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A novel solar PV integrated fuzzy-logic controlled UAPQC device for power quality enhancement

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ABSTRACT

A novel solar photovoltaics (PV) connected unified active power quality conditioner (UAPQC) device is extensively adopted for enhancing the voltage and current quality of the distribution system. In a three-phase distribution system, the proposed UAPQC mitigates both load-side and source-side allied power quality (PQ) issues. Furthermore, as part of the distributed generation (DG) system, active electricity from solar PV is injected into the grid or source when solar PV is available. In this regard, the proposed UAPQC has been operated by using a workable control method, in both PQ improvement mode and DG incorporation mode. The direct current-link (DC-link) control of the shunt voltage source inverter (VSI) utilizes the proportional-integral controller, which is not suited for the regulation of DC-link voltage at the desired level because of improper selection of gain values. In this work, an intelligent fuzzy-logic DC-link control of UAPQC evidences the intelligent knowledge base for better regulation of power-quality issues. The suggested fuzzy-logic controlled UAPQC device's performance for both PQ improvement and integration of DG is validated using the MATLAB/Simulink computing tool, and simulation findings are given with an appealing comparison analysis.

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1. INTRODUCTION

The development of new industries, rapid population growth, and the diminishing of natural resources are the primary reasons for developing additional power generation units to meet the necessary power demand. Millions of rupees are spent to build modern power plants, and transmission facilities to meet the load demand [1]. Significant efforts have been made worldwide to adopt renewable energy for power generation such as distributed generation (DG) [2]–[5]. The DG primarily serves as a backup energy source to supply constant power for powering the load when power outages or grid isolation. The DG provides reliable energy, the required load demand, low transmission loss, and costs, as well as increased efficiency, [6]. In many numerous sources of energy, solar photovoltaics (PV) serves a significant part in the DG-powered distribution system due to its environmentally friendly, virtuous, abundant nature, and noise-free characteristics [7]. During DG operations, the absorbed solar energy is directly connected to the point of common coupling (PCC) of the distribution network via power-electronic converters with an appropriate control structure [8].

The successful operation of the DG scheme in distribution networks is dependent on a number of constraints, including stable-flexible power supply, continuous support, and power quality (PQ) norms [9], [10]. Because of the significant implications for users and utility-grid systems, receiving quality power is a lot of consideration in secondary distribution systems. It is expanding as a result of the widespread usage of massive power-electronic loads such as industrial speed drives, switched-mode load equipment, arc furnaces, heavy-inductive loads, and so on. The emergence of PQ issues causes severe issues in the distribution system, impacting supply terminal voltage, current, and fundamental frequency [11]. Poor PQ in the distribution system is primarily caused by supply voltage harmonics, sags-swells in supply voltage, current harmonics, unbalanced loads, low reactive power demand, and non-unity supply power factor, among other things [12], [13].

A lot of researchers and power professionals feel compelled to develop modern mitigation technologies using custom-power technology (CPT) [14], [15]. Various CP devices are available to alleviate respective PQ difficulties, resulting in a distribution system that is sinusoidal in nature, stabilized fundamentally based, and linear in nature. The static synchronous compensators, distribution static compensator (DSTATCOM) [16], an active power filter (APF) [17], dynamic voltage restorer (DVR) [18], and unified power quality conditioner (UPQC) [19] are examples of prominent CP devices. The UPQC is the most influential compensatory device for resolving both current-voltage-related PQ difficulties, according to the literature. The usage of voltage source inverter (VSI) components designed as a series shunt-constitute powered by a common direct current (DC) capacitor for PQ enhancement in distribution systems is investigated in [20]. On the other hand [21], looks at a solar PV-driven UPQC model for DG activities to control sudden load changes. Similarly, Yang and Jin [22] look at improving performance in doubly-fed induction generator-based wind energy systems with the use of UPQC equipment and a complex dual-control structure. Along with enhancing PQ, the introduction of renewable energy sources is critical for maintaining grid standards by using individual VSI operations, as stated in [23], [24].

The proposed unified active power quality conditioner (UAPQC) gadget necessitates well-functioning control algorithms to extract reference voltage and current signals from the supply voltage and nonlinear load currents. In general, the synchronous reference frame (SRF) control model [25] has been utilized to extract reference voltage to the UAPQC device's series-VSI, and the instantaneous real power (IRP) control model [26] has been employed to obtain reference current to the UAPQC device's shunt-VSI. The DC-link control of shunt-VSI utilizes the proportional-integral controller, which is not suited for the regulation of DC-link voltage at the desired level because of improper selection of gain values. In this work, an intelligent fuzzy-logic DC-link control of UAPQC evidences the intelligent knowledge base for better regulation of power-quality issues. The suggested fuzzy-logic controlled UAPQC device's performance for both PQ improvement and integration of DG is validated using the MATLAB/Simulink computing tool, and simulation findings are given with an appealing comparison analysis.

