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Improvement of Power Quality with LPF-PI-MSRF Controller in Fuel Cell Integrated Unified Power Quality Conditioner

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Abstract: In modern world, power demand is increasing every day, and with that, power quality complications are also increasing. In order to rectify these power quality problems, we are using custom power devices to reduce these problems. In that custom power device, UPQC is the best device to reduce most of the power-related issues in the electricity market. The growing penetration of fuel cells and other renewable energy sources into the electrical grid calls for efficient ways to handle power quality problems. In order to develop power quality in dispersed generating systems, this paper suggests a novel approach that integrates a fuel cell (FC) with a unified power quality conditioner (UPQC). By reducing voltage sags, swells, harmonics, and other power quality disruptions, these technologies work in concert to create a power supply that is more dependable and resilient. The beneficial effects of fuel cells and UPQC combine in the Fuel Cell-UPQC (FC-UPQC) system. While UPQC is a flexible power-conditioning tool that can handle a variety of power quality problems, fuel cells provide clean and sustainable power generation. By integrating these technologies, a complete solution is achieved, which encourages the effective use of renewable energy sources while also guaranteeing a steady supply of electricity. The architecture of the FC-UPQC system is discussed in the article, along with an overview of its main parts and how they work. In order to maximize the integrated system's performance and guarantee smooth operation and significant power quality improvement, control solutions are discussed. The efficiency of the suggested FC-UPQC system under various operating situations and power quality disturbances is validated by the simulation results.

Keywords- Fuel cell (FC), Power Quality (PQ), Fuel cell integrated Unified Power Quality Conditioner (FCIUPQC), Distributed Generation (DG*)*.

I. INTRODUCTION

Increasing utilization of renewable sources into power systems has been prompted in recent years by a growing need for clean and sustainable energy solutions. Among these sources, fuel cells have emerged as promising alternatives, offering high efficiency and low environmental impact. Concurrently, the evolving power grid landscape requires advanced technologies to address issues with power quality imposed by distributed energy production. This paper introduces a pioneering concept: the integration of Fuel Cells (FC) with UPQC, to improve distributed generation systems' power quality [1]. Integration of renewable energy, particularly fuel cells, into power grids is essential for reducing dependence on conventional fossil fuels and mitigating environmental concerns. Distributed generation systems, with their decentralized nature, pose challenges related to voltage variations, harmonics, and other power quality issues[2].

Fuel cells offer a clean and sustainable energy source, with the potential for distributed energy generation, making them ideal for addressing environmental and energy security concerns [4]. Unified Power Quality Conditioners have proven effective in mitigating various power quality disturbances, making them a suitable choice for enhancing grid stability. The primary objective of the project is to establish an extensive approach (FCIUPQC) for power quality enhancement in distributed energy systems by developing and analyzing the combination of fuel cells with UPQC [5]. To create control schemes that minimize fuel cell and UPQC synergistic operation in order to reduce harmonics, voltage sags, swells, and other issues with power quality [6].The study focuses on architectural design, control strategies, and evaluation of the FCIUPQC in context of distributed generation systems. Economic and environmental aspects of deploying FCIUPQC are considered, emphasizing the potential benefits and feasibility of such integrated systems [24].

The world of today is experiencing a sharp rise in power quality (PQ) issues, with emission-free electricity being the only consistent power source. Power supply distortion, such as voltage sag-swell, and reactive compensation issues, affects AC power systems [5]. Electrical devices that receive poor power quality performs abnormally in AC loads [8],[9],[10]. To enhance the power quality, we have to use devices like UPQC to overcome all PQ issues. As seen in Fig. 1, this device customized device that combines a series APF and shunt APF with a DC capacitor. Common names for the SHAPF and SEAPF are DVR and DSTATCOM,

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respectively [3]. Now a day, the use of distributed generations is rapidly increasing due to the scarcity of power demand. Micro-turbines, fuel cells, biomass, photovoltaic, wind turbines that are commonly used for DG- Distributed generation [11]. This DG are applicable for standalone and grid-interrelated etc. By using these DG, we are having lot of benefits such as environmentally friendly and emission free power generation.

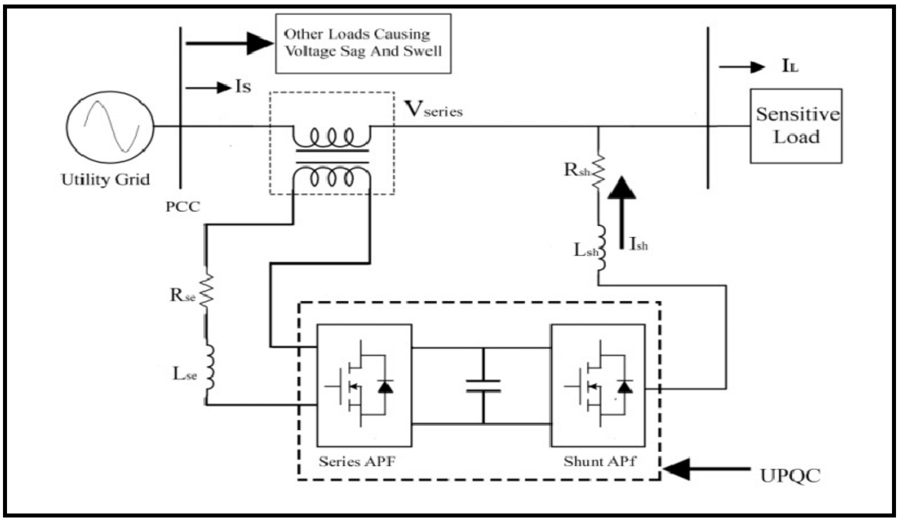

Figure. 1. Block diagram of UPQC

The literature review discussed fuel cells (FCs), a different source of energy that was highlighted by N. Agrawal et al. FCs generate heat, vapor, and water as byproducts [13]. FC comes with a boost conversion because the voltage needed level should be higher than supply. A comparison is made between the suggested approaches and the traditional average current mode control method. A. Ahmad, et.al 2019, Evaluate the efficiency of the permanent magnet synchronous generator [19]. Q. Chen *et al.* 2019, presents a review of hydrogen oxygen fuel cells. Employing the principles of both static and dynamic models, a simulation model of hydrogen oxygen fuel cells is constructed in this work. It has been confirmed that the simulation model's static and dynamic features match the hydrogen oxygen fuel cell well, improving the model's accuracy and reliability. F. El Otmani *et al.*2020, concentrate on going through the fuel cell limitations caused by the low provided energy and the nonlinear characteristic P-I [16]. Because of this, To increase the fuel cell's output of electricity and ensure that it tracks its maximum power point (MPPT), a two-stage converter is advised. M. Essoufi, et.al 2020, offers a fuel cell-powered primary source and a Li-Ion battery-powered secondary source energy management plan for a hybrid electric car [17]. Fuzzy logic underpins our suggested method, which respects both the battery charge and the dynamic limits of power sources to reduce hydrogen use while enhancing their longevity.

