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| Research Article

Improvement of Power Quality Using a Hybrid Unified Power Quality Conditioner with Distributed Generation

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Annotation
Power quality disturbances such as voltage sags, swells, harmonics, and short interruptions can significantly impact the operation of sensitive electrical devices. This paper proposes a hybrid Unified Power Quality Conditioner (UPQC) integrated with Distributed Generation (DG) to improve power quality in distribution systems. The system combines series and shunt Compensator with renewable energy inputs to stabilize voltage, minimize harmonic distortion, and enhance supply reliability. Simulation results and model of a 50 KVA grid is considered. The Extensive simulation results have carried out in PSIM software based under various loading and fault scenarios confirm the system's effectiveness in mitigating power disturbances and supporting green energy integration. The hybrid approach demonstrates enhanced voltage regulation and total harmonic distortion (THD) reduction, making it suitable for the result produced by the proposed method it is compared with the conventional UPQC method.

Keywords: Power quality, UPQC, distributed generation, harmonic mitigation, voltage and current compensation.

I. INTRODUCTION

The quality of electrical power is a critical factor in the performance and longevity of modern electronic equipment. With the increasing penetration of nonlinear loads and renewable energy sources, power quality issues such as voltage fluctuations, harmonics, and momentary interruptions have become more frequent in distribution systems. The quality of electrical power is a critical factor in the performance and longevity of modern electronic equipment. With the increasing penetration of nonlinear loads and renewable energy sources, power quality issues such as voltage fluctuations, harmonics, and momentary interruptions have become more frequent in distribution systems. Series active filters connected through a common DC link. While this configuration efficiently manages conventional power quality problem, it integration with Distributed Generation (DG) can further enhance system performance by injecting locally generated renewable energy into the grid. The hybrid UPQC with DG not only addresses voltage sags, swells, and harmonic distortions but also contributes to improved system stability and energy sustainability. In this study, a simulation model of a hybrid UPQC integrated with DG is developed and analyzed. The objective is to evaluate the system's capability under various disturbance conditions using parameters such as voltage profile, harmonic distortion, and reactive power compensation. The simulation results validate the proposed configuration's ability to improve power quality and support the results are compared with DG and without DG and also compared form the source side and load side has been compensates the disturbances on both side with superior capability.

II. CONFIGURATION OF HYBRID UPQC

The Unified Power Quality Conditioner (UPQC) is a custom power device composed of two voltage source converters (VSCs) connected back-to-back with a common DC-link capacitor. One converter operates as a series active filter, which is connected in series with the supply through series transformers and compensates for voltage-related issues such as sags, swells, and harmonics. The second converter functions as a shunt active filter, connected in parallel with the load via an inductor, and is responsible for mitigating current-related disturbances such as harmonics, unbalance, and reactive power. The coordinated control of both converters allows the UPQC to maintain a regulated sinusoidal voltage at the load terminals and a balanced sinusoidal current from the source thereby enhancing the overall power quality at the point of common coupling (PCC).

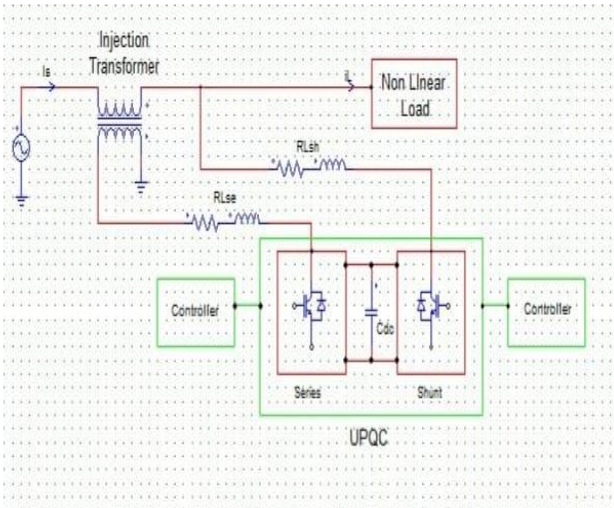


Fig. Schematic diagram of UPQC

A. shunt compensator Control

The shunt compensator, an essential component of the Unified Power Quality Conditioner (UPQC), is connected in parallel with the load at the Point of Common Coupling (PCC). Its main role is to address current-related power quality problems, including harmonic distortion, reactive power compensation, and load imbalances within the distribution system. By injecting or absorbing the required compensating current, it ensures that the source delivers only-frequency currents to the load balanced, sinusoidal, and fundamental frequency currents to the load.

