbances in AC systems is depicted in Table 1.

### 1.7 PQ issues in DC systems

Power quality challenges in DC systems are distinct from AC PQ issues. A power converter is the main component of a DC system. Because PE converters switch, they introduce voltage and current harmonics into the system. There are four types of PQDs in a DC system: fault current, inrush current, harmonic current, and grounding.

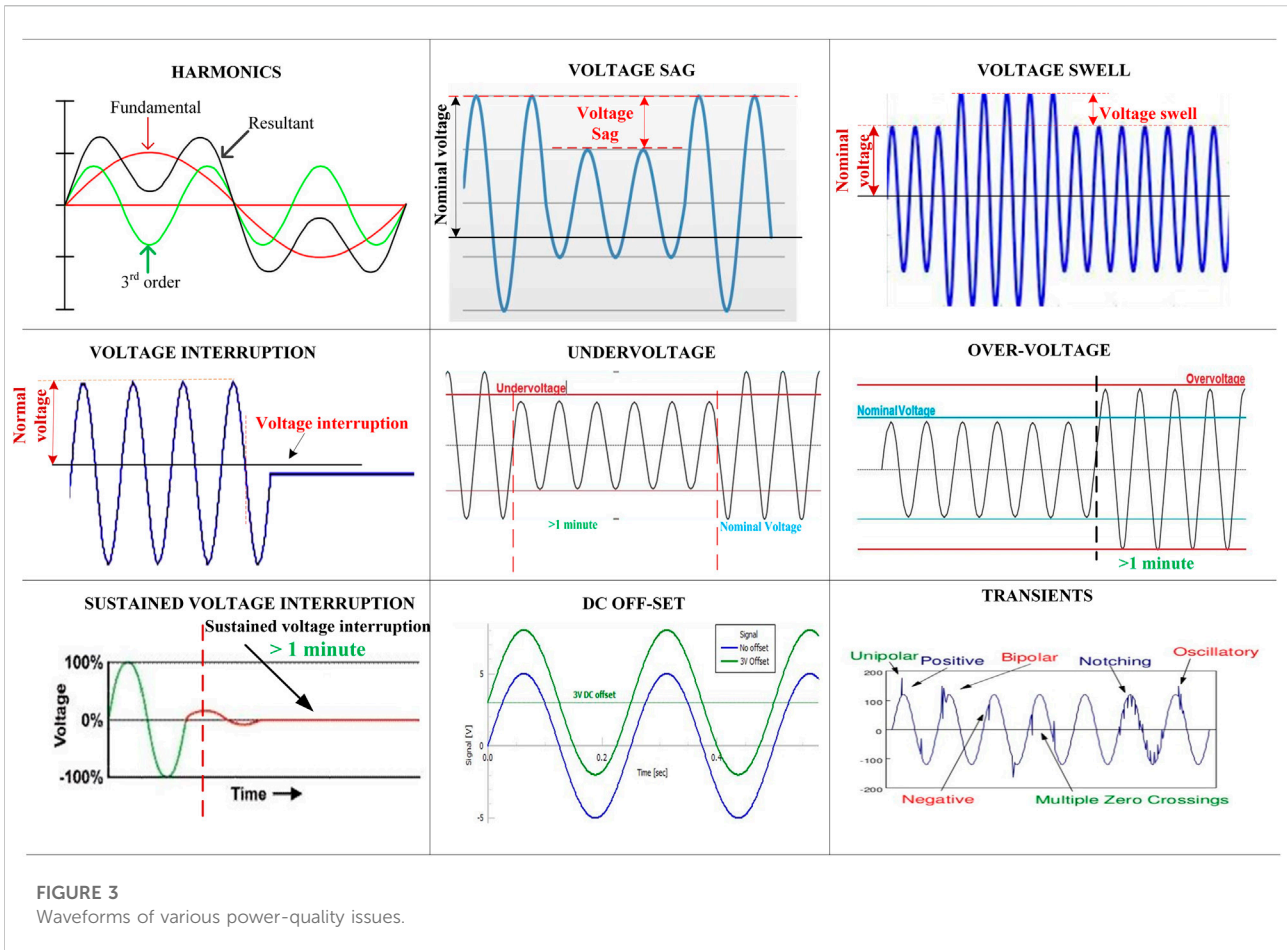


FIGURE 3 Waveforms of various power-quality issues.

### 1.7.1 Inrush current

When a power source is turned on, it draws a large initial current. This is an “inrush current.” In a DC system, inrush currents are associated with the initiation of an IM or transformer. By contrast, PE converters connect the DC link to the load (Hoshi et al., 2012). The waveform of an inrush current is shown in Figure 4A with an electromagnetic interference (EMI) filter. The EMI filter will use capacitance C1 across the input line. The DC–DC converter will have capacitance C2 and C3 on both sides. Auxiliary capacitance C4 could be used across the load. Each of these capacitors needs current to maintain its stable voltage at SS. A surge current occurs when the input supply is turned on. This peak current fully charges C1 and C2. The second crest current occurs when the DC–DC converter is turned on, charging C3 and C4 to SS values (Asakimori et al., 2014). High inrush currents can cause system voltage sags, affecting other devices. Transitive

### 1.7.2 Fault current

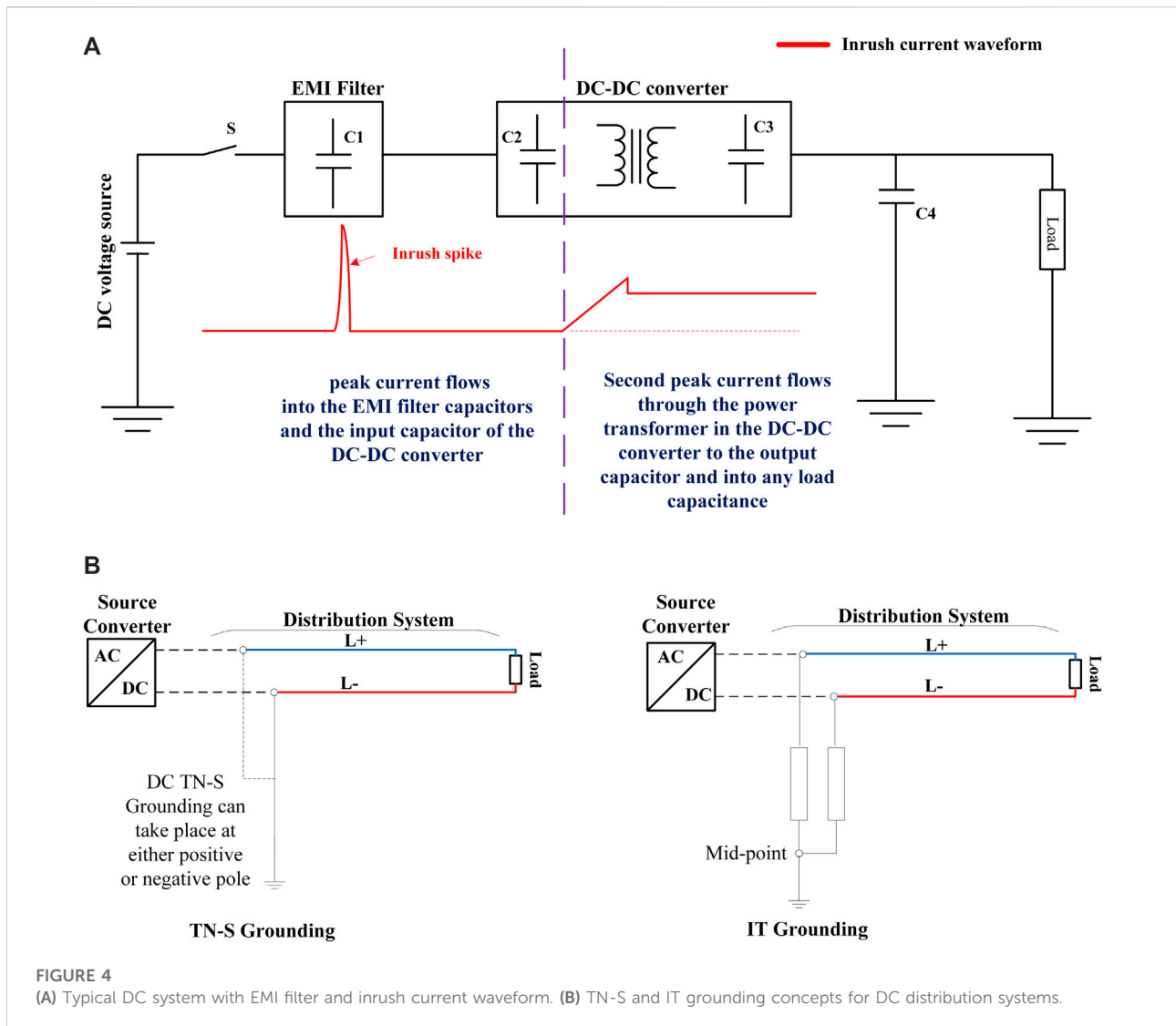
Faults in an AC system usually do not affect voltages due to impedance. However, DC system faults affect voltage and

must pass through DC bus converters or power supplies, limiting fault current (Kwasinski and Onwuchekwa, 2011). Limiting faults reduce system stress by avoiding a transient voltage spike, whereas reducing available fault current increases network voltage disturbance (He and Li, 2011). Overcurrent relays are often employed to protect devices. Low fault current makes protection settings difficult to find. This increases inrush current, which must be decreased by soft-starting or charging in advance (Giancaterino, 1994).

### 1.7.3 Harmonic current

As stated previously, systems have no harmonic currents or voltages in DC circuits. Except for the fundamental frequencies, a DC system has many frequencies that are integer multiples of 0 Hz. However, the presence of oscillations (current, voltage, or both) in a DC system necessitates the generalization of harmonic analysis to DC systems (Zhang et al., 2000). There are filters to decrease harmonics and voltage oscillations in DC systems. Filters should be used in HVDC system design to reduce harmonic





and circulating currents (Bierhoff and Fuchs, 2008). Resonant damage is also a problem in low-DC-voltage systems. Low-DC-voltage systems can have undesirable resonant currents, EMI, and voltage variations; hence, a thorough harmonic analysis is required (Liang et al., 2021).

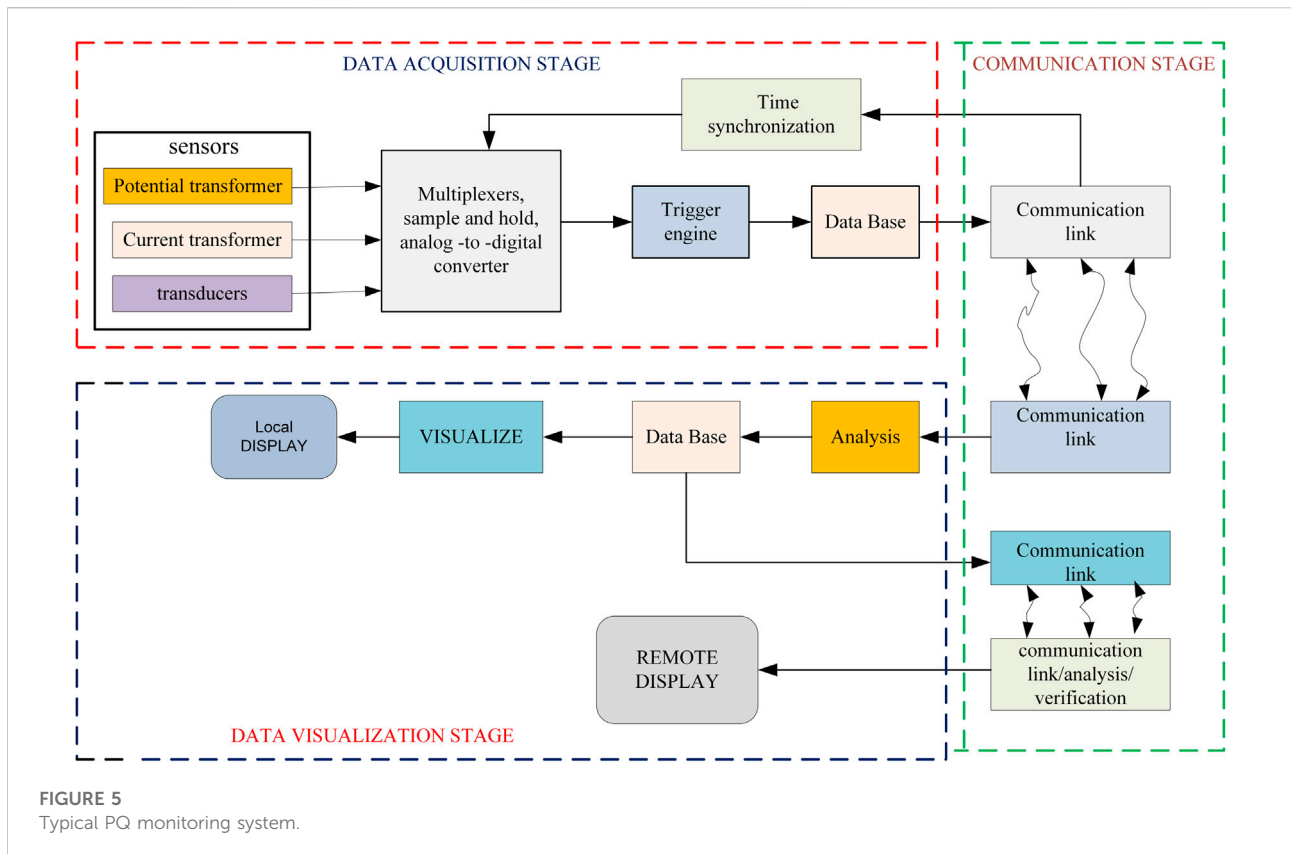
### 1.7.4 Grounding/earthing

While grounding protects against lightning, it also protects against electrical shocks from exposed metal parts. Figure 4B shows the TN-S and IT earthing ideas for the DC distribution system. DC system grounding affects PQ and protects greatly during fault circumstances. TN-S earthing is used to connect one of the poles to protective Earth at low DC voltages. This method restricts the voltage on a line-to-ground failure and halves the system voltage to ground for high DC voltages, such as 380 or 400 V, providing improved safety over the TN-S method (Wannurzana, 2010).