T. Hong, et.al 2020, the study presents a less cost with DC to DC converter with fuel cell electric car [14]. Three operation modes are proposed to meet the needs of the heavy-duty vehicle's powertrain system and fuel cell stack. X. Huang, et.al 2006,[18] In this paper, the fuel cell's DG application is given additional consideration. Within the context of DG, a comparison of various fuel cell types is done. O. Khurshid, et.al 2019, The work is to construct an experimental setup for assessing the performance of a hybrid system that consists of fuel cells, batteries, hydrogen production, and solar photovoltaics[20].

II. PROPOSED MODEL - FCIUPQC SYSTEM

In this paper, the combined operation of the UPQC with the dispersed generation was developed. The combined model contains series and shunt compensators collectively with dispersed generators, which were connected to the DC-link side through a rectifier. All voltage and current related issues in both interrelated and also in islanding mode were compensated by using this model.

The generation of renewable energy sources is rising daily in result of the massive rise in energy demand. As a result, distributed generation is emphasized as a solution to the problems encountered by conventional sources. The distributed generation integrated UPQC has a unique feature that even in grid failure uninterrupted power is supplied to load using distributed generation It eliminates issues affecting voltage and current in the power network and provides voltage aid in the event of a grid failure. [8]-[10].

Two sub-modes comprise the distributed generation integrated UPQC operation in the interrelated mode. There are two types of flow modes: forward and backward. When the mode is in forward flow, DG feeds power to the load through SAPF in addition to the main source, while in reverse flow, DG incorporates actual power into main source over a series APF. In the event of a fault, the proposed DG integrated UPQC switched from interconnected to islanded mode of operation, and SAPF supplied vital power to the load. The DG converter maintains the voltage at the PCC while the series APF is unplugged in islanded mode. As quickly as grid power is available again, the SAPF resolve the connection [24].

A system termed Fuel Cell Combined Unified Power Quality Conditioner utilizes power electronics and fuel cells to control the electrical power quality that is supplied to a load. [12].The FCIUPQC comprises of fuel cell, DC-DC converter, & unified power quality conditioner. The fuel cell generates DC power, which then stepped up or down by DC-DC converter and converted to AC power by DC-AC inverter. In order to provide the load a clean and steady electrical supply. [21], [22]. In this study, we integrate fuel cells with UPQC as a distributed generating system. Fuel cells work best in dispersed generating applications because of its fundamental property, which is their batteries' constant supply of hydrogen and oxygen. The fuel cell unit has a size range of 1 to 200 kW. Polymer-Electrolyte Membrane-PEM type FC is discussed in this work.

A PEM fuel cell consists of three components: the anode, cathode, and electrolyte. The electrode is made from porous with platinum material [23]. The porous electrode allows gases to pass through it. The chemical reaction that takes place in the electrolysis is shown

Anode Part - $H_2 \rightarrow 2H^+ + 2e^-$ (1)
Cathode Part - $0.5\ O_2 + 2H^+ + 2e^- \rightarrow H_2\ O$ (2)

The complete reaction is $H_2 + 0.5\ O_2 \rightarrow H_2$ (3)

Proton membrane fuel cell utilizes a solid electrolyte and requires a catalyst to initiate a reaction that generates the essential protons and electrons. A DC load is powered by these electrons, which are obtained at the anode terminals. The protons that are obtained at the cathode terminal simultaneously move in the direction of the interchange membrane. Water (H2O) is created at the cathode when protons, electrons, and oxygen (O2) mix. This chemical process results in the generation of electrical energy from the fuel cell [15].

The output voltage V_{FC} is

$$V_{FC} = E_{NERNST} - (V_{ACT} + V_{OHMIC} + V_{CON}) \quad (4)$$

for ƞ cells, voltage is given by

$$V_S = ƞ * V_{FC} \quad (5)$$

where E_{Nernst} - Thermodynamic potential,
$V_{ƞac}$ - Activation overvoltage,
$V_{ƞohmic}$- Ohmic overvoltage,
$V_{ƞcon}$ - Concentration over potential.

The Nernst potential E_{Nernst} is,

$$ENernst = [1.229] - [0.85 * 10^{-3} (298.15-T)] + 4.3085 * 10^{-5} *T* [0.5\ ln\ (P_{O2}) + ln\ (P_{H2})] \quad (6)$$

Activation Polarization Loss

It can be used to measure the catalyst effectiveness at a given temperature.

$$V_{ACT} = T[\zeta 1/T + \zeta_2 + \zeta_3 * ln\ (C_{O2}) + \zeta 4 * ln\ (I_{FC})] \quad (7)$$

Concentration Polarization Loss

$$Vcon = -B\ ln\ [1 - (J / J_{MAX})] \quad (8)$$

Ohmic polarization loss

$$V_{OHMIC} = I_{FC} (R_M + R_C) \quad (9)$$

Resistance to electron flow is denoted by Rc, and resistance to proton flow by RM.

The design process for a FCIUPQC starts by determining the appropriate sizing of various components such as the Renewable System, DC capacitor link, and DC voltage link level.

A. DC Link Voltage

It is defined by the system's per-phase voltage as well as the level of modulation used. The DC link voltage magnitude in a three-phase system needs to be more than twice the per-phase voltage's peak value. It is defined as,

$$V_{dc} = \frac{2\sqrt{2}\, V_{LL}}{\rfloor 3 * m} \quad (10)$$

It is assumed that the Depth of Modulation (m) is one

B. DC Capacitor (Link) Rating

The formula is as follows:

$$C_{dc} = \frac{23\ k\ a\ V_{ph} I_{sh}\ t}{0.5 * (V_{dc}^2 - V_{dc1}^2)} \quad (11)$$

Where, a - overloading factor = 1.5, t is the min time essential for achieving steady value, k factor reflects the variation in energy, where the value is 0.1.