$$i_d^* = i_{dDC} + i_{loss}$$

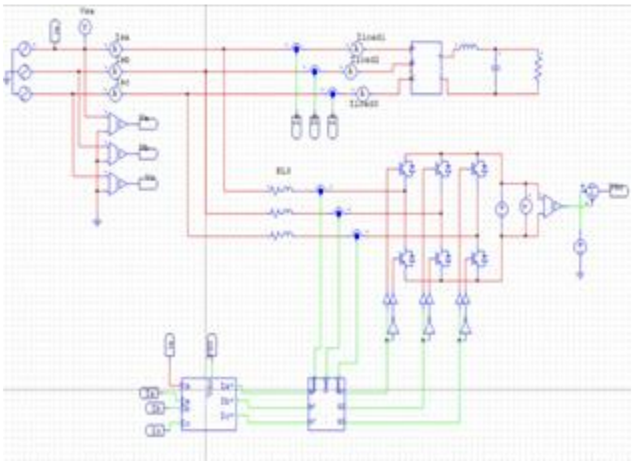


Fig 1 Simulation model of shunt Compensator

Designing a shunt compensator involves the careful selection of essential parameters, such as the DC bus voltage, the capacitance of the connected DC link capacitor, and the specifications of the interfacing inductor.

- **Shunt Controller Design:**

VDC=(2∗√2∗VLL)/(√3∗m)----------------- (9)

- Selectionof DCbus capacitor:-

12*CDC*(VDC2 –VDCL2)= 3k1Valt-------------------(10)

- Selection ofInductorforVSC

Lsh= (√3∗m∗VDC) /(12*a*fs*Icr.pp) ---------------- (11)

$$\begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad \text{------- (12)}$$

The design process for the shunt controller involves several key steps, as illustrated in, and fig 1 At the outset, the three-phase load currents ILA, ILB, ILC are measured. These currents are subsequently transformed into the dq0 rotating reference frames using the mathematical approach outlined in Equation (12)

If the source current contains harmonic components, the corresponding **dq0-**

$$\begin{aligned} i_q &= i_{qDC} + i_{qAC} \\ i_d &= i_{dDC} + i_{dAC} \end{aligned} \qquad (13)$$

$$i_d^* = i_{dDC} + i_{loss} \qquad (14)$$

$$\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \times \begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} \qquad (15)$$

Transformed currents will also exhibit both AC and DC elements, as expressed in Equation A Low-Pass Filter (LPF) is utilized to isolate the fundamental (DC) component by filtering out the harmonic (AC) elements. The utility power must correspond to the average (DC) part of the direct axis current to maintain a steady DC-link voltage and offset the internal losses within the active power filter (APF).The reference current in the d-axis is then calculated using: Equation (14) provides the reference current in the dq0 reference frame, which is then converted back to the abc frame using the inverse transformation shown in Equation(15).The reference current is fed to a comparator, which generates the corresponding switching signals used to control the operation of the shunt inverter switches.

- **Results of shunt comparator:**

The FFT analysis of the current waveforms depicted in Figures 6 and 7 is presented below. Table 1 summarizes the amplitude and percentage of the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic components relative to the fundamental current. It also provides a comparative view of these harmonic levels before and after the integration of the shunt compensator.

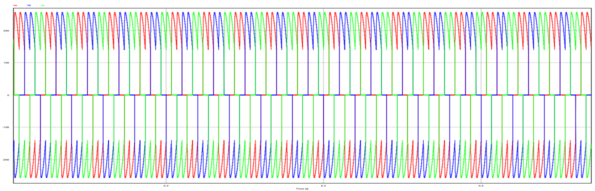


Fig 2 Current at PCC without Shunt Compensator

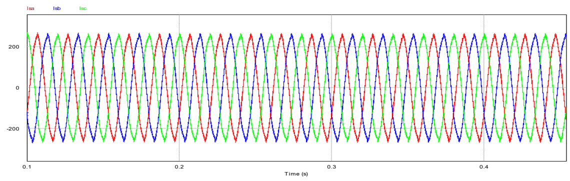
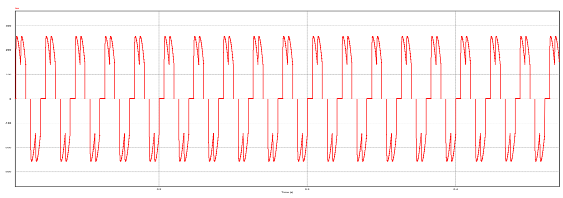
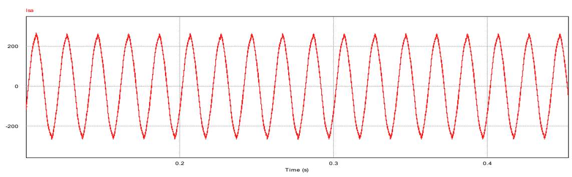