## 2 Power-quality monitoring and mitigation techniques

### 2.1 Overview of the power quality monitoring system

Figure 5 illustrates a block diagram of a typical PQ monitoring system. Data acquisition, communication, and data visualization are the three main stages of the system. Current transformers (CTs), potential transformers (PTs), and transducers (XD) are used as sensors in the data acquisition stage to measure electrical and nonelectrical parameters. Voltage and current measurements are converted to digital signals using digital circuits such as multiplexers (MUX), analog-to-digital converters (ADCs), and sample and hold (S & H) circuits. To protect against extremely erratic PQ disturbance, data should be



continuously recorded and processed, increasing memory requirements. The trigger engine determines which and how much data to save in the database (DB) (Divyalakshmi and Subramaniam, 2017). Real-time data are time synchronized to the required level of accuracy for the application. There are multiple time synchronization techniques, including the use of GPS, Inter-Range Instrumentation Group (IRIG), and Network Time Protocol (NTP) RFC-5905 (Bingham, 2001).

Data are transferred between communication centers in the second stage. IEEE standard 1159.3-2009 (Cookson and Stirk, 2019) standardizes PQ data transmission based on the EPRI (Electric Power Research Institute) (IEEE std 1159.3, 2004). Finally, the PQ monitoring system visualizes data as time plots. Nowadays, a variety of software applications are used to analyze and visualize large amount of data. Remote visualization can usually happen *via* web browsers. This method of visualization has alleviated some issues with running proprietary software on user's PCs, including conflicts and upgrades.

The process of evaluating PQ is depicted in Figure 6. The evaluation process begins by classifying the problems. The first stage includes transients, harmonics, flicker, voltage unbalance, and voltage interruption. The second stage is problem

characterization, which can be accomplished through measurements or data collection to ascertain the causes, characteristics, and impact of equipment. After defining the problem, it is necessary to revisit the equipment design or specifications, end-user customer interface, end-user customer system, utility transmission, and distribution system in order to determine the range of possible solutions. The following step is to evaluate the solutions. In this section, modeling or analysis procedures are used to evaluate technical alternatives. The final step is to evaluate the economics of the best solution.

### 2.1.1 PQ monitoring and analysis tools

As previously stated, harmonics hinder the electric networks PQ and harm equipment's safety. Enhancing PQ is the primary goal of harmonic signal compensation. Numerous harmonic analysis tools exist to improve the quality of power, including the fast Fourier transform (FFT), singular value decomposition (SVD), and artificial neural network (ANN), among others. When using the FFT for a harmonic analysis of power systems, the method of synchronized sampling and integral period truncation has some issues. Frequency, phase, and amplitude have all been found and corrected with FFT several times, including using window functions and interpolation

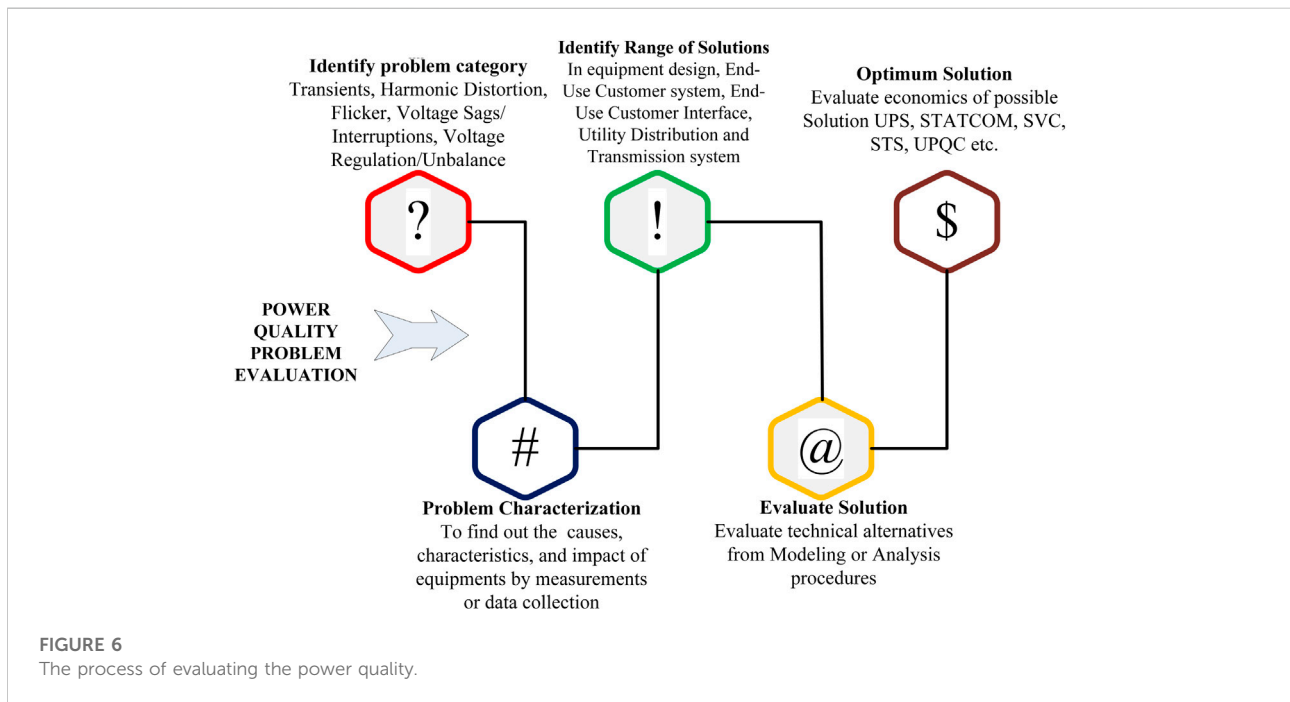


TABLE 1 Summary of power quality disturbances in the AC system.

Power quality disturbance	Causes	Effects	Severity
Transients	Oscillatory transient	Line and facility load switching, cable switching, and back-to-back capacitor switching	Catastrophic
	Impulsive transients	Lightning	Catastrophic
Short-time voltage variations	Voltage sag	System malfunctions, source voltage fluctuation, starting of heavy loads, inadequate wiring, and inrush currents	Moderate
	Voltage swell	Source voltage fluctuation, stop of heavy loads, inadequate wiring, and inrush currents	Mild
Long-time voltage variations	Under voltage	Load switching	severe
	Over voltage	Transformers taps are set incorrectly, large loads are switched off, or a large capacitor bank is energized	severe
	Sustained voltage Interruption	Protection device failure, insulation failure, or control malfunction	Moderate
Waveform Distortion	DC offset	Switching of transformer	Moderate
	Harmonics	Nonlinear loads and switching operation of PE devices	Moderate
	Noise	Electromagnetic interference and improper grounding	Mild
Power frequency variation	Heavy loads	Mainly effects sensitive equipments and motors	Mild



TABLE 2 Overall comparison of various DSTATCOM.

Mitigation equipment	Additional tool/ method	Capability				Remarks
		Voltage sag	Voltage swell	Loss reduction	Cost minimization	
DSTATCOM	MOPSO	✓	✓	✓	—	DSTATCOM positioning whenever DGs are already present
	Fuzzy-ACO methodology	✓	✓	✓	✓	—
	PEM	✓	✓	✓	—	Load uncertainty has been modeled and considered
	QL index	✓	✓	✓	—	Only wind generation is considered
	IA	✓	✓	✓	—	DGs are not considered
	HSA	✓	✓	✓	—	—
	PSO algorithm	✓	✓	✓	—	Only rooftop PV generation is considered
	SSO algorithm	✓	✓	✓	—	—
	PSOA	✓	✓	✓	—	Positioning of both the DG and DSTATCOM
	Nelder–Mead algorithm	✓	✓	✓	✓	When DGs are already present, deployment of DSTATCOM done
	DEA	✓	✓	✓	—	Reconfiguration of the network and assignment of D-STATCOM
	NSGA	✓	✓	✓	—	The uncertainty associated with the load was taken into account
	Firefly algorithm	✓	✓	✓	✓	As a case study, a source of harmonics was chosen
	Modified CSO	✓	✓	✓	—	Both D-STATCOM and DG have been allocated
	Hybrid GA and ACO	✓	✓	✓	✓	—
BGSA	✓	—	✓	—	Analyses of short circuits and reliability evaluations have been conducted	

algorithms. To address several flaws in existing correction methods, [Dugan et al. \(2017\)](#) proposed an improved algorithm. The SVD technique is a highly reliable and computationally stable mathematical technique for solving rectangular over determined systems of equations. Additionally, the method can be used to calculate the fundamental frequency of highly distorted periodic signals. However, the SVD computation is significantly more complex than the FFT computation and requires additional numerical manipulations ([Hossain et al., 2018](#)). [Zeng et al. \(2011\)](#) proposed a novel method for measuring power harmonics based on an artificial neural network (ANN). It analyzes and calculates the three-phase current for the current and previous sample times using a multilayer feed-forward neural network (MLFNN) and then extracts the harmonic components of the three-phase current. The NN structure is discussed, as is the learning algorithm used to train it.

Monitoring is necessitous not exclusively for reliability indices and power flows but also for the nonsinusoidality of the supply voltage waveform. The usage of phasor measurement units (PMUs) can significantly enhance the observability of electric power systems

([Lobos et al., 2006](#)). LabVIEW, a monitoring and analysis tool, was also developed. To predict the harmonics of a power system, we use the “ADALINE (Adaptive Linear Neuron)” neural network. ADALINE has three sequences: input, output, and a desired response sequence. Additionally, it has an adjustable parameter called the weight vector. To create the Fourier coefficients of the ADALINE signal, the signals’ weight vector is adjusted nonlinearly based on a stable difference error equation ([Dash, 1996](#)). Wavelet transform (WT) is one of most powerful approaches for extracting features because it incorporates a multiresolution analysis (MRA) approach. WT is superior to FT in numerous ways ([Moravej et al., 2010](#)). Using the estimated and detailed WT coefficients, numerous statistical parameters of PQD signals, such as amplitude, mean, median, energy, standard deviation, and entropy, can be computed. Over the last 2 decades, numerous researchers have extensively used three variants of WT to recognize PQ disturbances: continuous WT (CWT), discrete WT (DWT), and wavelet packet transform (WPT) ([Nath et al., 2012](#)).

The Hilbert transform (HT) operator is a linear one and used to trace the signals’ amplitude envelope. When applied to real data, the HT will turn a sequence of these actual numbers

into an analytical signal with two separate components: one component with the original numbers and another is an imaginary component containing the Hilbert transform. An imaginary version of the original sequence is created by a 90° phase shifting. In order to identify the instantaneous attributes of a time series, specifically the amplitude and frequency, the Hilbert transform is useful. Hilbert transform works a lot faster than wavelet transform because it does not require an exhaustive testing of all possible wavelet families (Jayasree et al., 2010).

## 2.2 PQ mitigation techniques

Power quality disturbance mitigation is required to guarantee the efficient and secure functioning of sensitive equipment, particularly for distributed generating networks connected to the grid. The daily increment of nonlinear loads (NLs) in these networks aids utilities in reducing electrical consumption by removing inefficient, large loads. These NLs are more productive because of their electronic front ends, but they considerably increase the harmonic injection into the distribution network. In general, CPDs are used in the distribution system to mitigate different PQ issues, whereas FACTS devices are utilized in transmission networks to address the problem of low PQ. DSTATCOM, DVR, and UPQC may be designed with a variety of topologies, which are primarily categorized by the following: 1. distribution system (3P3W and 3P4W), 2. arrangement of the power electronic switching devices, and 3. type of converter employed. In addition, the 3P3W and 3P4W devices are separated into isolated and nonisolated systems

depending on the transformer used to ensure total isolation between the VSC and the supply, as well as neutral current compensation. Typical transformer topologies include star-delta, zigzag, T-connected, and star-hexagon. In this section, some PQ mitigation techniques such as STATCOM, UPQC, and UPS are addressed (Sao et al., 2002; Milanović and Zhang, 2010; Madhana and Mani, 2022).