C. Interfacing Inductor of SC-Series Compensator

The series compensator's interacting inductor's rating is influenced by factors such as the amplitude of the ripple current during swell conditions, the *f* switching frequency, and the *V* voltage of the DC link.

$$L_r = \sqrt{3} * M\ V_{DC} K_{SE} /(12af_{SE}\ I_r \quad (12)$$

D. Interfacing Inductor of SC -Shunt Compensator

The amount of the ripple current, the frequency at which the switches operate and DC-link voltage are some of the variables that impact the interface inductor rating in a shunt compensator. The mathematical formula for inductor is

$$L_f = \sqrt{3} * M\,V_{DC}\ /(12af_{SH}\,I_{cr}) \tag{13}$$

E. Series Transformer(injected)

The series compensator's modulation index should be kept close to unity in order to operate it with the fewest possible harmonics. The series injection transformer rating appears as follows:

$$S_{SE} = 3V_{SE} * I_S \tag{14}$$

F. Design of DC–DC with Boost Converter

The power input of DC-DC with boost converter is 133.7 W (PV rated power), and it's input voltage is 14.81 V (PV voltage), its final output voltage is 700 V, and switching frequency f is 10 kHz, and it's inductor current ripple and capacitor voltage ripple percentages are actually 1% respectively.

Table 1: FCIUPQC Parameters

System	Values
Source Voltage	3-Ph, 400 V, 50 Hz , Resistance: 0.1Ω; Inductance: 0.15mH
Series & Shunt compensator	Inductance: 3 mH
Injection Transformer	frequency:50Hz ,Voltage : 240 , Resistance :0.002,Inductance: 0.08
Link Capacitance	Capacitance:0.0022f ; Voltage: 700V
Loads	Unbalanced Load: 400V, f :50hz, Active power :5e3 & 10e3 Non Linear load: Resistance: 30Ω; Inductance: 20e3H

III. CONTROLLER DESIGN

The UPQC is based on two-control strategies .one on the Shunt converter side and other on the series converter side. We have to use these two types of converters to resolve the voltage and current-related problems. The two Converters area SHAF (shunt active filter) & SEAF (series active filters). Control strategies for these two are discussed below [8]-[11].

A. Control of SHAF

In shunt, active filter is connected across shunt converter, which is used to compensate all the current related issues at the shunt side of FCIUPQC system. A Shunt Active Filter typically operates by injecting compensating currents to the electrical system to counteract undesired harmonic currents and maintain a desired power factor. Here's a general overview of the control strategies employed in Shunt Active Filters, A common control strategy for Modified SHAF involves using a control for the compensating current, using a PI controller. The PI controller adjusts the amplitude and phase of the injected current to minimize the deviation of the system's current from the desired reference [12].

To determine the actual and reactive power components, the SHAF analyzes the instantaneous voltage and current. The controller then generates compensating currents to ensure that the reactive power is minimal or zero. Transforming the three-phase currents and voltages into a dq reference frame simplifies the control of SHAF. The controller operates in the dq frame to independently regulate the real and reactive power components. Hysteresis controllers compare the actual current with a predefined reference band. If the current deviates outside the band, the controller generates compensating currents to bring it back within the band. This method is effective for mitigating harmonic currents. Modified SHAF often employs PWM techniques to generate the compensating currents[7]. PWM ensures the precise control of the injected currents by modulating the width of the pulses based on the control signals. Adaptive control techniques adjust the controller parameters based on the varying characteristics of the load and system.

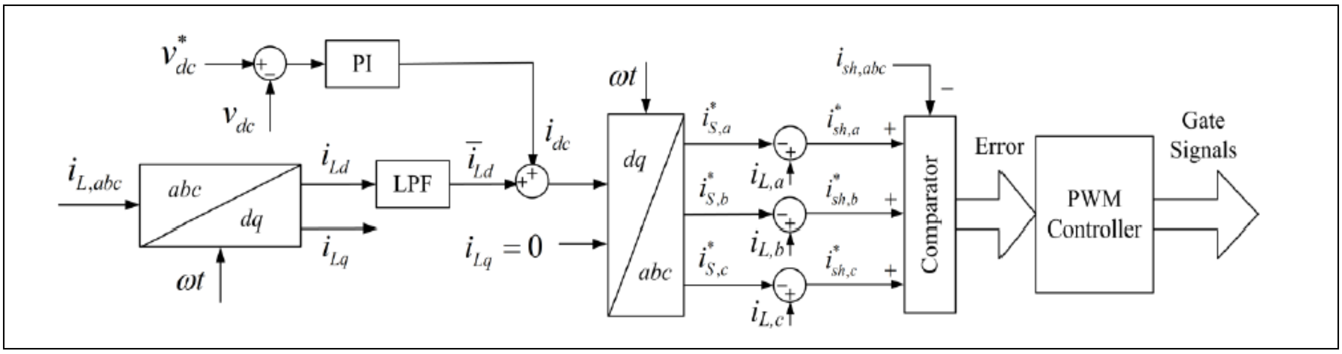

Figure 3. LPF-PI-MSRF Controller based Shunt Active Filter Control Structure

B. Control of SEAF

In series, active filter is connected across the series converter, which compensate all the voltage-correlated issues at the Series side of FCIUPQC system. In series, active filter inserts voltage in phase same as that of voltage across the grid. The control of a Modified Series Active Filter (MSEAF) is crucial for mitigating voltage sags, swells, and other disturbances in electrical power systems. Introducing compensating voltages to control the voltage at PCC, is the primary objective of a series active filter. [8].