Fig 3 Current at PCC with Shunt Compensator



Time from 0.05s	Frequency 50HZ
Time to 0.3s	I(RL1a) 61%
R 2.25 ohm	I (RL1a) vs vsa(P.F.) 0.741

Fig 4 Current of Phase A at PCC without Shunt Compensator



Time from 0.05s	Frequency 50HZ
Time to 0.3s	I(RL1a) 3.54%
R 2.25 ohm	I (RL1a) vs vsa(P.F.) 0.84

Fig 5 Current of Phase A at PCC with Shunt Compensator

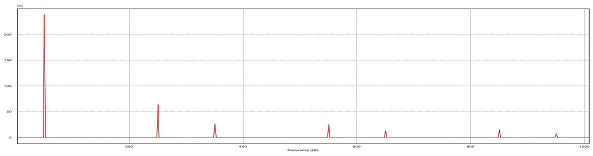


Fig 6 FFT analysis of current at PCC without shunt compensator

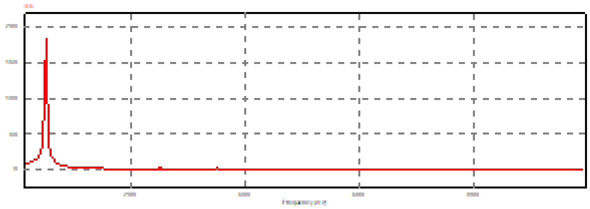


Fig 7 FFT analysis of current at PCC with shunt compensator

Based on the results, it can be concluded that the shunt compensator effectively mitigates harmonic distortion swell & sag. The current Total Harmonic Distortion (THD) at the Point of Common Coupling (PCC) has been effectively minimized, dropping from 61% to just 3.54%.Table 1 Shown to Voltage Harmonic Amplitude & Percentage Before and After Compensator

TABLE 1

Sr. No	Harmonics	Before compensation (amplitude)	After compensation (amplitude)
1.	Fundamental	235.88	236.87
2.	5th	64.29	2.94
3.	7th	27.18	2.34
4.	11th	25.91	1.49
5.	13th	13.58	1.30

B. Series compensator Control

A series compensator consists of the following components.

- voltage source converter (VSC) or Current source converter (CSC)
- Injection transformer (IJT)
- Series interfacing inductor (Lse)
- Energy storage element (CDC) (Capacitor for VSC and inductor for CSC)
- Controller
- Ripple filter

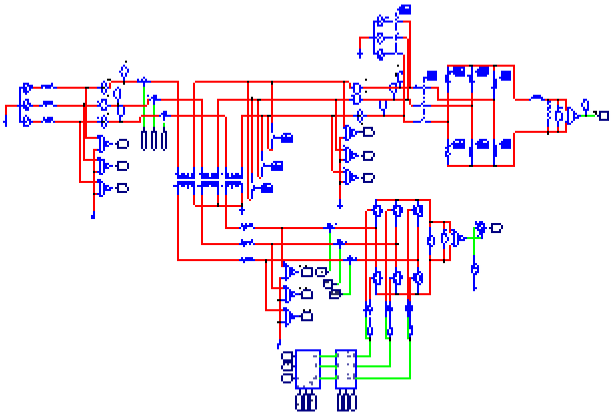


Fig 8 simulation model of series compensator

To address these power quality concerns, a series compensator, which includes a voltage and current source, is integrated at the PCC, utilizing an injection transformer for voltage and current injection into the compensator's operation. Based on these signals, the controller generates the necessary gate signals for the VSC switches to operate accordingly.

To design an effective series compensator, several key parameters must be determined. These include the required DC bus voltage, the size of the connected capacitor, the inductance value of the interfacing inductor, the power rating, and the turn's ratio of the injection transformer. Equations (9), (10), (11), and (12) are used to calculate these values.