2. PROPOSED CONCEPT

Figure 1 depicts the design of the suggested multi-functional UAPQC device. The suggested UAPQC device is an excellent choice for driving a non-linear unbalanced load over a three-phase 3-wire secondary distribution system. The designed solar PV-connected UAPQC is built in a series-shunt fashion to a distribution system for DG operation and also to improve voltage and current quality. The UAPQC comprises dual-VSIs, control schemes, a gate-drive system, a DC-capacitor unit, and line interface filters. The UAPQC device of shunt-VSI operates as shunt-connected active filtering in PQ improvement mode, alleviating all current affiliated problems such as current harmonic distortions, load balancing, reactive-power control, and sustaining suitable power factor. The UAPQC of shunt-VSI is interfaced with the PCC of the distribution network through external an RL filter that eliminates inconsistent elements and notching impacts. Similarly, the series-VSI UAPQC device functions as a series-connected active filtering to alleviate all voltage-related issues such as voltage sag-swells and load balancing. The UAPQC of series-VSI is coupled to the distribution system of PCC via a 1:1 line connected transformer with external RC filters that eliminate inconsistent notching impacts.

The available solar PV electricity is sent directly into the distribution system in DG mode to compensate for fluctuations in load during the grid isolation condition. It also reduces supply current usage when solar PV power is available via a DC-DC boost converter; it achieves a high boost voltage, which is managed by an incremental conductance-maximum power point (INC-MPPT) control unit. Under fluctuating irradiance and temperature conditions, the INC-MPPT control unit maximizes power extraction from solar PV. The available solar PV power is transferred to the distribution system via the UAPQC device's shunt-VSI, which is controlled by the IRP controller.

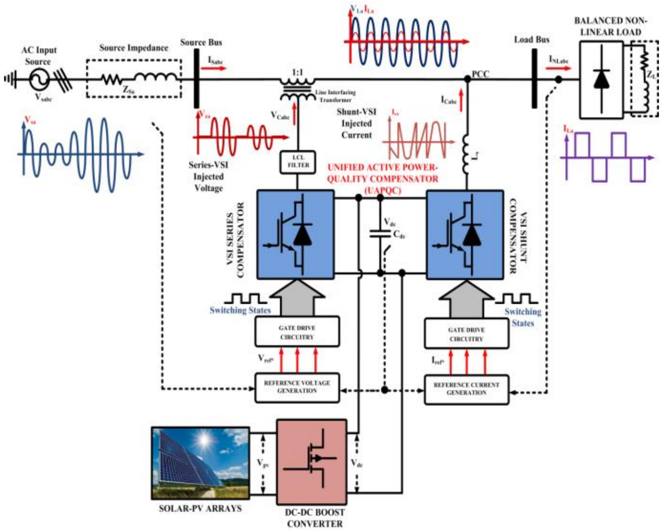


Figure 1. Design of suggested multi-functional UAPQC device

3. CONTROL SCHEMES

3.1. Synchronous reference frame controller for series connected VSI of UAPQC device

The UAPQC of series VSI is utilized to adjust for any voltage-related PQ concerns at the power distribution system's PCC. The effective operation of the UAPQC's series VSI is based on the development of a reliable voltage-reference signal utilizing an SRF control with a sufficient supply voltage setting. The schematic design of the SRF controller for the UAPQC's series-connected VSI is shown in Figure 2. The proportional-integral (PI) controller's result is interpreted as a voltage reference signal ($V^*_{dq.ref}$) since the error occurrences are minimized. The reference signals in the dq-frame are then re-transformed into the precise activity-based costing (ABC) using the inverse-Park's conversion method, as given in (1) and (2).

$$V^*_{dq.ref} = (V_{dq.ref} - V_{dq.act}) \tag{1}$$

$$\begin{bmatrix} V_{a.ref} \\ V_{b.ref} \\ V_{c.ref} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & sin\theta & 1 \\ cos\left[\theta - \frac{2\pi}{3}\right] & sin\left[\theta - \frac{2\pi}{3}\right] & 1 \\ cos\left[\theta + \frac{2\pi}{3}\right] & sin\left[\theta + \frac{2\pi}{3}\right] & 1 \end{bmatrix} \begin{bmatrix} V^*_{d.ref} \\ V^*_{q.ref} \end{bmatrix} \tag{2}$$