### 2.2.1 Distribution static compensator

To enhance PQ, DSTATCOM (shunt-connected CPD) is commonly utilized in DS (Yusuf, 2004). It has propensity to inject and observe reactive power at a faster rate due to presence of high switching frequency IGBT, which supports PF correction, improving voltage profile and voltage. Also, it can provide harmonic filtering and reduce fluctuations caused by the PV system, which increases PV installation (Chen et al., 2013). Figure 7 shows the DSTATCOM system connected to PCC (DSTATCOM system configured with a coupling transformer, inverter, and battery energy storage system). A DSTATCOM generates an adjustable AC voltage source from a DC capacitor (energy storage device) and a voltage source inverter (VSI) (Latran et al., 2015). The AC voltage source appears behind a transformer leakage reactance. Voltage differential across reactance causes active and reactive power transfer between feeders and DSTATCOM. The DSTATCOM is connected to electric networks where the voltage-quality challenge is a concern. All voltages and currents are monitored and supplied to the controller for comparison with directives. The controller provides a feedback control and produces switching signals to operate the primary semiconductor switches (IGBTs) of the power

TABLE 3 Overall comparison of various DVRs.

Mitigation equipment	Based on concept	Capability		Finding
		Voltage sag	Voltage swell	
DVR	Measuring RMS voltage	✓	×	Alleviate customers' sagging voltage problems at single and three-phase outputs
	RMS voltage	✓	✓	It is unable to determine the swell, fundamental frequency and harmonics
	WT	✓	✓	It is unable to determine the fundamental frequency and harmonics
	$V_{peak}$	✓	✓	Requires accurate WT-prototype selection and, possibly, a delay associated with WT-prototypes
	SRF	✓	✓	Sensing sags/swells with a quarter-cycle lag
	PLL	✓	✓	3-Ø power systems (not suitable for 1-Ø)with very small duration detection can use this device
	CFFFB	✓	×	Considered that the problem occurred in the system of wind farms
	WT	✓	✓	DFIG-based wind turbines with improved FRT capabilities
	DSP-based control	✓	✓	In addition to PQDs detection, harmonics are mitigated
	KF	✓	✓	DGs are not considered
				Offers excellent results with linear systems, but the KF needs to be enhanced for nonlinear ones

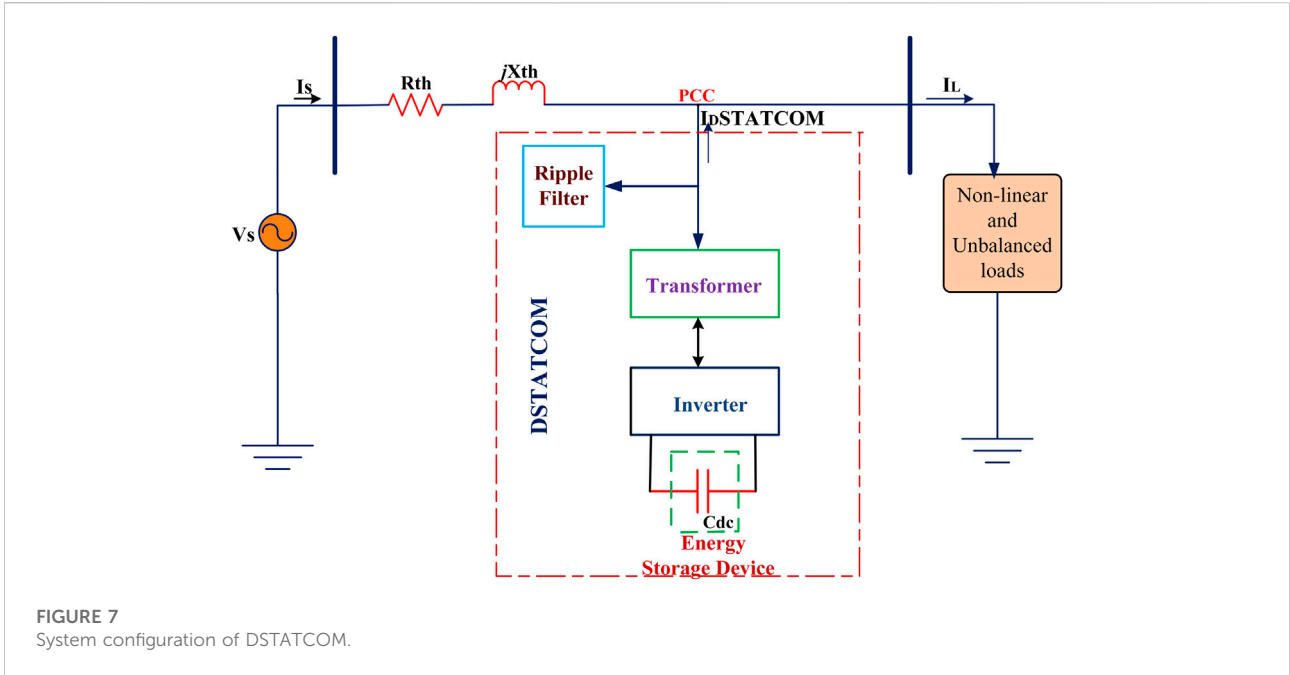


FIGURE 7 System configuration of DSTATCOM.

TABLE 4 Overall comparison of various UPQCs.

S.No	Type	Capability	References
1	UPQC-VAmin	By delivering series voltage in quadrature or phase, it compensates voltage sag with minimal VA loading	Kolhatkar et al. (2005) and Kolhatkar and Das (2006)
2	UPQC-P	It compensates for voltage sags by regulating real power	Lee et al. (2009)
3	UPQC-Q	By managing reactive power, it compensates for voltage sags	Hirofumi et al. (1984) and Basu et al. (2008)
4	UPQC-S	It prevents voltage sags by managing real and reactive power	Hannan and Mohamed (2005) and França et al. (2015)
5	UPQC-L	It is used to prevent the shunt inverter and passive filter from interfering with one other	Prieto et al. (2002)
6	UPQC-R	In addition to compensating for current harmonics and reactive current, it also corrects for any unbalance	Graovac et al. (2000)
7	UPQC-I	It is used to control the voltage. It also mitigates current harmonics, unbalanced loads, and voltage harmonics	Jindal et al. (2006)
8	UPQC-MC	For enhancing system performance, it is employed	Mohammadi et al. (2009)
9	UPQC-MD	It is used at medium voltage levels to increase power output	Pal et al. (2012)
10	UPQC-D	It is used in the utility to supply a three-phase four-wire system with 3P3W. It is also used to compensate transformer neutral current	Khadkikar and Chandra (2009)
11	UPQC-DG	To control DG power and provide electricity to loads linked to the PCC. Harmonics in voltage and current are compensated by this device	Mazumder et al. (2013)
12	UPQC-ML	It is thought of as an alternative way to get more power	Khadkikar (2011)

Note: UPQC-VAmin, minimum VA loading UPQC; UPQC-P, active power control UPQC; UPQC-Q, reactive power control UPQC; UPQC-S, simultaneous active and reactive power control UPQC; UPQC-L, left shunt UPQC; UPQC-R, right shunt UPQC; UPQC-I, interline UPQC; UPQC-MC, multiconverter UPQC; and UPQC-MD, modular UPQC, UPQC-DG.

converter (Sirjani and Rezaee Jordehi, 2017). The classification of D-STATCOM topologies are as follows:

1. Three-phase three wire (3P3W)
  - A. Nonisolated
    - a. Three leg voltage source converters.
    - b. Two leg voltage source converters with split capacitor
  - B. Isolated
    - a. Three single-phase VSC topology
    - b. Isolated three leg system
    - c. Isolated two leg system
2. Three-phase four wire (3P4W)

- A. Without transformer
  - a. Four leg VSC
  - b. Three leg VSC
- B. With transformer nonisolated
  - a. Three leg VSC
  - b. Two leg VSC
- C. With transformer isolated
  - a. Three leg VSC
  - b. Two leg VSC
  - c. Three single-phase VSC

### 2.2.1.1 Survey on optimal allocation of distribution static compensator and control strategies

Rezaeian Marjani et al. (2019) proposed a multiobjective optimization algorithm based on particle swarm optimization (MOPSO). The voltage profile index, load-ability index, and active power loss are esteemed as objectives in optimization practice. In the suggested strategy for identifying the final solution, technique for order performance by similarity to ideal solution (TOPSIS) was utilized. Objective functions in Hussain and Subbaramiah (2013) consisted of power loss and voltage profile. An analytical method was developed and tested in a 33-bus radial system. Also, the result of proposed method was compared with a genetic algorithm (GA). In Bagheri Tolabi et al. (2015), ant colony optimization (ACO) has been utilized for appropriate placement of DSTATCOM in the combination of PV array in an attempt to minimize true power losses, optimize voltage profile, and establish load balancing on feeders. In 2014, Akbari-Zadeh et al. (2014) employed bat swarm optimization algorithm to find location of D-STATCOM for load uncertainty. The effect of uncertainty loads can be modeled using a new stochastic structure for D-STATCOM allocation and sizing difficulties. The presented design was validated on IEEE 69-bus DS. Roy et al. (2013) examined the impact of D-STATCOM in reactive power management with wind generation to improve voltage stability. Taher and Afsari (2014) presented the immune algorithm (IA) to decide the best allocation of D-STATCOM with the following objective functions: 1) reduce power loss and 2) improve voltage and current profile in DS. Allocation and sizing of D-STATCOM were performed using the harmony search (HS) algorithm, in which copper loss minimization is considered as an objective. The described methodology has been tested on IEEE 33-bus DS. The results show the outperformance of the proffered HS algorithm with respect to IA (Yuvaraj et al., 2015). The PSO algorithm was introduced in Pezeshki et al. (2018) to maintain voltage magnitude and unbalancing within the probabilistic limit by considering cost of compensation in DS. Abbasi et al. (2015) present D-STATCOM allocation considering active and reactive uncertainty loads. Scenario generation is used to model the effect of uncertainty; for optimization, a social spider optimization (SSO) algorithm is employed. In order to reduce power loss and improve voltage profile, Prabu and Muthuveerapan (2007) proposed a penguin optimization

search algorithm (PSOA). Reducing active power losses and improving the voltage stability index were done using hybrid of imperialistic competition and the Nelder–Mead algorithm (Chabok and Ashouri, 2016) to resolve allocation of the D-STATCOM problem. In Jazebi et al. (2011), allocation of D-STATCOM and reconfiguration were held out to retain the voltage profile and reduce power loss, employing a differential evolution algorithm (DE). The results testify the outperformance of proposed DE with respect to conventional PSO. In 2018, Shahryari et al. (2018) employed Monte Carlo simulation (MCS) and the nondominated sorting genetic algorithm (NSGA) for D-STATCOM allocation considering load uncertainty. Voltage stability, power loss, and voltage deviation are objectives. Farhoodnea M et al. applied the firefly algorithm for optimal placement of D-STATCOM, and the main aim of this study was maintaining a fair voltage profile and alleviate harmonics. Here, four D-STATCOM were employed, and the final findings are compared with GA and PSO. Bagheri Tolabi et al. (2015) proposed modified cat swarm optimization (CSO) for optimal placement of D-STATCOM and DG. The functional objective of this work is improving the voltage profile and minimizing the copper losses. The proposed ICSO method overcomes drawbacks of CSO such as less accuracy and a low convergence rate. Fuzzy-based ant colony optimization is applied for optimal placement of the PV array and D-STATCOM. The idea of fuzzy helped in dealing multiple PQ issues. Objectives of this work are minimizing losses and improving feeder load balancing and voltage profiles. The proposed fuzzy-ACO shows its outperformance over fuzzy-GA and fuzzy-PSO (Bagheri Tolabi et al., 2015). In Akbari-Zadeh et al. (2014), D-STATCOM placement was considered to decrease active power losses and voltage deviation using the point estimate method (PEM) for uncertainty loads. Hybrid GA and ACO were proposed in Bagherinasab et al. (2013), where three D-STATCOM are utilized for the IEEE 30-bus network. The objective of this study is reducing energy losses. ACO is used to find a suitable place for locating three D-STATCOM, and the reactive power delivered or absorbed by DSTATCOM was calculated using GA. Similar to Bagheri Tolabi et al., in Kamel et al. (2019), optimal placement of DG and D-STATCOM can be done using the method of clustering. In Salman et al. (2012), the author used the binary gravitational search algorithm (BGS) for D-STATCOM placement in order to improve reliability and minimize number of sags propagated through DS. Table 2 summarizes the full review of DSTATCOM and its capabilities.