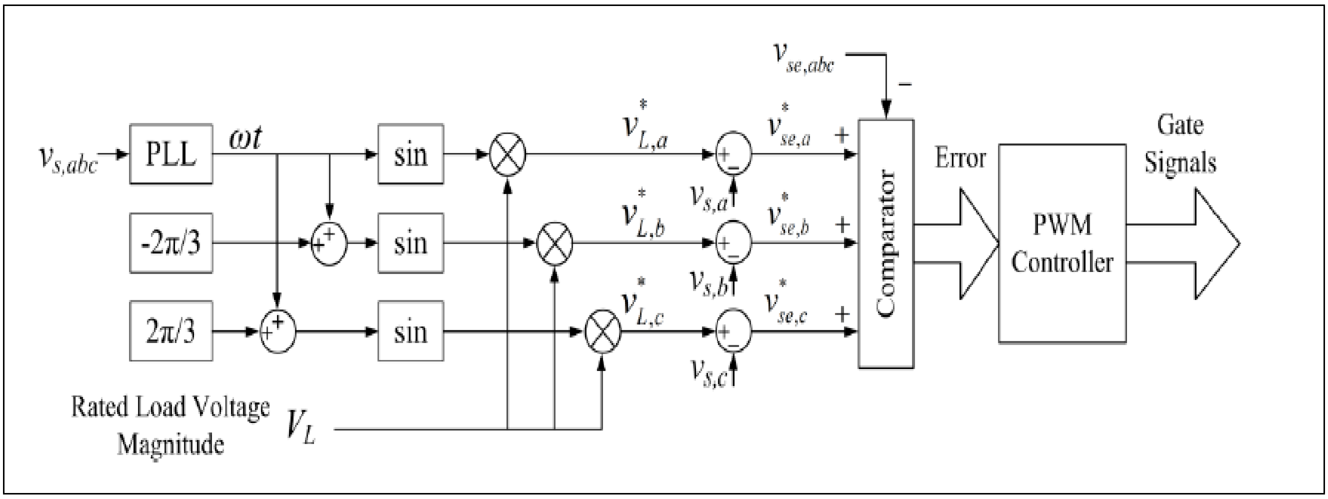

Figure 4. LPF-PI-MSRF Controller based Series Active Filter's Control Structure

Here's an overview of the control strategies commonly employed in Series Active Filters: The PI controller is a standard choice for regulating the compensating voltage in a SEAF. The controller generates compensating voltages to minimize reactive power and correct the system voltage. Transforming the three-phase currents and voltages into a dq reference frame simplifies the control of Series Active Filters. The controller operates in the dq frame to independently regulate the real and reactive power components. The Series Active Filter typically uses a Voltage Source Inverter (VSI) to generate the compensating voltage. VSI control involves modulating the output voltage based on the reference voltage and system conditions. Series Active Filters often employ PWM techniques to generate the compensating voltage. [9]

PWM ensures precise control of the injected voltage by modulating the width of the pulses based on the control signals. Hysteresis controllers compare the actual voltage with a predefined reference band. If the voltage deviates outside the band, the controller generates compensating voltages to bring it back within the band. Control strategies may include features to limit the injected voltage to a predefined maximum value.

IV. RESULTS

The proposed FCIUPQC's performance is examined with single and three-phase faults, linear, nonlinear, and unbalanced loads using MATLAB/Simulink.

A. Voltage Sag-Voltage Swell

The voltage sag/swell is occurred in grids due to instantaneous changes in loads. Due to this, Power Quality Problems are raised. Fig 5 and 6 shows the performance of FCIUPQC under such voltage conditions.

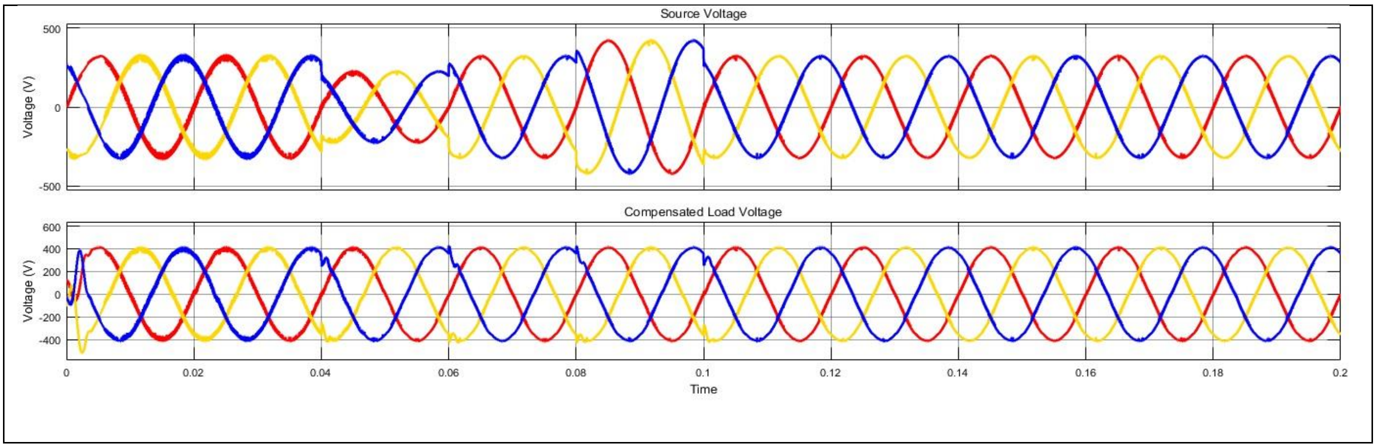

Figure. 5. Waveform for the Source voltage and Compensated voltage.

The Voltage sag exits during 0.04 to 0.06 seconds and voltage swell exits during 0.08 to 0.1 seconds.

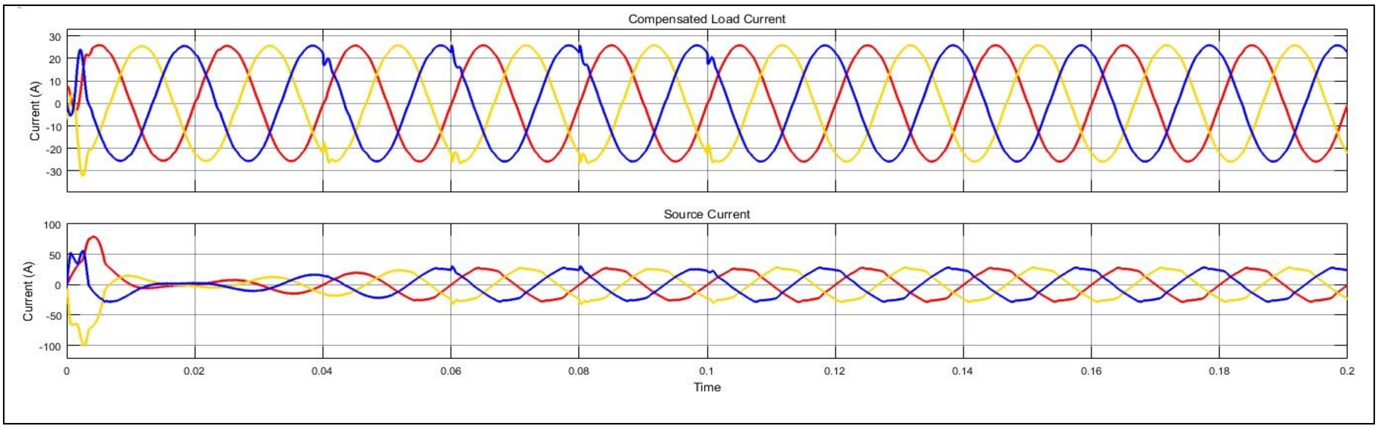

Figure. 6. Waveform of Compensated load Current and source current.