Determining the DC bus voltage:-

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

Selection of DC bus capacitor:-

12 * CDC * (VDC2 – VDCL2) = 3 k1VaIt

Transformation ratio of transformer:

$$K_{DVR} = \frac{V_{VSC}}{V_{DVR}}$$

The reference frame theory serves as a fundamental

$$L_{se} = \left(\frac{\sqrt{3}}{2}\right) * m_a * V_{DC} * \frac{K_{DVR}}{6 * a * f_s * \Delta I_{DVR}}$$

tool in the design of this controller. By transforming the system variables into a synchronously rotating reference frame, complex AC system analysis can be simplified to DC equivalents, facilitating the design of linear controllers. The block diagram illustrating the implementation of this control strategy is presented in Figure 8 Sensed voltage at PCC are transferred to the dq0 frame using Equation.20.

$$\begin{bmatrix} V_{sq} \\ V_{sd} \\ V_{s0} \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \text{----- [20]}$$

The d and q axis voltages consist of both fundamental and harmonic components.

$$V_{sq} = V_{qDC} + V_{LqAC}$$

$$V_{sd} = V_{dDC} + V_{LdAC} \quad \text{---------- [21]}$$

The fundamental components are extracted using a Low-Pass Filter (LPF). To keep the voltage at the load terminal constant and equal to its reference value (VL*) the load terminal voltage is determined using Equation (22), and the output of the PI controller is used as the voltage injected by the Voltage Source Converter (VSC).

The reference quadrature axis load voltage is

The reference direct axis load voltage is

$$V_L = \sqrt{\frac{2}{3}} \times \sqrt{(V_{La})^2 + (V_{Lb})^2 + (V_{Lc})^2} \qquad \text{---------- [22]}$$

$$V_{Lq}^* = V_{qDC} + V_{qr} \qquad \text{--------- [23]}$$

$$V_{Ld}^* = V_{dDC} \qquad \text{---------- [24]}$$

$$\begin{bmatrix} V_{La}^* \\ V_{Lb}^* \\ V_{Lc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \times \begin{bmatrix} V_{Lq}^* \\ V_{Ld}^* \\ V_{L0}^* \end{bmatrix} \qquad \text{--------- [25]}$$