### 2.2.2 Dynamic Voltage Restorer

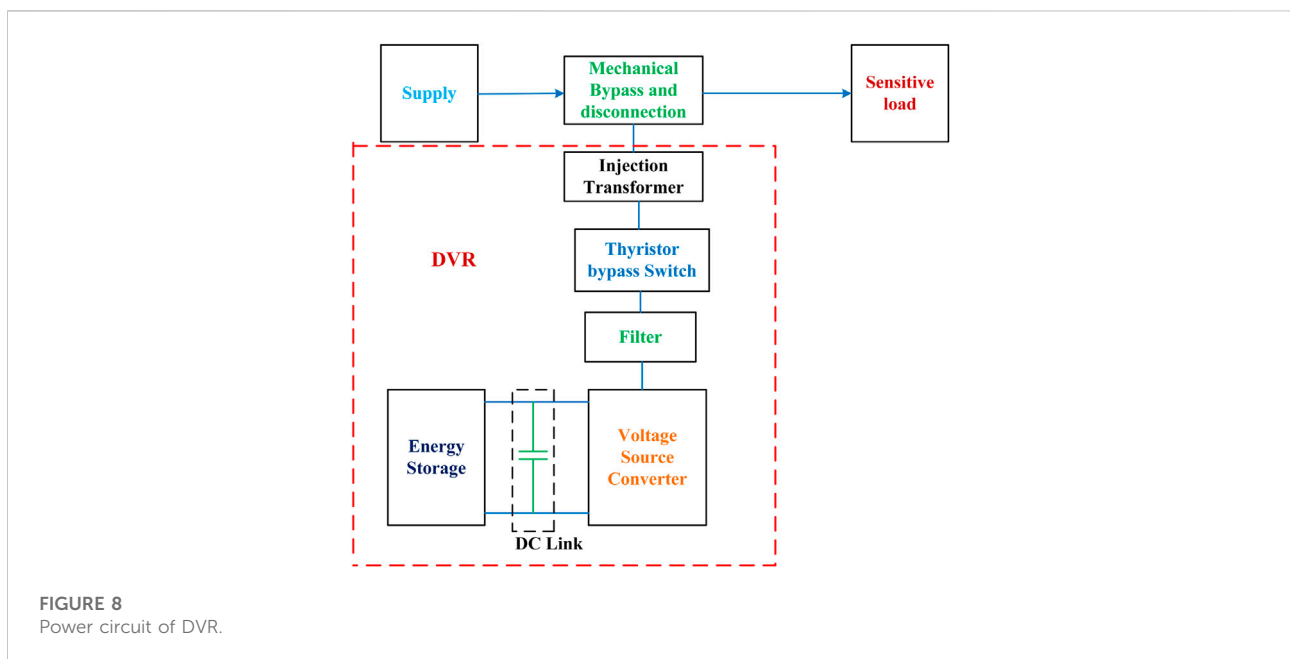
DVR is the high-performing and most economical solution to compensate upstream voltage complications in DS. DVR may be taken into consideration as a variable or a controllable voltage source connected in series between PCC and load (Cárdenas et al., 2015). It has energy storage and a series converter. It is connected to the system in series.

Whenever the system is subjected to an abnormality or low voltage, the series voltage is injected using a converter. The injected voltage will adjust for the voltage of the system. Consequently, the DVR continually checks the supply line voltage and compares it to the reference AC supply; it then provides the appropriate voltage to correct for voltage variations. It supports to control and maintain a load voltage profile by exchanging reactive power between DVR and DS. Figure 8 gives the power circuit of DVR with energy storage, DC link, converter, filter, injection transformer, bypass, and disconnection equipment as basic elements (Yue et al., 2007). The different topologies of DVR are as follows:

1. Energy storages
  - A. Without energy storage
    - a. DVR with no energy storage
  - B. With energy storage
    - a. Constant DC link voltage
    - b. Variable DC link voltage
2. Inverter topology (multilevel inverters)
  - a. Diode clamped
  - b. Cascaded H-bridge
  - c. Flying capacitor
3. 3-Phase inverters
  - a. Three-phase four-line half bridge
  - b. Three-phase four -line bridge
  - c. Three-phase H bridge
  - d. Three-phase DVR with a split capacitor
  - e. Three-phase push pull inverter

### 2.2.2.1 Survey on dynamic voltage restorer control strategies

Using the cascade H-bridge DVR, Al-Hadidi et al. (2008a) developed a new configuration to mitigate the sever and long duration sagged voltages at customer loads. Moreover, it is suitable for both single- and three-phase sag compensation. Al-Hadidi et al. (2008b) proposed a new technique to alleviate sag by utilizing energy storage capability a cascaded inverter-type DVR. The injected active and reactive power is calculated analytically under different situations of load magnitude and PF. The start/end-point voltage sag and swell in DS can be effectively detected and alleviated in Ali et al. (2018); the authors used RMS detection strategy. Nielsen et al. (2004) presented topologies without DC-link energy storage for three-phase DVRs. The schemes are based upon direct converters so that three independent three-phase to single-phase direct converters are used. In 2016, Messiha, M.A. et al. utilized wavelet transform technique to detect PQD and voltage sag is stabilized effectively (Baraket, 2018). Capacitor-supported interline DVR is addressed in Abdollahzadeh et al. (2014) to mitigate voltage disturbances in DS. In Remya et al. (2018), a PI-based DVR is proposed to mitigate PQ issues successfully in distribution PT DSS power plant. In DVR, with a traditional controller, the application of DVR is limited to low operating level only. To extend application of DVR for varying operating conditions in a higher distribution level artificial intelligence-based controllers such as space vector pulse width modulation (SVPWM), artificial neural network, and fuzzy logic are reported in literature. Generally, ANN has an ability to mimic the decision-making capability of a human or a complex system. The ANN controller-based DVR is reported in Sundarabalan and Selvi



(2015), where ANN is capable of constitute the nonlinear correlation among input and output, but the performance depends on a neural network structure and number of training data considered. Unlike ANN, the fuzzy logic controller has definite decision-making based on imprecise or ambiguous data. In [Mani and Siddappa Naidu \(2015\)](#), the authors presented the impact of fuzzy logic controller (FLC) in application of DVR. FLC effectively reduces the transient overshoot of VSI. [Ding et al. \(2002\)](#) utilized a SVPWM-based DVR to mitigate PQ issues under an unbalanced system condition. In addition, it reduces the effect of load voltage negative sequence component on the performance of DVR. In [Rini Ann Jerin et al. \(2017\)](#), a feed-forward vector control algorithm is used to mitigate voltage disturbances. Using this algorithm, DVR generates firing signal for the VSI to inject appropriate compensation voltages. A PV-based DVR is reported in the study by [Divyalakshmi and Subramaniam \(2017\)](#) to mitigate PQ problems. The function of PV is that it not supplies power only to the load but also to the DC-link of DVR. Here, a wavelet transform based controller is employed to transform the PV system role into DVR and to identify PQ event. In 2017, [Rini Ann Jerin et al. \(2016\)](#) introduced a feed-forward and feed-back control of DVR for the improvement of fault ride-through (FRT) capability in the doubly fed induction generator-based wind turbine. In [Li et al. \(2018\)](#), a DVR-based strategy is proposed for the mitigation of voltage sag in DS through DVR for improving power system quality. [Table 3](#) contains the findings of the in-depth investigation on DVRs capabilities.

### 2.2.3 Unified power quality conditioner

Because of nonlinear loads present in power system induces PQ complications, such as harmonics, voltage dips, and spikes in the system. UPQC is employed to enhance the PQ at distribution level. UPQS is a combination of series and shunt active power filter connected back-to-back through a common DC-link capacitor ([Fujita and Akagi, 1998](#)). [Figure 9](#) illustrates the basic schematic diagram of UPQC with series and shunt active power filter. It consists of DC link capacitor in between the series and shunt controller. The series controller can be used for series compensation and the shunt controller for current compensation. During compensation, the DC capacitor rating for both controllers should be the same. The shunt active filter improves PF, mitigates harmonics in load current and load unbalance whereas the series active filter can alleviate supply side disturbances such as harmonics, voltage dips/spikes, flicker, and voltage unbalance in a network-like distribution ([Faranda and Valadè, 2002](#)). The topologies of UPQC are as follows:

1. Converter topology
  - a. Current source topology
  - b. Voltage source topology
2. Three-phase four-wire system
  - c. Three-phase four-wire four-leg topology
  - d. Three-phase four-wire neutral clamped topology
  - e. Three-phase four-wire capacitor-connected shunt VSI

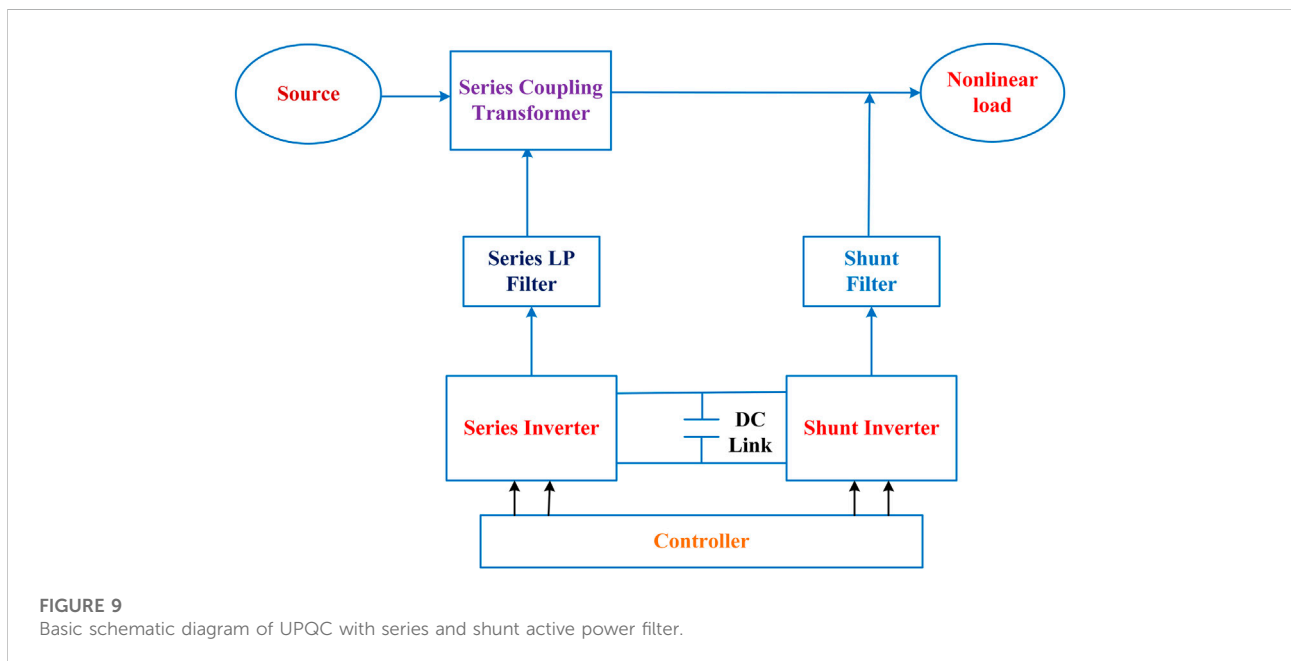




TABLE 5 Important power-quality standards and their guidelines.

Power quality standard	Guidelines
IEEE standard 519-2014	Limits voltage harmonics up to 1 kV and current harmonic orders 35th to 50th
IEEE standard 141-1993	property preservation, simplicity, personal safety, care and maintenance, voltage regulation with in the tolerance limit as well as reliability and flexibility
IEEE standard 1159	Definition of power quality terms, effects of poor power quality on utility and customer equipment, monitoring of power quality, and measuring electromagnetic phenomena
IEC 61000-3-2 (1995-03)	To limit the harmonic currents for equipments with input currents of 16 A or less
IEEE standard 1250-1995	Momentary voltage changes in an AC system, how they affect new, sensitive user equipment, and how to reduce these effects to limit harmonic distortion
IEC/TS 61000-3-4 (1998-10)	To limit the harmonic currents for equipments with input currents of 16 A or more
IEEE standard P1409	Developing guidance for custom power devices to deal with power quality issues
IEC standard 61000-4-15	Flicker meter-functional and design specifications
IEEE standard P1547	Integrating distributed generation to the electrical grid
IEEE standard 1547a-2014	Allows the equipment to withstand voltage sag with greater stability

TABLE 6 Comparison of all PQ mitigation techniques with its capabilities.

s.no	Mitigation equipment	Capability							
		Voltage Sag	Voltage Swell	Transient	Harmonic distortion	Frequency deviation	Interruption	Flicker	Noise
1	Passive filter (PF)	×	×	×	✓	×	×	×	×
2	Active filters (AF)	×	×	×	✓	×	×	×	×
3	Static VAR compensator (SVC)	✓	✓	✓	×	✓	×	×	×
4	Static synchronous compensator (STATCOM)	✓	✓	✓	×	✓	×	×	×
5	DVR	✓	✓	×	×	×	×	×	×
6	UPQC	✓	✓	✓	✓	✓	✓	✓	✓
7	UPS	✓	✓	✓	✓	✓	✓	✓	✓

TABLE 7 DC Link voltage comparison of MF-IUPQC with different controllers.

Parameters	With PI controller	With fuzzy controller	With ANFIS controller
Rise time (ms)	36.033	10.826	1.358
Slew rate (/μs)	0.291	1.049	8.279
Overshoot	0.258	0.192	0.041
Settling time(ms)	>5τ	15.473	1.967
RMS	12.89 KV	14.41 KV	14.56 KV
Peak value	15 KV	16.2 KV	16.5 KV
Peak time (sec)	0.199	0.18	0.187

TABLE 8 THD during current harmonics.