B. When load is Non-linear

A non-linear loads illustrate that current is not pure sinusoidal which contains harmonics that can cause power issues, this effect other devices which are connected to the grid. Fig7,8,9 shows the responses of load current, compensated load current and THD Values.

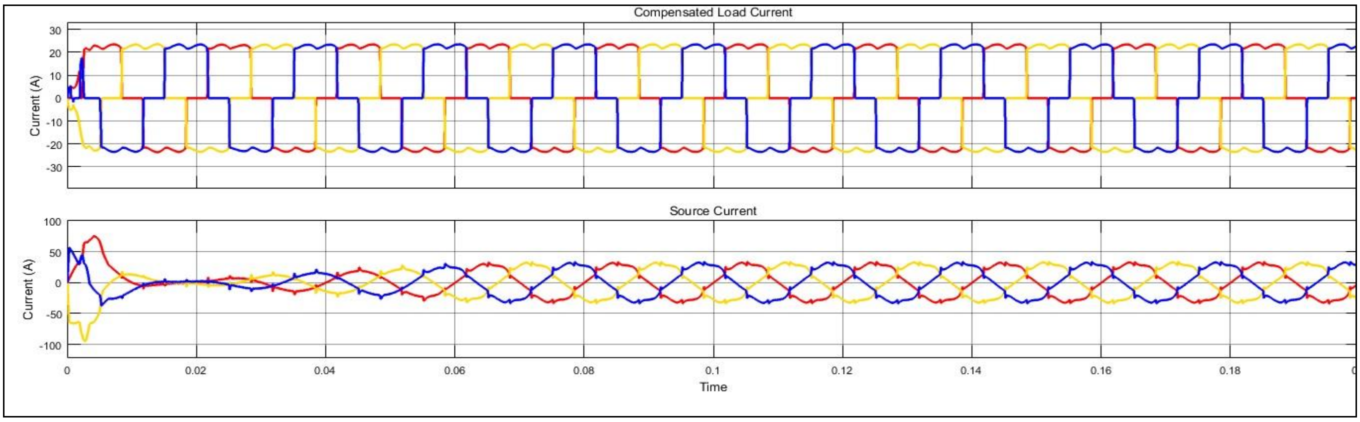

Figure. 7. Waveform of compensated load current and Source current.

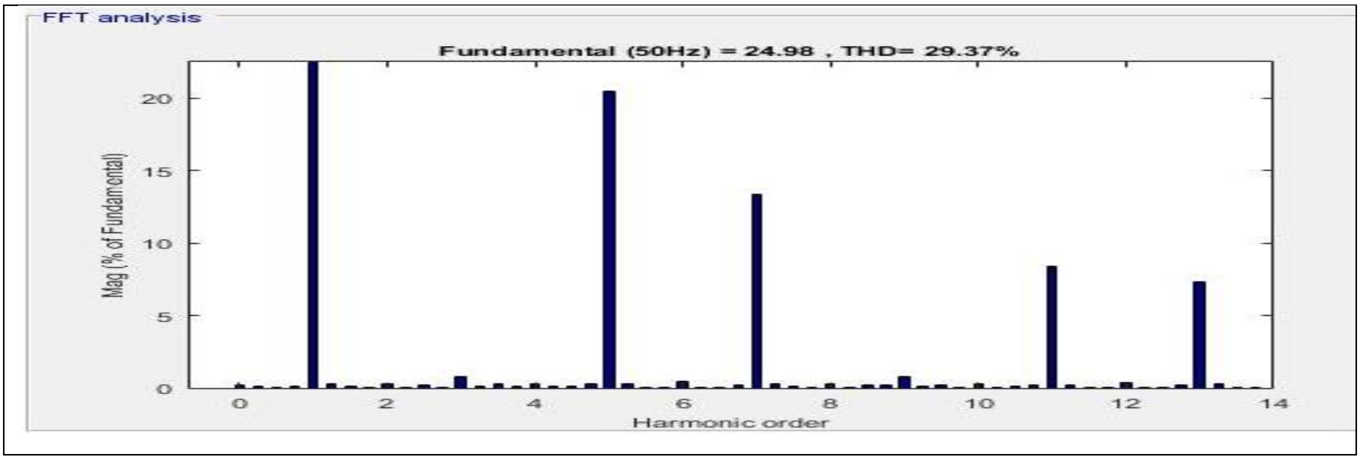

Figure. 8. THD Value before Compensation

We can see from the above figure that there will be a major improvement in THD. Figures 7 and 8 illustrate the THD values of the nonlinear load . Positively, THD has decreased from 29.37% to 8.86%.