3.2. Instantaneous real power control for shunt-connected VSI of UAPQC device

In most cases, the IRP controller performs Clarke's translation technique, which converts conventional ABC into symmetric coordinates in a static frame. The (3)-(6) are used to calculate the immediate values of both real and reactive powers in a symmetric frame.

$$p = v_{st.\alpha} i_{NL.\alpha} + v_{st.\beta} i_{NL.\beta} \tag{3}$$

$$q = -v_{st.\beta} i_{NL.\alpha} + v_{st.\alpha} i_{NL.\beta} \tag{4}$$

In a symmetric frame, the affected non-linear load currents can be defined as (5).

$$\begin{bmatrix} i_{NL.\alpha} \\ i_{NL.\beta} \end{bmatrix} = \frac{1}{\Delta_k} \begin{bmatrix} v_{st.\alpha} & v_{st.\beta} \\ -v_{st.\beta} & v_{st.\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{5}$$

Where,

$$\Delta_k = v^2_{st.\alpha} + v^2_{st.\beta} \tag{6}$$

The resulting actual currents are then routed via a high-pass filter, allowing more complex elements to get particular signals that act as references. The high-frequency signal sections are treated, leading to an element of loss denoted as ($P_{.Loss}$). Additionally, by utilizing the right gains levels for the PI controller used in the DC regulation section, which is coupled to the basic controller, the DC voltage collected by the solar PV of the shunt-VSI remains continuously constant. The DC regulation section corrects errors induced by the variance of the real DC voltage ($V_{dc.a}$)and the corresponding reference DC voltage ($V^*_{dc.r}$). The (7) and (8) show the outcome of the controlling section at the nth point.

$$V_{dc.er} = V^*_{dc.r} - V_{dc.a} \tag{7}$$

$$\Delta_{ia.dc} = K_{p.d} * \left(V_{dc.er(n)} - V_{dc.er(n-1)}\right) + K_{i.d} * \left(V_{dc.er(n)}\right) \tag{8}$$

The performance and operation of a PI controller are always dependent on the choice of feasible gains with necessary steps using the Ziegler-Nichols method. Because of this method, the traditional PI controller does not auto-tune the gain values during parametric variations, sudden variations, and affecting the overall system stability. The significance of an intelligent fuzzy-logic controller in the symbolic representation of an inference system through eminent advanced knowledge is realized. This fuzzy-logic controller exemplifies the intelligent knowledge-based process, which includes fuzzy-logic membership functions and a fuzzy-logic rule base. These fuzzy-logic membership functions and fuzzy-logic rules are key components in fuzzy-logic controllers by incorporating significant human knowledge into an artificial knowledge base. Several attempts have been made to interpret the necessary enhancement in system performance by incorporating the superior learning technique to commute the fuzzy logic rules and fuzzy-logic membership functions. The fuzzy-logic rule base is the heart of fuzzy-logic control and the gathering of the necessary information for depicting data manipulation values, linguistic models, and fuzzy-logic rule characterization, among other things [27].

$$e(s) = V^*_{dc.r} - V_{dc.a} \tag{9}$$

$$\Delta e(s) = e(s) - e(s-1) \tag{10}$$

Where, $e(s)$ and $\Delta e(s)$ are the error and change in error. The related fuzzy-logic membership functions and fuzzy-logic rule base are depicted in Figure 3 and Table 1.

Figure 4 depicts the schematic architecture of the proposed fuzzy-logic IRP controller. As a consequence, the acquired reference currents($i^*_{cr.\alpha\beta}$) in the $\alpha\beta$ -frame are reverted into the initial ABC frame using the reverse of Clarke's translation procedure, yielding the final reference current ($i^*_{cr.abc}$) as illustrated in (9).

$$\begin{bmatrix} i^*_{cr.a} \\ i^*_{cr.b} \\ i^*_{cr.c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i^*_0 \\ i^*_{c.\alpha} \\ i^*_{c.\beta} \end{bmatrix} \tag{9}$$