- **Results with Series Compensator**

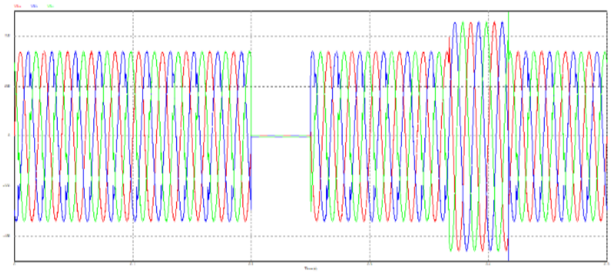


Fig 9 Voltage at PCC without Series Compensator

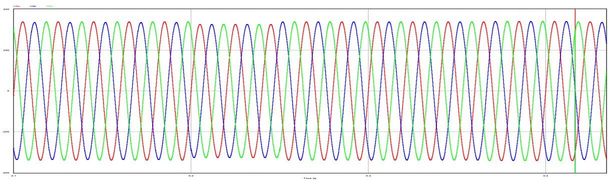


Fig 10 Voltage at PCC with series Compensator

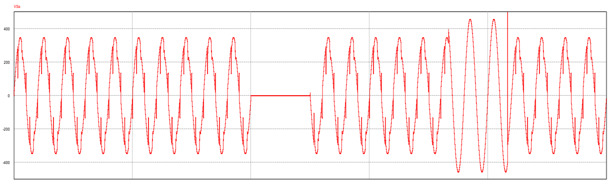


Fig 11 Voltage of phase A at PCC without series Compensator

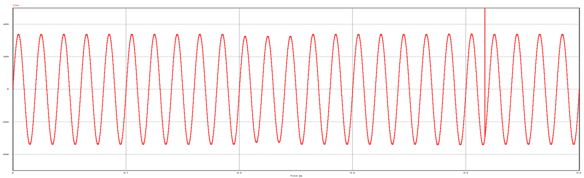


Fig 12 Voltage of Phase A at PCC with Series Compensator

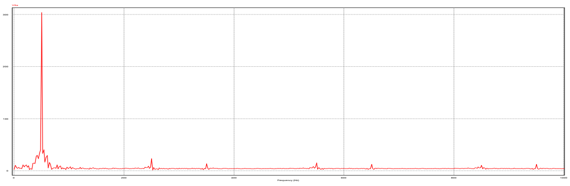


Fig 13 FFT analysis at PCC side without series active filter

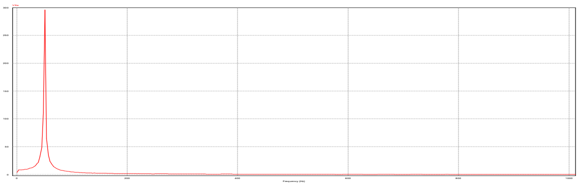


Fig 14 FFT analysis at PCC side with series active filter

Based on the results, it can be conclude that the series Compensator effectively mitigates Harmonic distortion Swell & Sag. Table 2 Shown to Voltage Harmonic Amplitude & Percentage before and After Compensation.

TABLE 2

Sr. No	Harmonics	Before compensation (amplitude)	After compensation (amplitude)
1.	Fundamental	304.1	318.92
2.	5th	23.28	1.34
3.	7th	13.91	0.29
4.	11th	12.98	0.27
5.	13th	12.67	0.25

III. COMBINATION OF SERIES & SHUNT UPQC COMPENSATOR

The Unified Power Quality Conditioner (UPQC) is an advanced system aimed at improving power quality by mitigating various voltage and current-related disturbances in distribution networks. It combines two key components—a series active filter and a shunt active filter—to ensure a consistent and high-quality power supply to consumers.

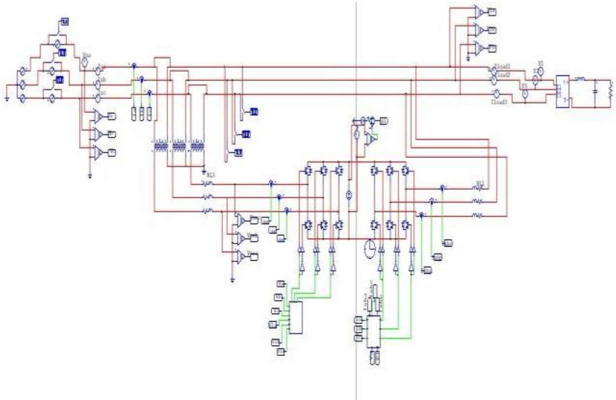


Fig 15 UPQC

The FFT analysis of the current and Voltage waveforms depicted in Figures 20 and 21 is presented below. Table summarizes the amplitude and percentage of the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic components relative to the fundamental current. It also provides a comparative view of these harmonic levels before and after the integration of the UPQC.