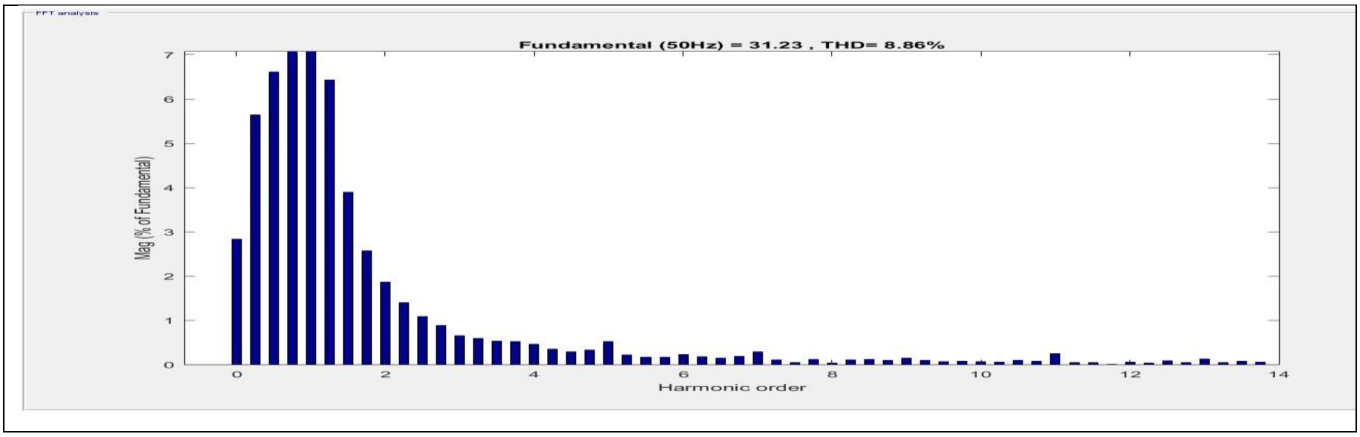

Figure. 9. THD Value after Compensation

C. When 1-Phase Fault Occurred

The Fig. 10 Shows, 1-Phase fault has occurred in Phase A at a time interval of 0.04 sec to 0.05 sec and also Compensated voltage and voltage inject by the inverter. Figure 10 and 11 shows the response of Voltage and Current Waveform with single Phase fault.

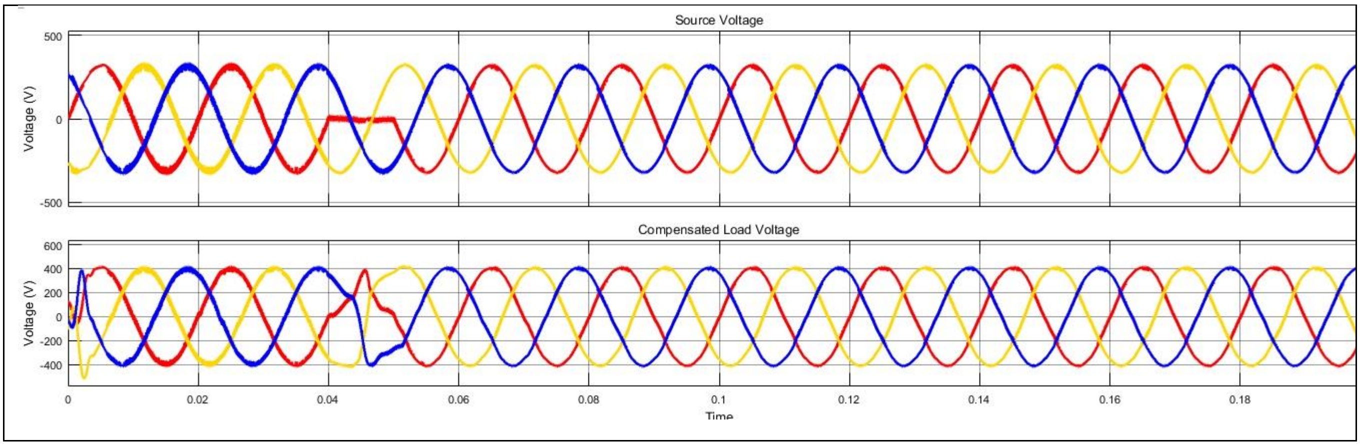

Figure. 10. Waveforms of Source voltage and Compensated voltage

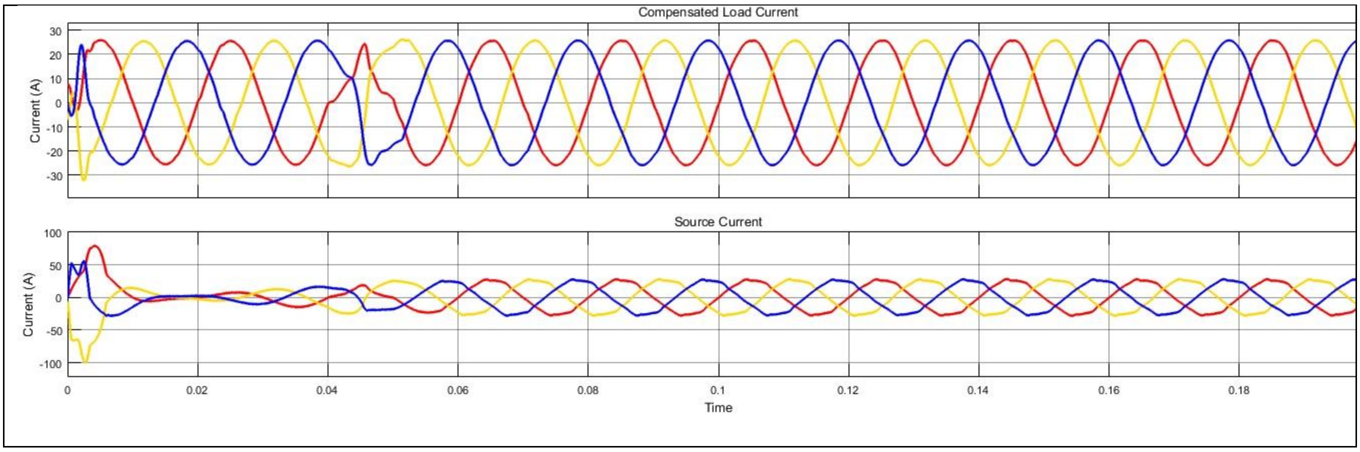

Figure. 11. Waveform of Compensated current and source current

E. When 3-Phase Fault Occurred

UPQC is able to compensate the absence of voltage in a short time. So, if three phase fault occurred across the load then the FCIUPQC compensate the voltage and current relates issues as shown in the fig12 and 13.