Controller	THD of current from load to source			
	Over feeder 1		Over feeder 2	
	Load side	Source side	Load side	Source side
PI	28.02	3.75	28.02	3.63
FUZZY	20.56	2.67	21.32	2.47
ANFIS	8.46	1.32	7.69	1.56

### 2.2.3.1 Survey on unified power quality conditioner control strategies

For the very first time, [Fujita and Akagi \(1998\)](#) suggested a back-to-back topology of series and shunt APFs that could compensate for voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics; tested it with an experimental setup; and titled it “unified power quality conditioner” (UPQC). Similar to the unified power flow controller (UPFC) used in the transmission system, UPQC is employed in the distribution system ([Faranda and Valadè, 2002](#)). Based on topology, in [Hingorani \(2007\)](#) UPQC are classified into two types: 1) voltage source inverter (VSI)-based UPQC and 2) current source inverter (CSI)-based UPQC. The switching action is accomplished by the use of a pulse width modulation (PWM) technology ([Fabula et al., 2021](#)). In CSI-based UPQC the voltage blocking diode is connected in series with IGBT. Comparing these two configurations shows how VSI benefits our operation. The VSI design is capable of multilevel processing, but is also less expensive than the CSI design ([Graovac et al., 2000](#)). The classification of UPQC is further subdivided into single-phase and three-phase supply systems, depending on the supply system. Additionally, single-phase and three-phase systems can be classified as single-phase two-wire, three-phase three wire, or three-phase four wire. For single-phase and three-phase systems, voltage sag and swell concerns are common, however voltage unbalancing in three-phase systems is beneficial. Current harmonics and load reactive current are serious issues in a single-phase system ([Corrêa et al., 2003](#)). Also, with a three-phase four wire design, an additional, unbiased current compensation ring is required. In [Chakraborty et al. \(2007\)](#) utilized p-q theory-based active filtering named universal active power line conditioner ([Aredes et al., 1998](#)) and unified PQ conditioner to solve power flow and PQ issues, respectively. Further Distributed intelligent energy management system (DIEMS) is used to optimize operating cost. Without proper forecasting, DIEMS cannot function. Fuzzy ARTMAP neural networks are utilized to anticipate daily schedules. A novel optimization approach is developed, using linear programming and heuristics. On the basis of peer-reviewed publications. [Table 4](#) summarizes the

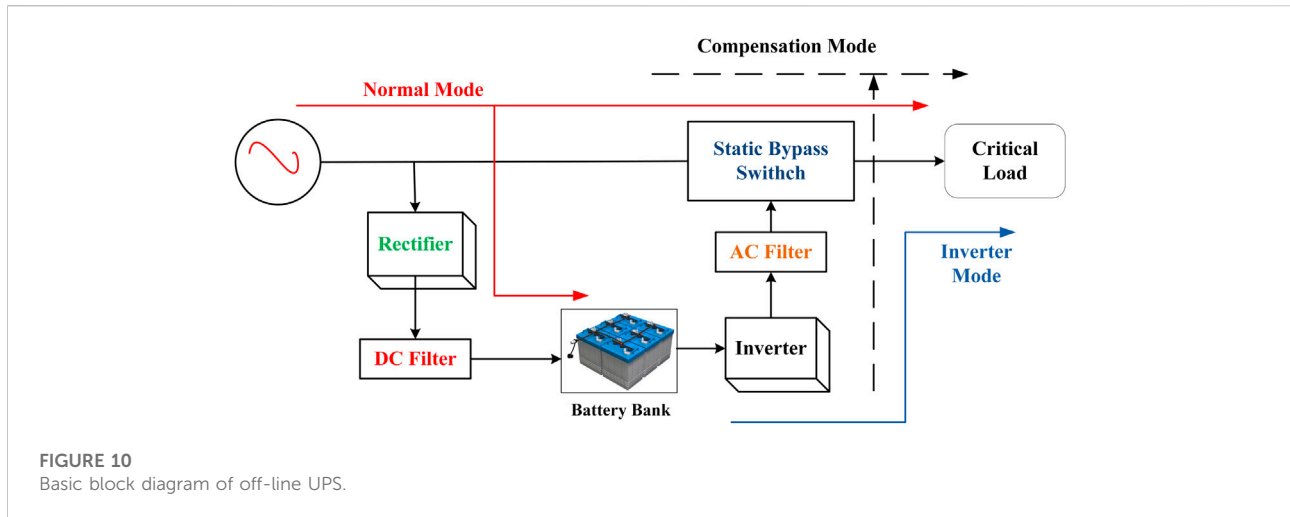
various kinds of UPQCs and their associated applications. For PQDs such as voltage drop, swell, imbalance, and harmonics and for load current problems such as unbalance, neutral current, and reactive current, the literature shows that UPQC is effective.

### 2.2.4 Uninterruptable power supply

When the utility mains are unavailable, an uninterruptible power supply (UPS) system provides safe, conditioned, and uninterruptible power to critical loads such as data centers, airline computers, medical support systems in hospitals, communication networks, and many others. The offline UPS consists of a rectifier, DC filter, battery bank, an inverter, an AC filter, and a static bypass switch, as depicted in [Figure 10](#). Generally, it is installed between commercial utility mains and critical loads. When there is a power outage or other abnormality, the UPS effectively switches from mains power to its own power source almost instantaneously ([Guerrero et al., 2007](#)). The output of the UPS system should usually be controlled sinusoidally with a low THD regardless of changes in the connected system voltage and load. UPS systems can be broadly classified into two types: static UPS systems and rotary UPS systems. Static UPS systems are suitable for small loads and rely on power electronics converters and inverters to process, store, and deliver power in the event of grid failure, whereas rotary UPS systems are suitable for large loads and rely on motors and generators ([Blondel and Monney, 2009](#); [Lu et al., 2019](#)).

#### 2.2.4.1 Survey on uninterruptable power supply

According to UPS operation and configuration, UPS systems are classified into three types. Online, offline, and line-interactive are the three categories ([Karve, 2000](#)). However, among these topologies, the line-interactive UPS system ([Bukhari et al., 2013](#)) has always been preferred by industrial consumers due to its high efficiency and power-compensating capabilities in comparison to the offline and online UPS topologies ([Bukhari et al., 2017](#)). It is further subdivided into two distinct topologies for the line-interactive UPS system. The first topology connects the inductors in parallel with the critical load and utility grid. In another topology, a bilateral converter is connected parallel to the



**FIGURE 10**  
Basic block diagram of off-line UPS.

utility and operates differently during regular and irregular power obligations. When connected to a regular power source, it acts as a battery charger (Kawabata et al., 1989; Yeh and Manjrekar, 2007). However, when abnormalities occur, it acts as an inverter, providing backup power to the load. The primary objective of this topology is to suppress the harmonics of the input current (Jou and Wu, 1995). However, a negligible amount of reactive power compensation will be required (Nakata, 2019; Zhao et al., 2019). The addition of a triport transformer between the load and utility for isolation increases the size of the system. In Sivamani et al. (2021), a novel improved single-phase line-interactive UPS has been proposed for low-power applications. When input power is present, the UPS functions as an output voltage regulator, an active power filter, and a battery charger. In the event of a power failure at the input, the UPS supplies a regulated sinusoidal voltage to the load, drawing energy from the battery. In another research study, Kwon et al. (2001) propose a transformer-less line-interactive uninterruptible power supply (UPS) with low ground leakage current. A high-efficiency bidirectional inverter with low ground leakage current is suggested for performing line-interactive UPS functions. The parasitic capacitance between the inverter and the AC voltage ground is clamped to zero voltage during a positive line cycle and to the AC voltage during a negative line cycle as the inverter operates. Using a mix of supercapacitors and liquid nitrogen (LN2), the first uninterruptible power supply (UPS) was presented in Choi and Yang (2018), which can replace traditional UPS systems such as fuel-burning engines or batteries with this highly viable option.

## 2.3 Review on controllers used in CPDs

The widely used controller in CPDs are as follows:

- A. PI controller
- B. Phase shift control
- C. Hysteresis controller
- D. Sliding mode controller
- E. One cycle control

### 2.3.1 PI controller

Commonly, the PI controller is utilized to provide a regulated gating signal for the voltage source converters functioning. The PI controller compares the observed bus voltage to the reference voltage and then creates an error signal. Figure 11A shows the schematic representation of PI controller.

$$v_{de(n)} = v_{dc(n)}^* - v_{dc} \tag{1}$$

where  $v_{de(n)}$ ,  $v_{dc(n)}^*$ ,  $v_{dc(n)}$  represent the dc error voltage, reference dc voltage, and dc bus voltage during the  $n$ th time interval, respectively.

$$v_{0(n)} = v_{0(n-1)} + K_p \{v_{de(n)} - v_{de(n-1)}\} + k_i v_{de(n)} \tag{2}$$

The subscripts  $n$  and  $n-1$  denote past and current states, respectively. Also,  $a$  and  $b$  represent the proportional and integral gains of the PI controller, respectively.  $c$  is the magnitude of the reference supply current,  $I$ . From the source reference current, the remaining three-phase reference currents are derived. After producing the reference current, the PI controller produces the precise switching signals needed for the functioning of the six VSC switches (Patel and Sahu, 2016).

### 2.3.2 Hysteresis control

The primary function of the control scheme is to produce gating signals for the inverter with minimal current error. Identifying the difference between the actual and source currents, the controller provides the error signal. The

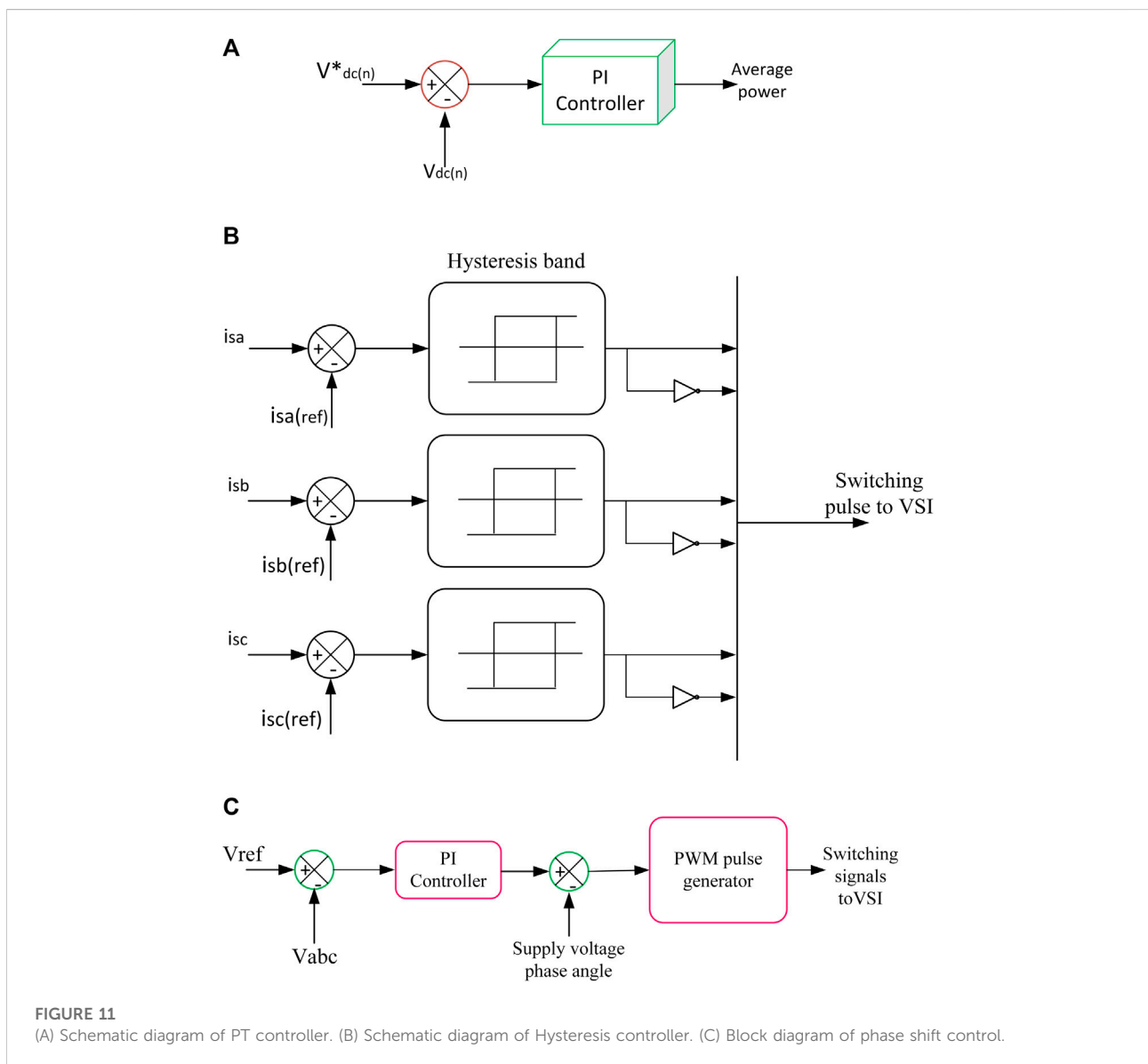
erroneous signal is then compared to the hysteresis band, which typically yields 1%–5% of the current value. The following is the logic employed by the hysteresis controller (Latran et al., 2015).

IF  $i_{sa} < i_{sa}^* - h_b$ : the lower switch of VCS is ON. ELSE the upper switch is ON.

Here,  $i_{sa}$ ,  $i_{sa}^*$  and  $h_b$  represent the source and reference currents and the hysteresis band, respectively. The value of the hysteresis band  $h_b$  is variable. This controller operates well and quickly when the hysteresis band is narrow. As it expands, the system becomes increasingly unstable. The hysteresis controller is seen schematically in Figure 11B (Srikanthan and Mishra, 2010).