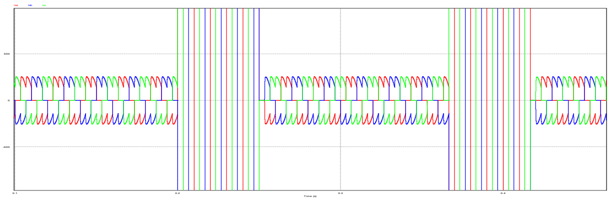


Fig 16 Current at PCC without UPQC

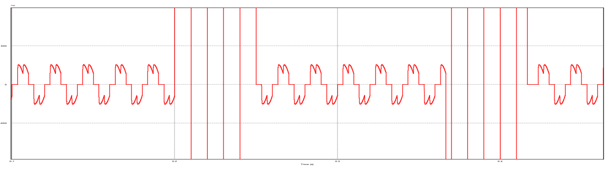


Fig 17 Current at PCC with UPQC

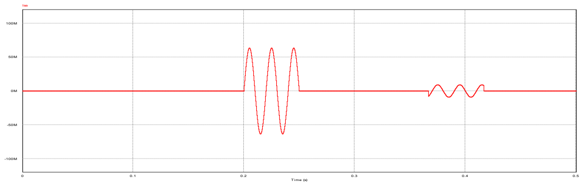


Fig 18 Current of Phase A at PCC with UPQC

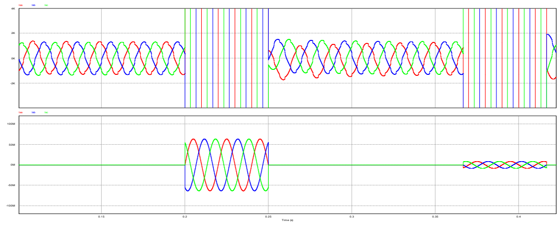


Fig 19 Current at PCC side with UPQC

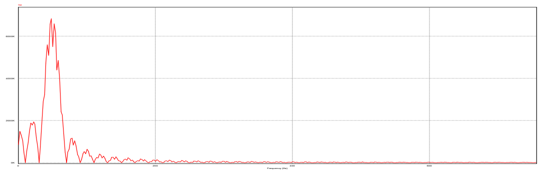


Fig 20 FFT analysis of Current at PCC side with UPQC

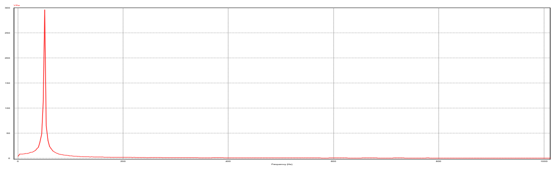


Fig 21 FFT analysis of voltage at PCC side with UPQC

TABLE 3

Sr. No	Harmonics	Before compensation (amplitude)	After compensation (amplitude)
1.	Fundamental	63917.55	65061.47
2.	5th	1661.24	56.1695
3.	7th	1174.34	26.02
4.	11th	754.22	23.4269
5.	13th	631.88	12.3879

TABLE 4

Sr. No	Harmonics	Before compensation (amplitude)	After compensation (amplitude)
1.	Fundamental	304.1	318.92
2.	5th	23.28	1.34
3.	7th	13.91	0.29
4.	11th	12.98	0.27
5.	13th	12.67	0.25

IV. DISTRIBUTED GENERATION

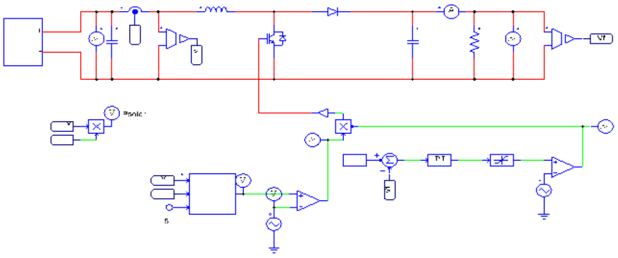


Fig 22 Simulation model of DG

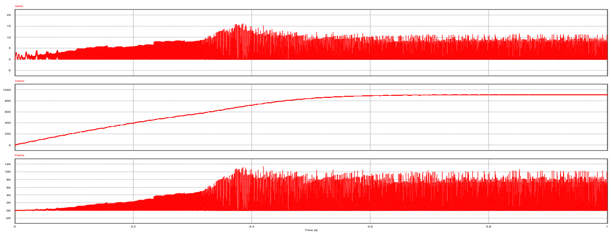


Fig 23 Output of Current, Voltage and Power

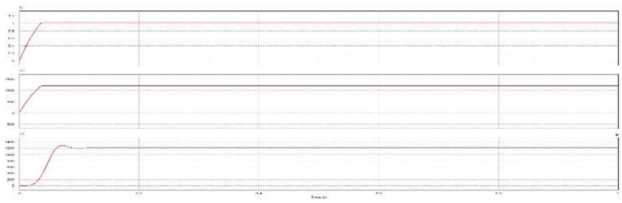


Fig 24 Output of Boot Converter I, V, P

V. COLLABORATION OF UPQC WITH DG

Figure 25 illustrates the simulation model of a UPQC-DG system integrated into a three-phase, three-wire distribution system. Figures 26 and 27 Voltage Waveforms and display the current waveforms at the Point of Common Coupling

(PCC) under two conditions: without controller implementation and with the controller in operation.