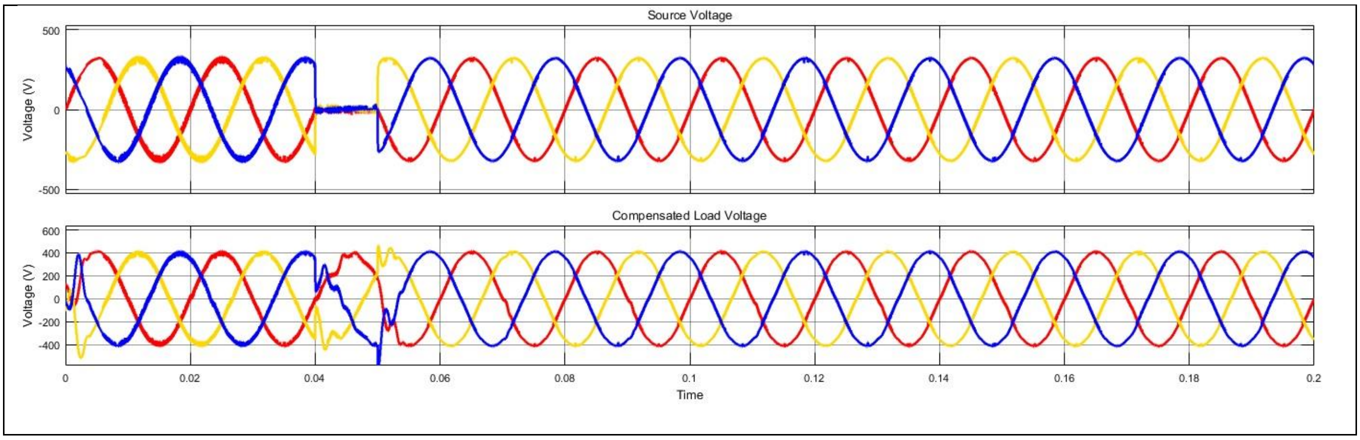

Figure. 12. Waveform of the Source voltage and Compensated voltage

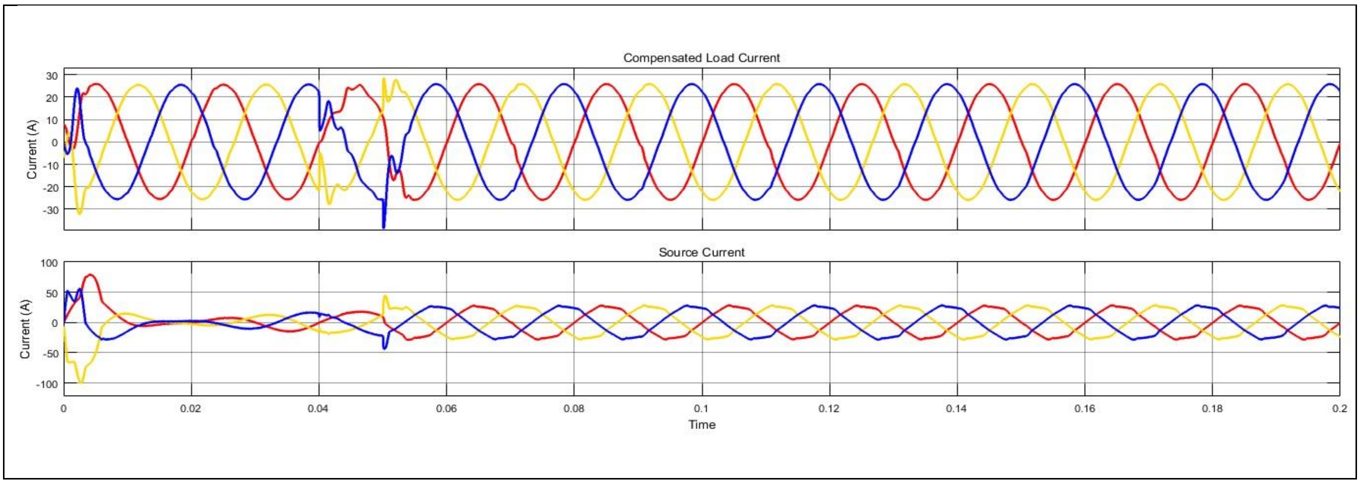

Figure.13 . Waveform of compensated Load current and Source current

F. When Load is Unbalanced

In order to make the three-phase load unbalanced we have to allocate different impedances for each phase, this shows that the load is unbalanced. Figures 16 and 15 show the responses of the source & compensated load voltage and load and current, respectively.

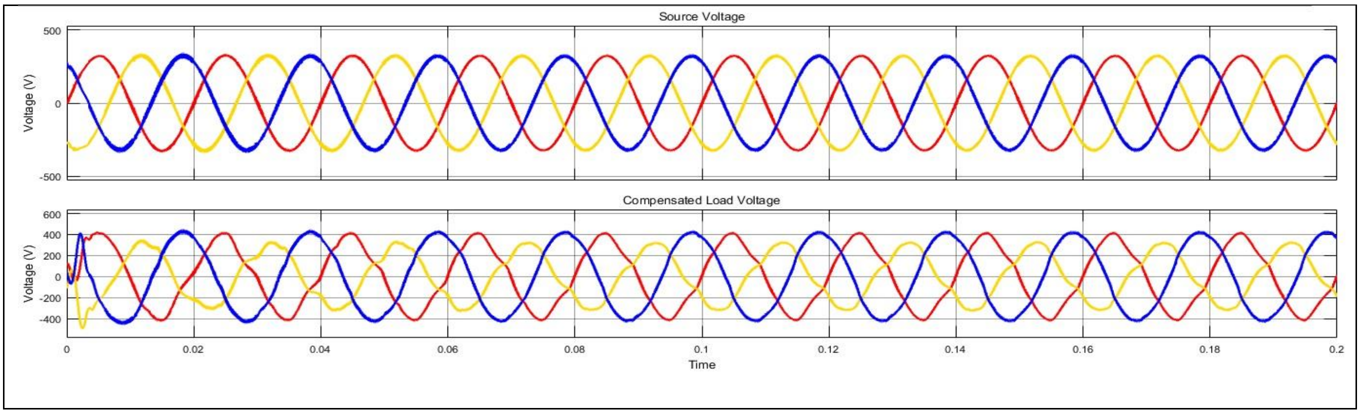

Figure. 15. Waveform for Source Voltage and compensated load Voltage

G. When Load is Resistive and Balanced

The response of power factor, reactive power, and active power for a resistive load linked to the grid is displayed in Figure 14.