### 2.3.3 Phase shift controller

Utilizing a phase shift control approach, DSTATCOM’s voltage regulation is attained. In this method, as seen in Figure 11C, the RMS voltage of the load is measured and compared to the reference voltage, and an error signal is produced (Masand et al., 2006). The error signal is then sent to the PI controller as an input. The output angle of the PI controller corresponds to the angle between the VSC output voltage and the AC supply terminal voltage. The signal necessary to activate the PWM generator is then produced by adding the output of the PI controller to the phase angle of the balanced supply voltages. The primary benefit of this technology is its practical applicability. However, it cannot



perform harmonic reduction for nonlinear loads (Kumar et al., 2013).

### 2.3.4 Sliding mode controller

This approach applies a discrete input signal to a system whose outcome is not proportional to the change in input. The signal modifies the system's dynamics and causes it to slide along the cross section of its typical performance. The controller's model is based on the state variable values  $X_1$ ,  $X_2$ , which are described as (Singh et al., 2008):

$$v_{de(n)} = v_{dc(n)}^* - v_{dc} = X_1 \quad (3)$$

$$v_{de(n)} - \frac{v_{de(n-1)}}{T_x} = X_2 \quad (4)$$

where  $v_{de(n)}$ ,  $v_{dc(n)}^*$  and  $v_{dc(n)}$  represent dc error, reference dc, and dc bus voltages at the  $n$ th time period, respectively, and  $T_x$  represents the sampling interval. The state variables are used to calculate the switching functions  $y_1$  and  $y_2$ .

Here,  $Z$  is the switching plane function, and its expression is as follows:

$$Z = C_1 X_1 + C_2 X_2 \quad (5)$$

Using the following equation, we get the value of the reference supply current  $I_{sref}$ .

$$I_{sref} = C_3 X_1 Y_1 + C_4 X_2 Y_2 \quad (6)$$

The values of three-phase reference current are derived from the supply of reference current. The information is then provided as input to the controller, which generates gate pulses for the instrument. The optimal performance is achieved by fine-tuning the gain constants  $C_1$ ,  $C_2$ ,  $C_3$ , and  $C_4$ .

### 2.3.5 One cycle control

In this strategy, there is no need to determine the reference voltages or currents. This will have two circuits, a three-phase bridge and an N-half-phase bridge. The benefit of the neutral line compensation bridge is that it eliminates the harmonic current existing in the line at different frequencies (Jayachandran and Murali Sachithanandam, 2016). The control circuit comprises the OCC core, the current selection, the feedback circuit, the integrator, and reset. This control circuit will aid the operation of the vector.

## 3 PQ standards

The problems associated with PQ necessitate the creation of appropriate standards. Standards are primarily designed to improve the reliability, safety, and efficiency of products. In order to better study for and respond to future challenges, researchers and organizations such as the Electric Power Research Institute (EPRI), the IEEE 1159 working group,

the Pennsylvania–New Jersey–Maryland (PJM) area, and the California Public Utility Commission (CPUC) have been collaborating. Table 5 depicts the fundamental underlying principles of the various power quality standards. The important IEEE and IEC PQ standards are discussed in the following subsections.

### 3.1 IEEE standard 519-2014

The IEEE standard 519-2014 is the revision of IEEE std 519-1992, which specifies voltage harmonics limits up to 1 kV and current harmonic orders 35th to 50th, and was recently issued. In addition, two new measurement methods have been introduced: very short-time measurements for 1 day with a time interval of 3 s and short-time measurements for 1 week with a time interval of 10 min. IEEE 519 discusses allowable nonfundamental frequency waveform distortion when it connects from the source to the load at a location known as the “point of common coupling (PCC).” As specified in IEEE 519-2014, the limits specified in this standard are applicable only for steady-state operation at PCC. These limits may be exceeded during transient conditions (Committee et al., 2014).

### 3.2 IEEE standard 141-1993

IEEE standard 141-1993 (Recommended practice for industrial plant electric power distribution) is a revision of ANSI/IEEE standard 141-1986, and this guide provides an in-depth analysis of fundamental electrical power system considerations. This standard establishes guidelines for property preservation, simplicity, personal safety, care and maintenance, as well as reliability and flexibility. Furthermore, IEEE std 141 specifies voltage regulation within the tolerance limit under all load conditions (IEEE std 141, 1993).

### 3.3 IEEE standard 1159

IEEE standard 1159 (Recommended practice for monitoring electric power quality) describes how to monitor the PQ of AC systems. Monitoring of PQ can be improved by interpreting results obtained from appropriate monitoring locations and systematic studies. To obtain useful and accurate voltage and current data, it is necessary to use proper and safe measurement techniques. This standard specifies methods for measuring electromagnetic phenomena and the impact of poor PQ on utility and customer equipment. Figure 2 illustrates the IEEE 1159 classification of PQ issues. This recommended practice defines nominal conditions and deviations from these nominal

conditions that may originate in the source of supply or load equipment or from interaction between source and load (IEEE Std, 1995).

### 3.4 IEC 61000-3-2 (1995-03)

It provides current harmonic limitations for felicitous electrical and electronic devices with an input phase current of less than or equal to 16 A and is intended for connection to a low voltage DS. Type tests are used to ensure compliance with this standard. Bounds have not yet been considered for systems with a line to neutral voltage of less than 220 V.

### 3.5 IEEE standard 1250

IEEE standard 1250 (guide for service to equipment susceptible to momentary voltage disturbances) is a technical guide for momentary voltage disturbances in AC distribution and utilization systems. Computers and other electronic devices that use solid state electric power conversion are not resistant to abnormal conditions, such as faults and surges. Also, this equipment is more vulnerable to temporary voltage disturbances. This standard establishes upper and lower bounds on the effect of harmonic distortion. Additionally, IEEE 1250 specifies procedures for mitigating these effects (IEEE std 1250, 2011).

### 3.6 IEC/TS 61000-3-4 (1998-10)

IEC/TS 61000-3-4 specifies harmonic current emission limits for low-voltage power distribution equipment rated over 16 amps. Equipment with a rated input current more than 16 A per phase, intended to be connected to one of the following public low-voltage alternating current distribution systems: 240 V single phase, two or three wires; 600 V three phase, three or four wires. To establish whether or not equipment is suitable for connection, the guidelines define the information a supplier authority must offer.

### 3.7 IEEE standard P1409

Custom power devices are advantageous for mitigating voltage drops and outages. IEEE standard P1409 is a technical guide that provides guidance and performance expectations for the use of CPDs in electricity companies' DSs to improve power quality. It provides comprehensive information on CPDs as a possible solution to PQ problems.

### 3.8 IEC standard 61000-4-15

IEC standard 61000-4-15 describe functional and layout specifications for flicker measuring equipments supposed to signify the precise perception level of flicker for all realistic voltage fluctuation waveforms. The output of flicker-meters functioning in accordance with this standard is being used to determine the degree of flicker (International Standard International Standard, 2003).

### 3.9 IEEE standard P1547

This standard specifies criteria and requirements for interconnecting DG with the electric power system (EPS). IEEE P1547 specifies performance, testing, operating, safety, and maintenance criteria for interconnections.

### 3.10 IEEE standard 1547a

IEEE standard 1547a-2014 address new guidelines related to voltage dip. It consists of new settings that would typically permit the equipment to tolerate the voltage dip with increased stability (IEEE Std, 1995).

## 4 Proposed power quality mitigation technique

Detailed review on PQ mitigation techniques shows that the UPQC connected between the multiple feeders gives better performance. Commonly used PQ mitigation techniques with its capabilities are compared shown in Table 6. Moreover, control scheme is responsible for increasing the performance. Using nonlinear loads and integrating RES into the grid causes power quality disturbances (PQDs). This section describes using an adaptive neuro-fuzzy inference system (ANFIS) in an MF-IUPQC to address PQDs such voltage/current fluctuations and harmonic distortions. MF-IUPQC has four diode-clamped inverters on three legs. Switching is accomplished through the use of space vector pulse width/duration modulation (SVPWM). MATLAB/Simulink is utilized to implement the proposed control method. The effectiveness of the developed ANFIS controller is evaluated by comparison with the fuzzy logic (FL) and standard proportional-integral (PI) controllers. As demonstrates in Figure 12, the MF-IUPQC is formed by connecting two series VSCs and two shunt VSCs back-to-back via a common DC-link capacitor. Here, each VSC is separately controlled. Controllability and the generation of reference currents are the two primary considerations when operating the MF-IUPQC system. The most frequently utilized control



schemes in MF-IUPQC system control are synchronous reference frame (SRF) and PQ-theory.

The following are the major intuitions of this manuscript:

1. Based on ANFIs MF-IUPQC was developed in this article.
2. Enhances dynamic performance and provides smooth DC-link voltage.
3. THD is reduced below the IEEE 519-1992 permissible limit of 5%.

### 4.1 Control strategy

This design utilizes two VSC controls. Shunt voltage source converters (VSCs) regulate capacitor voltage and compensate for reactive and harmonic loads. Series VSCs minimize sag/swell, harmonics, and interruptions.

#### 4.1.1 Series compensation control

The SRF theory is used to control series VSC for each feeder, as illustrated in Figure 13A. Here, a three-phase source voltage is transformed to a rotating reference frame using Park's transformation. This is described in Eq. 7.

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin \omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos \omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (7)$$

The d-q frame reference voltage values are re-transformed into the abc frame using the inverse transformation procedure as described in Eqs 8, 9.

$$V_{dq}^* = V_{dqref} - V_{dq} \quad (8)$$

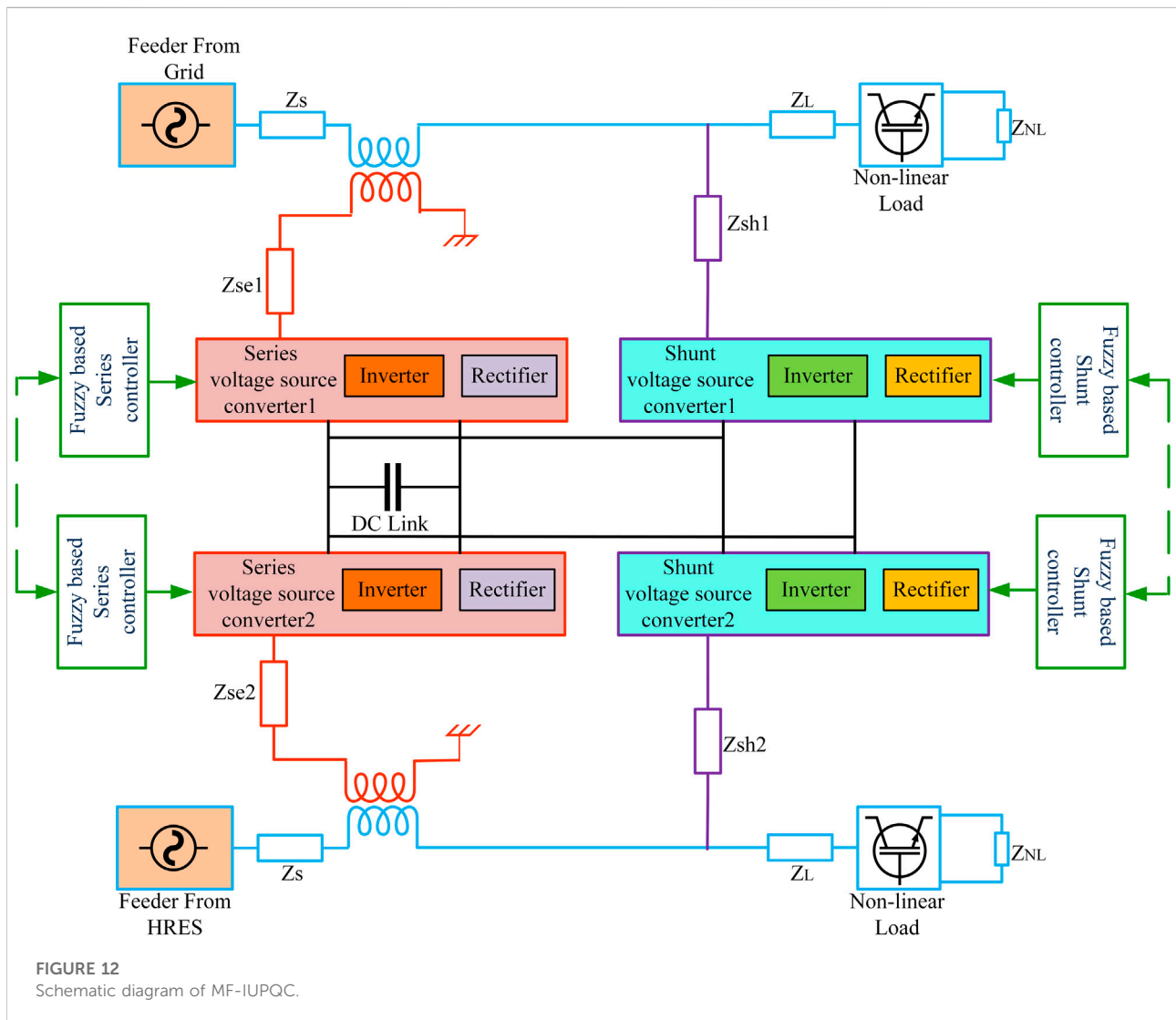


FIGURE 12 Schematic diagram of MF-IUPQC.

$$\begin{bmatrix} V_{La}^* \\ V_{Lb}^* \\ V_{Lc}^* \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \omega t & \sin \omega t & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \quad (9)$$

The switching pulses are obtained by comparing the reference ( $V_{Labc}^*$ ) and load ( $V_{Labc}$ ) voltages and then passing them *via* the SVPWM controller.