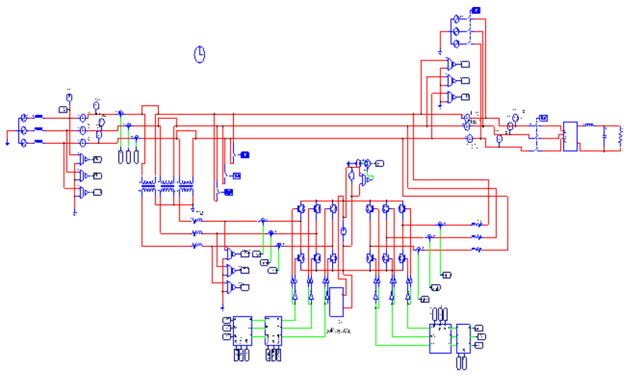


Fig 25 Simulation Model of UPQC–DG

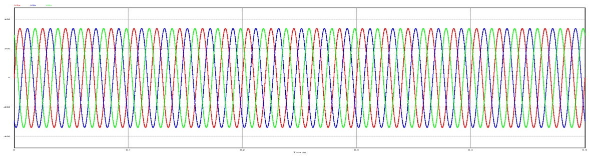


Fig 26 Voltage at PCC side with UPQC-DG

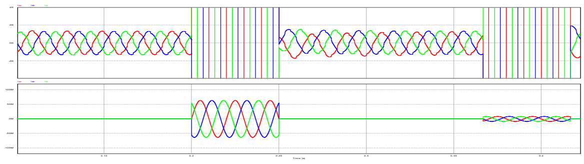


Fig 27 Voltage od Phase A with UPQC-DG

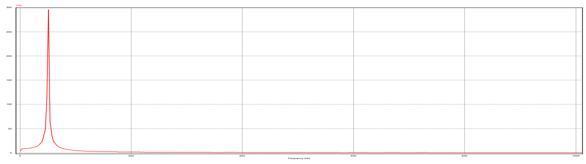


Fig 28 FFT analysis of V at PCC with UPQC- DG

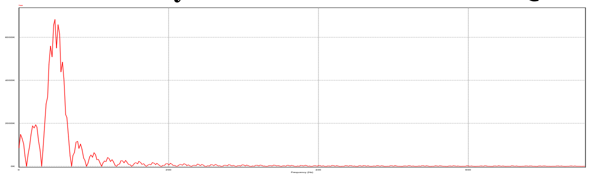


Fig 29 FFT analysis of I at PCC UPQC-DG

TABLE 5

Sr. No	Harmonics	Before compensation (amplitude)	After compensation (amplitude)
1.	Fundamental	304.1	320.9
2.	5th	23.28	1.03
3.	7th	13.91	0.24
4.	11th	12.98	0.22
5.	13th	12.67	0.19

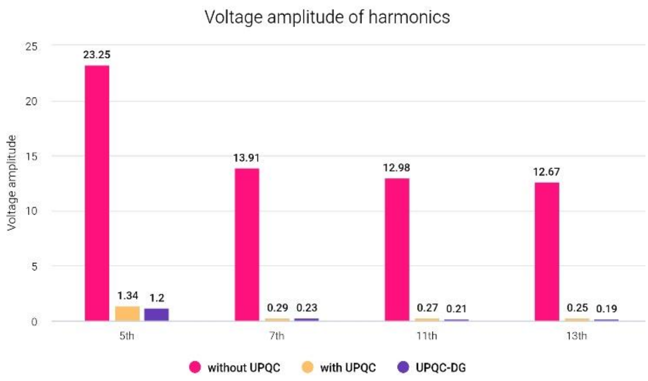


Fig 30 Voltage amplitude of harmonics

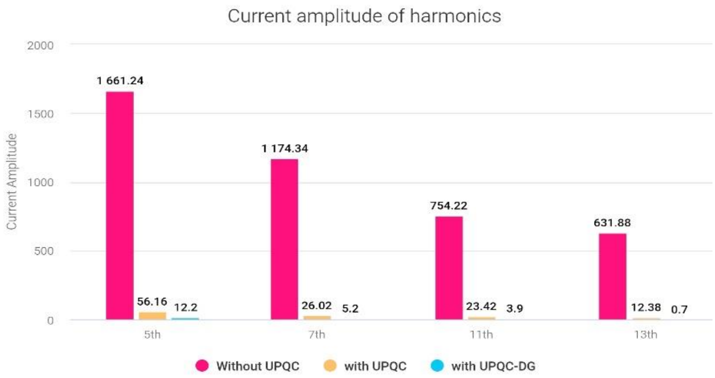


Fig 31 Current amplitude of harmonics

Conclusion

Simulation results carried out using the PSIM software validate the performance of the designed UPQC-DG configuration. A three-phase, three-wire distribution network with a non-linear load was modeled, incorporating both shunt and series compensators in conjunction with a photovoltaic-based distributed generator. The control mechanisms are implemented using dq0 transformation and PI-based control strategy. FFT analysis confirms notable improvements in harmonic suppression and effective mitigation of voltage sag and swell issues.

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