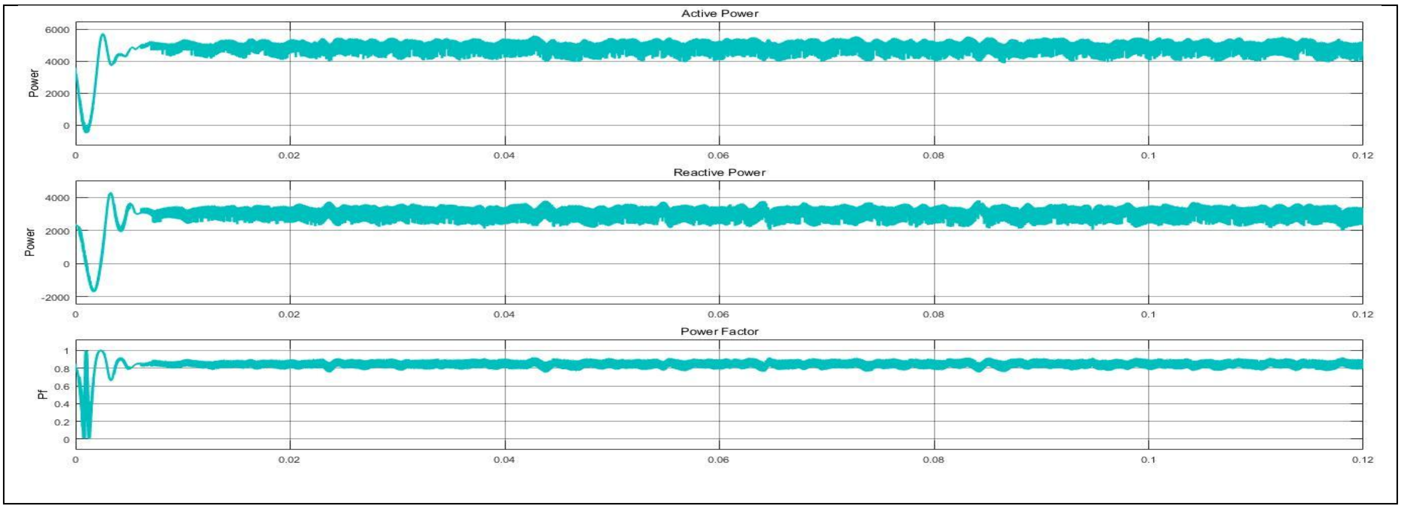

Figure. 14. Active power (P), reactive power (Q), and power factor (Cos Ø) waveforms

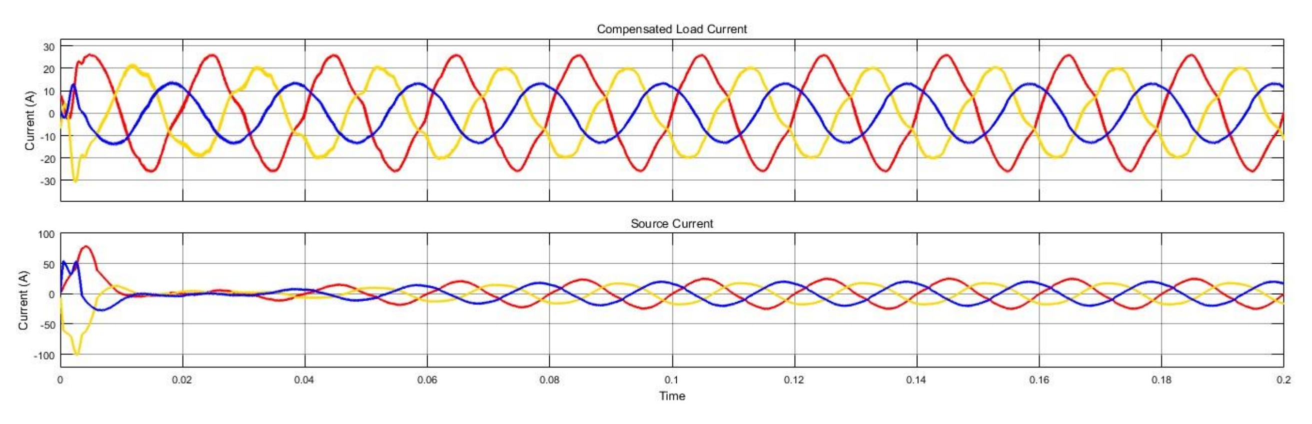

Figure. 16.Waveform for compensated load current and Source Current

Table 2: Voltage and Current of FC Based DG Integrated UPQC

Operating Conditions	Grid		Load		Grid	Load
	Voltage	Current	Voltage	Current	PF	PF
Voltage sag/Swell	400	24	400	26	0.9993	0.9996
Un balanced	400	24	400	25.5	09826	0.9992

3-Ph Fault	400	24	400	26	0.993	0.9999

Table 3: Harmonics of FC Based DG Integrated UPQC

Operating Conditions	Grid		Load	
	Voltage	Current	Voltage	Current
Voltage sag/Swell	8.66%	33.22%	6.23%	5.77%
Unbalanced	1.73%	39.98%	13.2%	10.62%
3-Ph Fault	34.16%	12.89%	8.89%	9.215

V.CONCLUSION

In the paper, the study is carried out on the FCIUPQC system's performance for voltage sag and swell, 1-Ø & 3-Ø faults, reactive power, and current compensation for non-linear loads and unbalanced loads. The execution of the FCIUPQC system has been verified in a MATLAB/Simulink environment. It was observed that the nonlinear load's harmonics are decreased by employing FCIUPQC. It is to be noted that FCIUPQC effectively compensates for the problems of supply failure, and it is an excellent solution for distributed generation to overcome all the power quality problems. Finally, the combination of fuel cells with UPQC presents a promising result for enhancing power quality in distributed generation systems. The FC-UPQC system not only addresses immediate power quality concerns but also aligns with the broader goals of achieving a sustainable and resilient power infrastructure. Furthermore, the environmental and economic benefits of the FCIUPQC system are highlighted. The utilization of fuel cells contributes to the reduction of greenhouse gas emissions, aligning with global efforts towards sustainable energy solutions. Additionally, the economic feasibility of deploying FCIUPQC systems in distributed generation scenarios is discussed, considering factors such as mathematical modeling and Simulation results power quality issues.

AUTHOR CONTRIBUTIONS

Methodology, software, analysis, conceptualization, and resources Author IES Naidu supervised the editing and review process, while author Satya Narayana Addala handled the writing. After reading the published version of the manuscript, the authors gave approval to it.

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DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

CONFLICTS OF INTEREST

No potential conflicts of interest were reported by the authors.

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