### 4.1.2 Shunt compensation control

The PQ-theory is used to control shunt VSC for each feeder, as illustrated in [Figure 13B](#). Here, the three-phase load voltages and currents are transformed to  $\alpha$ - $\beta$  coordinates. This is depicted in [Eqs 10, 11](#).

$$\begin{bmatrix} V_{L\alpha} \\ V_{L\beta} \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} I_{L\alpha} \\ I_{L\beta} \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \quad (11)$$

The instantaneous real and reactive components could be estimated using the above equations.

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_{L\alpha} & V_{L\beta} \\ -V_{L\beta} & V_{L\alpha} \end{bmatrix} \begin{bmatrix} I_{L\alpha} \\ I_{L\beta} \end{bmatrix} \quad (12)$$

### 4.2 ANFIS controller

ANFIS is a hybrid system that combines neural networks (NNs) and fuzzy inference techniques. Thus, it takes advantage of the fuzzy system’s ability to make inferences and the ability of neural networks to learn ([Pavan Kumar and Kartheek, 2016](#)). The ANFIS requires a collection of input–output data and maps the input data to the output using a set of membership functions (MFs). Ideally, the chosen MF should have as small an error as possible when comparing the actual output to the ANFIS-sketched results. To train the NN, we use a combination of the Gaussian MF and fuzzy input. The fuzzy inference system (FIS) is linked to a rule base in the NN block. The simulation parameters are shown below.

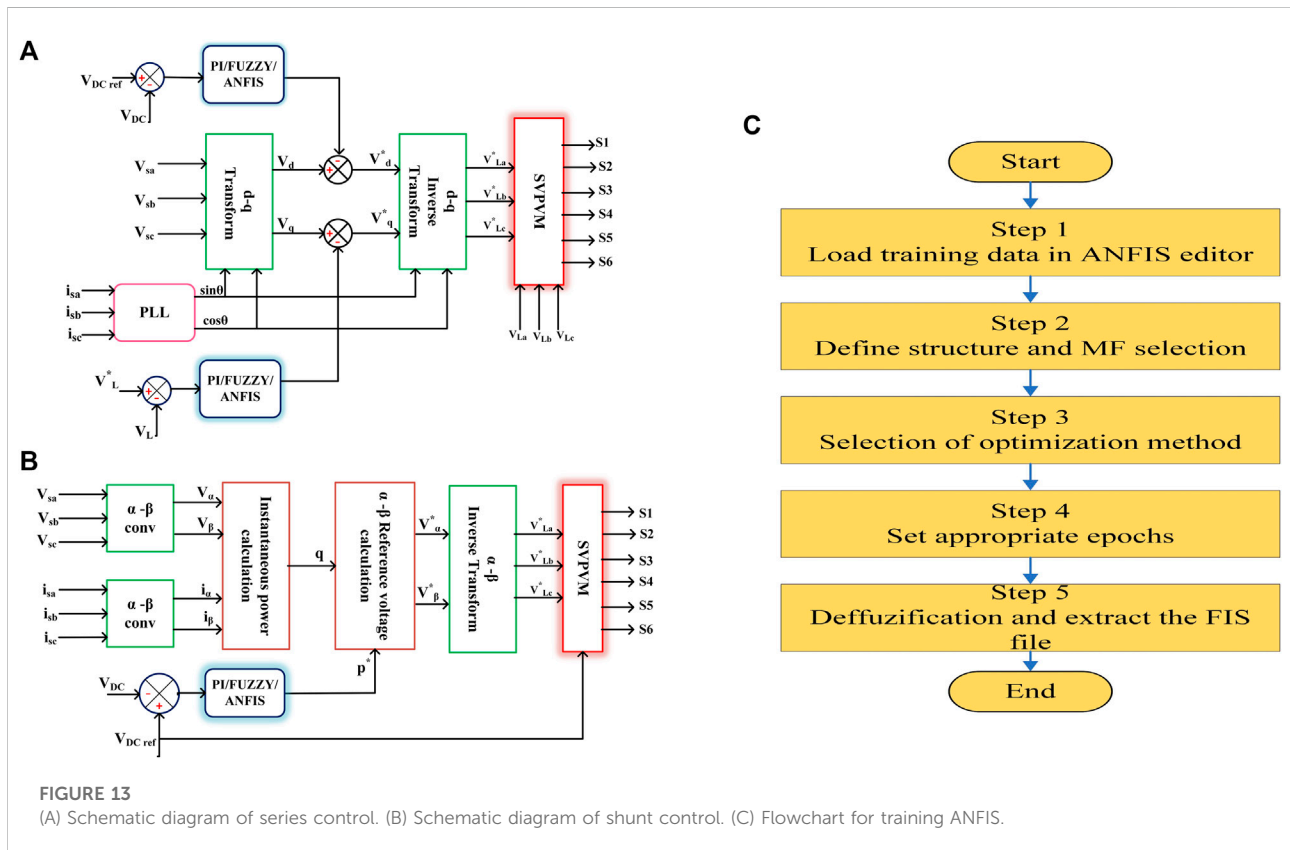


TABLE 9 THD during voltage harmonics.

Controller	THD during voltage harmonics			
	Over feeder 1		Over feeder 2	
	Source side	Load side	Source side	Load side
PI	30.17	5.21	28.26	4.83
FUZZY	30.4	3.71	27.28	3.60
ANFIS	30.35	2.73	28.14	2.08

Parameter	Value
Supply voltage of feeder 1 and feeder 2	11000 V
Supply frequency	50 Hz
DC link capacitor	2500 $\mu$ F
DC link voltage	1000 V
Battery capacity	58.5 Ah
BESS nominal voltage	576 V
PI controller gain	$K_p = 8$ ; $K_i = 120$
Fuzzy membership functions	7
Fuzzy rules	49
Type of MF in fuzzy	Triangular
Plot points	101
Number of Epoch	1000
ANFIS membership functions	3
ANFIS rules	9
Type of MF in fuzzy	Gaussmf

The FIS is being trained by BPA. The BP algorithm is utilized to train FFNN. Mamdani and Sugeno are the two most popular FIS (Kisi, 2013). Takagi Sugeno FIS is implemented in this case using ANFIS. Details of ANFIS training flowchart are depicted in Figure 13C.

#### 4.2.1 Simulation results and discussion

The performance of the MF-IUPQC is examined under voltage swell, sag, and harmonic conditions using ANFIS controlled MF-IUPQC. A nonlinear load is created by diode bridge rectifier; Third- and fifth-order harmonics are created deliberately in the two feeders; a voltage sag of 20% and a swell of 20% is introduced using a programmable voltage source.

##### Case 1: Performance of the system under voltage sag and swell conditions.

Voltage sag and swell are applied to the MF-IUPQC system over periods of 0.1–0.2 s and 0.3s–0.4 s, respectively. In Figure 14 the source voltages, injected voltages, and currents of both feeders using ANFIS controllers are presented.

From the waveforms, during voltage sag, the system voltage reduces by 0.2 p.u. magnitude while voltage swell increases it by 0.2 p.u. magnitude. Simultaneously, current increases in magnitude during the voltage sag period and falls in magnitude during the voltage swell period. To compensate for these effects, the series VSCs inject the compensating voltage and the shunt VSCs inject compensation current into the system. In other words, during low voltage, the reactive power from the DC-link capacitor is injected into the system.

From the DC link capacitor voltage waveform, demonstrating the system excellent dynamic response. A comparative analysis of response variables such as 1) rise time, 2) slew rate, 3) overshoot 4) settling time, 5) RMS voltage, 6) peak value, and 7) peak time values was conducted and is presented in Table 7.

##### Case 2: Performance of the system under current harmonics conditions.

A nonlinear load is created by diode bridge rectifier. In order to introduce nonlinearities into the load, the diode bridge rectifier supplies the resistive loads of 100  $\Omega$  and 200 ohms on feeders 1 and 2, respectively. The load, compensated, and source current waveforms of both feeders with ANFIS controllers are shown in Figure 15.

The load current of feeder 1 and feeder 2 is distorted (not pure sinusoidal) due to the presence of nonfundamental harmonics in the system. During current harmonics in the system, the shunt VSCs of IUPQC inject the compensating current into the system and the current harmonics get mitigated so that the waveform of the source current of both feeders is almost sinusoidal in nature.

The load current waveform contains harmonics due to the nonlinear load, whereas the source current is sinusoidal, resulting in a decrease in THD from load to source are tabulated in Table 8. From load current to source current the THD of first feeder is reduced from 8.46 to 1.32 percent and that of second feeder reduced from 7.69 to 1.56 percent. The DC link voltage demonstrates that the ANFIS controller performs well with current harmonics in the system.

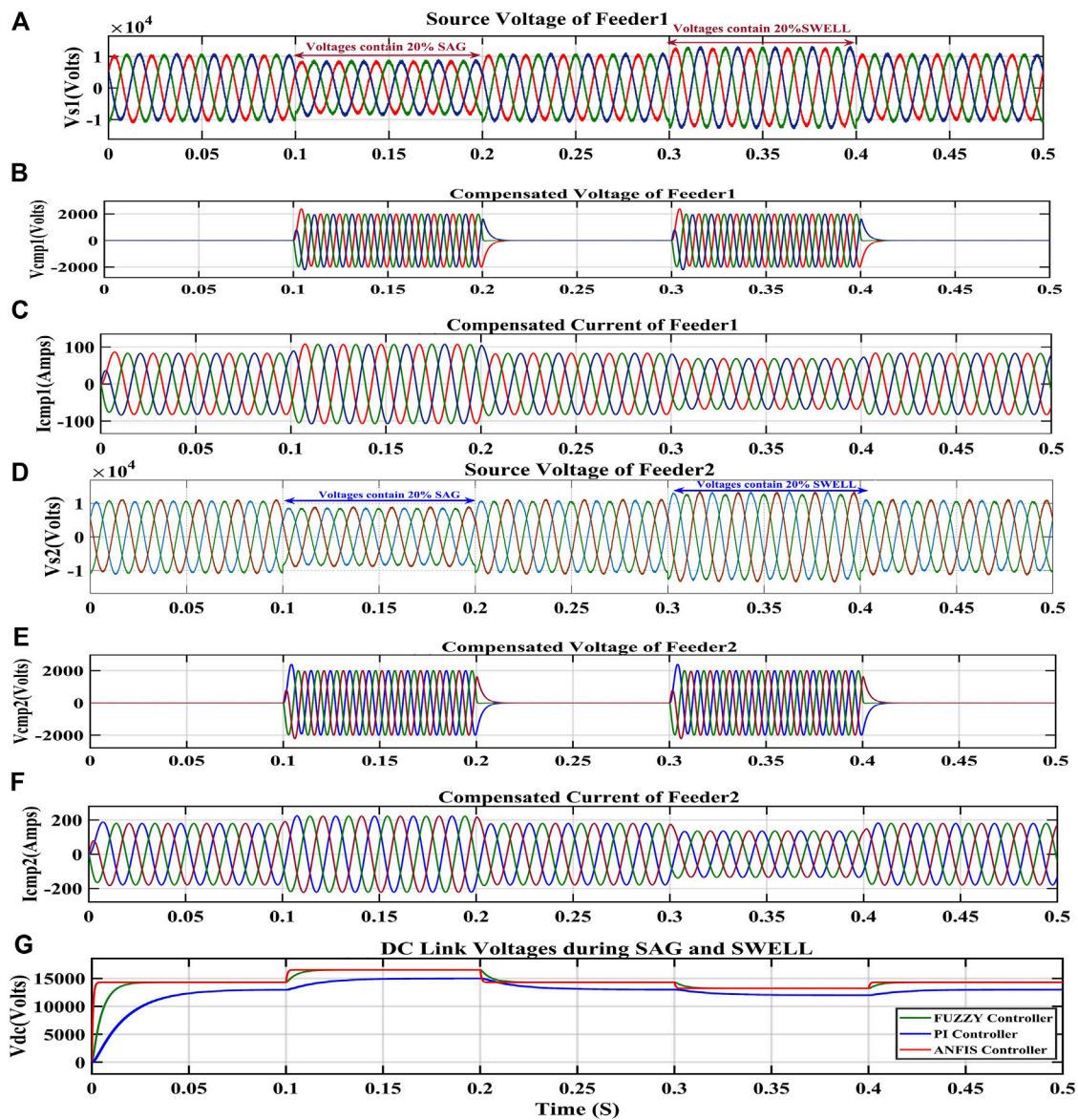


FIGURE 14 Waveforms of feeder 1 and feeder 2 under sag and swell.

**Case 3: Performance of the system under voltage harmonics conditions.**

In order to take into account, the voltage irregularities, harmonics of the third and fifth orders are purposefully generated inside the two feeds. To supply the loads, starting at  $t = 0.05$  s, the first feeder voltage is considered to have 15 percent third and 20 percent fifth-order harmonics, and the second feeder voltage is considered to have 15 percent third and 15 percent fifth-order harmonics.

The source, compensated, and load voltage waveforms of both feeders with ANFIS controllers are shown in Figure 16. The source voltage waveform of feeder 1 and feeder 2 contains

harmonics, whereas the load voltage is sinusoidal due to compensation voltage by the series VSCs of IUPQC, resulting in a decrease in THD from source to load. These results are tabulated in Table 9.

Compensated voltages are applied to the load side of both feeders in order to correct distorted voltages on the source side. The total harmonic distortion (THD) of Feeder 1 has decreased to 2.73 percent from 30.35 percent while the THD of Feeder 2 has decreased from 28.14 percent to 2.08 percent. The DC link voltage waveform demonstrates that the ANFIS controller performs well with voltage harmonics in the system.

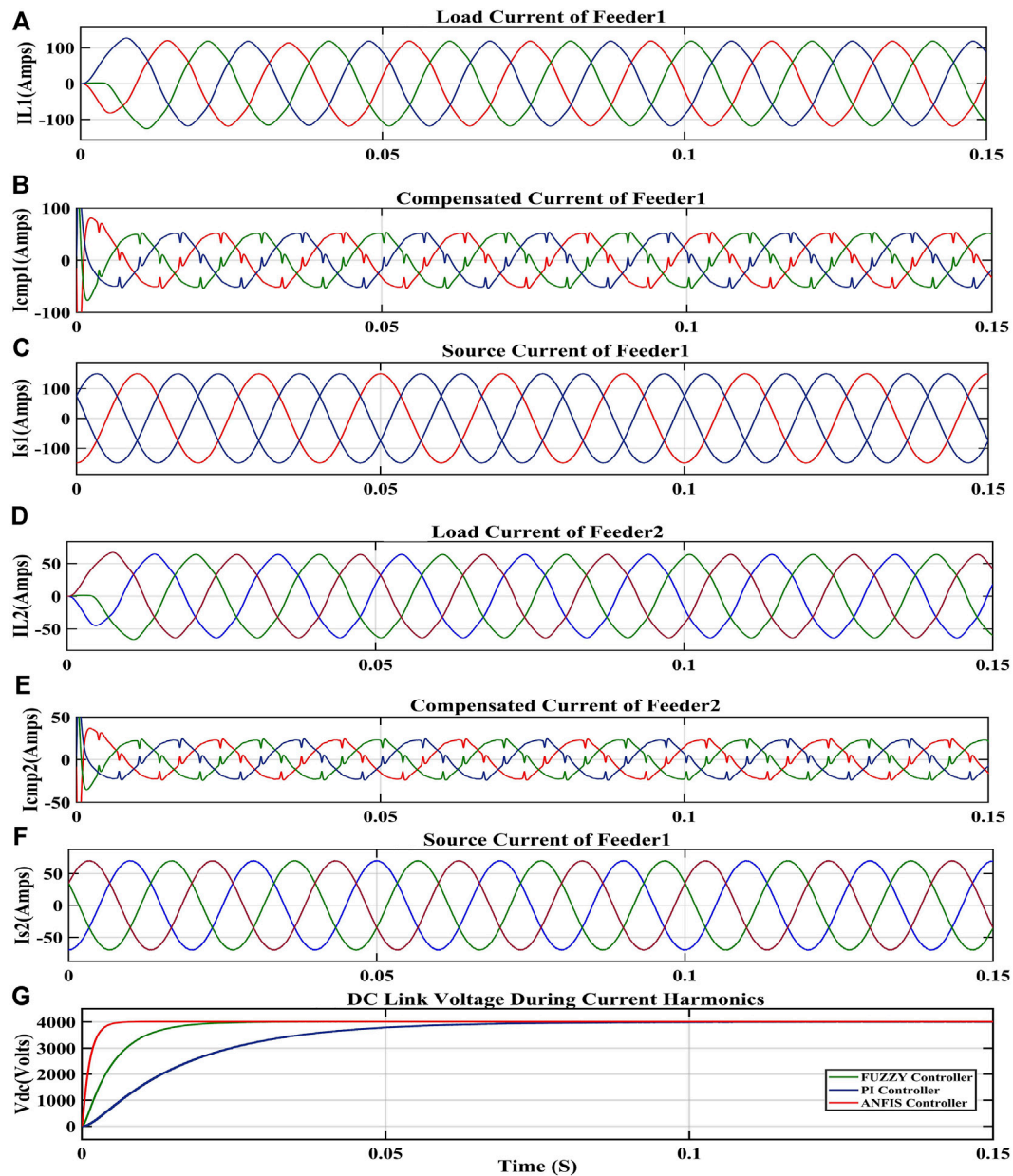


FIGURE 15 Waveforms of feeder 1 and feeder 2 under current harmonics.

### 5 Overall review of PQ mitigation techniques

Reviewing the literature, we can come to the following inferences and make recommendations for further studies:

- From PQ analysis tools we found that Fast Fourier transform (FFT), singular value decomposition (SVD),

and artificial neural network (ANN) are mostly used to analyze harmonics.

- In PQ monitoring system, current transformers (CTs), potential transformers (PTs), and transducers (XD) are used as sensors for collecting data and analyzed the data using data visualization methods in the form of graphs. They can help in predicting the power quality. Artificial intelligence (AI) techniques are seldom used by



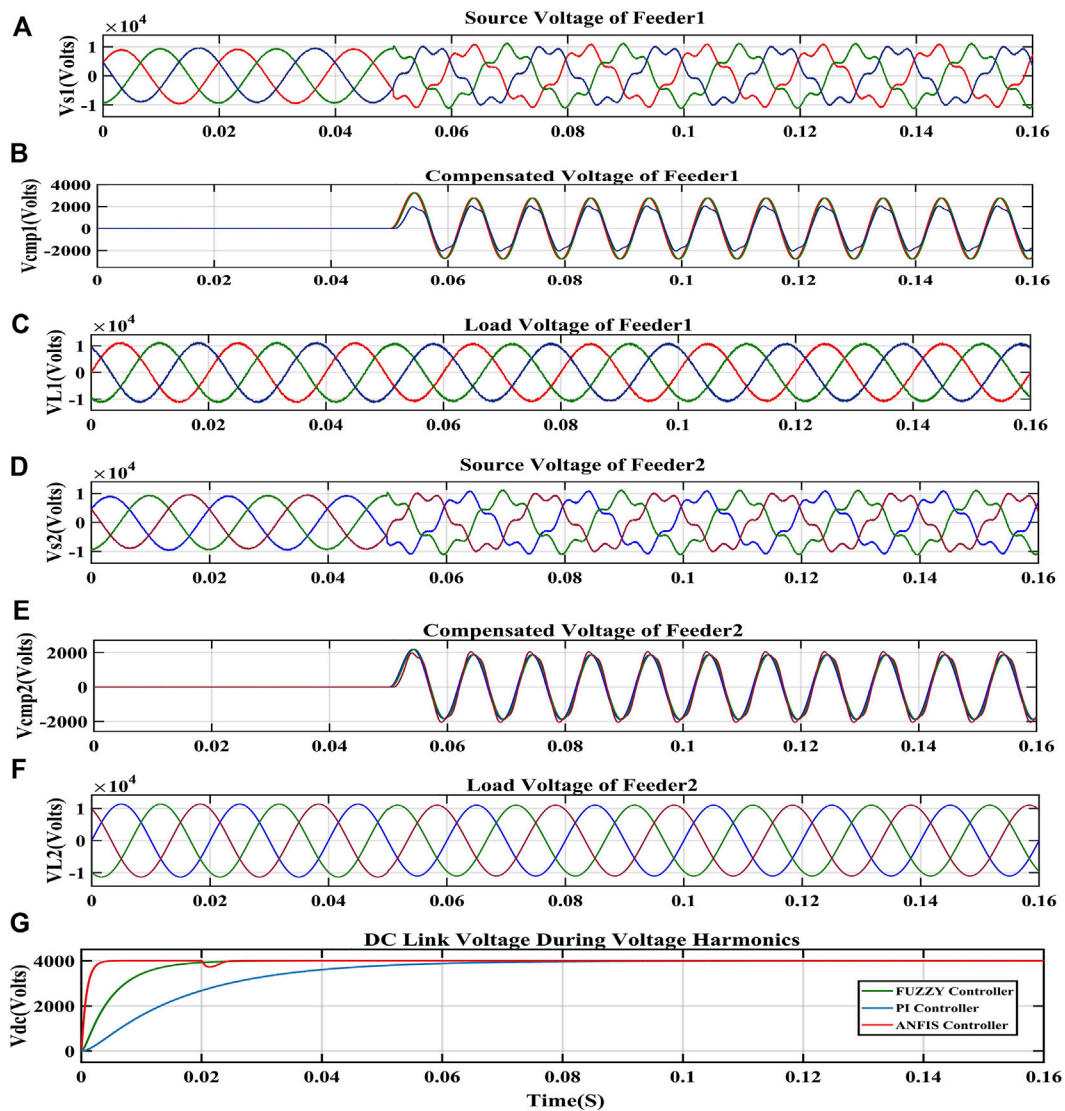


FIGURE 16 Waveforms of feeder 1 and feeder 2 under voltage harmonics.

researchers; they are the future solutions to analyzing and predicting more accurately.

- It can be observed that efforts to D-STATCOM placement and sizing optimization have made little growth over the last decade. It can also be inferred that most studies employed a single D-STATCOM to minimize power loss and did not investigate multiple D-STATCOMs in radial distribution networks. It is also determined that efficient D-STATCOM allocation for unbalanced distribution networks has not been done, and further research is suggested.
- By incorporating improved power converters into DVR, we may enhance its performance in terms of cost, efficiency,

reliability, simultaneous compensation of deep/long voltage sags/swells, and harmonics. The main focus has been on DVR and distributed generation integration. Future work should consider DVR, smart grids, and microgrids.

- This study briefly discusses the various configurations of UPQC. The UPQC scheme may be advantageous for concurrently resolving current and voltage-related power-quality issues.
- More changes will be made to power converters to increase power quality. Improved control strategies will be one among the enhancements. Using these control systems will allow for the production of more power with higher quality.
- Advanced microcontrollers and faster switching devices have led to more powerful, efficient, and affordable UPS systems



with and without transformers. New approaches are being developed to assure fast transient and dynamic response, reduced THD, effective voltage regulation, and load stability.

- If UPS technology improves, then fuel cells may replace batteries, and low-power applications will be beneficial. Fuel cells and supercapacitor UPS systems have not been much researched. Taking into account the pros of the hybrid system, we can expect an UPS system that is more advanced, has more features, and works better.

## 6 Conclusion

In this study, an attempt has been made to discuss a variety of PQ disturbances (PQDs) in AC and DC systems, PQ monitoring techniques, fundamental standards, and PQ mitigation approaches. Custom power devices such as DSTATCOM, DVR, UPQC, and UPS are the most recent evolution of interface devices designed to mitigate voltage/current disruptions and improve power quality by compensating for reactive and harmonic power generated or absorbed by the load. Finally, the use of an ANFIS in MF-IUPQC to address PQDs such as voltage/current fluctuations and harmonic distortions is described. To improve MF-IUPQC system performance, ANFIS was implemented and compared against PI and fuzzy. The presented system improves load voltage regulation and provides smooth DC-link voltage and harmonics compensation. The proposed systems' THD values for both the feeders are low when compared to those of competing controllers. The investigation found that the suggested MF-IUPQC system with ANFIS has better voltage profiles and harmonic reduction abilities.

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## Author contributions

Conceptualization, writing—original draft preparation, and editing: TR; conceptualization, review, editing, and supervision: KS. All authors have read and agreed to the published version of the manuscript.

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## Conflict of interest

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## Nomenclature

<b>DG</b> distributed generation	<b>IGBT</b> insulated gate bipolar transistor
<b>PQ</b> power quality	<b>EMI</b> electromagnetic interference
<b>CPD</b> custom power devices	<b>CT</b> current transformers
<b>PQDs</b> PQ disturbances	<b>PT</b> potential transformers
<b>SRCs</b> shunt reactive compensators	<b>XD</b> transducers
<b>SC</b> shunt capacitors	<b>MUX</b> multiplexers
<b>DSTATCOM</b> distribution static compensator	<b>ADCs</b> analog-to-digital converters
<b>DVR</b> dynamic voltage restorer	<b>S&amp;H</b> sample and hold circuits
<b>UPQC</b> unified power quality conditioner	<b>FFT</b> fast fourier transform
<b>UPS</b> uninterruptable power supply	<b>SVD</b> singular value decomposition
<b>PPF</b> passive power filters	<b>ANN</b> artificial neural network
<b>APF</b> active power filter	<b>MLFFNN</b> multilayer feed-forward neural network
<b>THD</b> total harmonic distortion	<b>ADALINE</b> adaptive linear neural network
<b>FACTS</b> flexible alternating current transmission system	<b>WT</b> wavelet transform
<b>SVC</b> static VAR compensator	<b>MRA</b> multiresolution analysis
	<b>HT</b> Hilbert transform