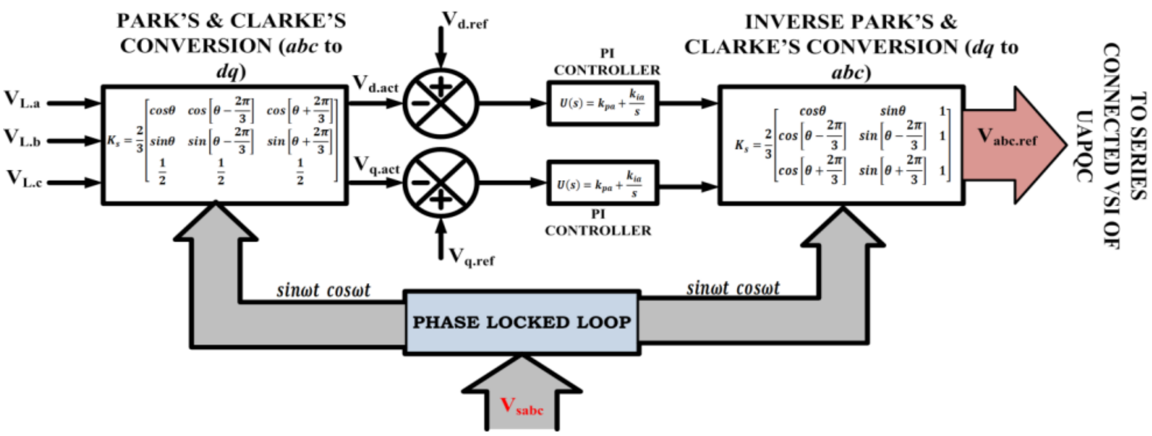


Figure 2. Schematic design representation of SRF controller for series VSI of UAPQC

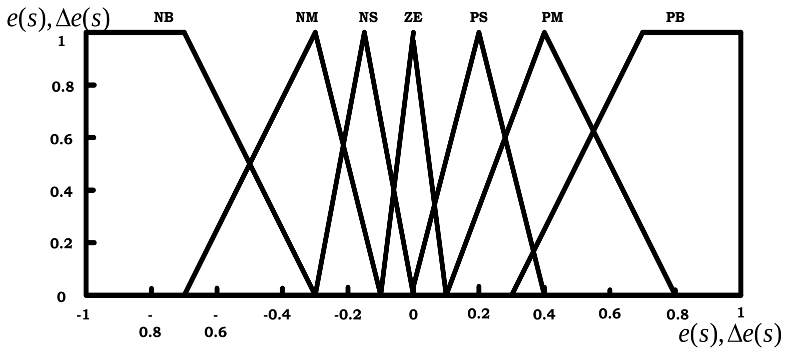


Figure 3. Fuzzy-logic membership functions

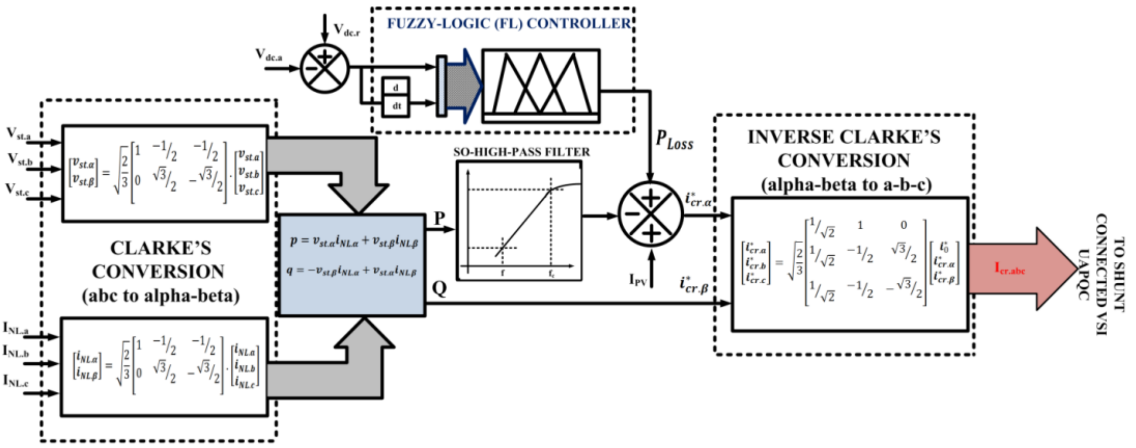


Figure 4. Schematic design of fuzzy-logic-IRP controller for shunt-connected VSI of UAPQC device

Ultimately, utilizing hysteresis current control (HCC) and sinusoidal pulse-width modulation (PWM), the retrieved reference voltages and currents from PI-IRP/SRF regulators are contrasted with accurate fundamental parameters for the generation of switching modes to shunt and series-connected VSIs of UAPQC. The suggested fuzzy-logic controlled UAPQC device's performance for both PQ improvement and integration of DG is validated using the MATLAB/Simulink computing tool, and simulation findings are given with an appealing comparison analysis. The system parameters are shown in Table 2.

Table 1. Fuzzy-logic rule base

$e(s), \Delta e(s)$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	NM	NS	ZE	PS	PM	PB

Table 2. System parameters

S. No	System parameters	Values
1	Supply voltage	V_{sabc}-415 V, F_S-50 Hz
2	Supply impedance	Rs-0.1 Ω, Ls-0.9 mH
3	Non-linear load impedance	R_{NL}-20 Ω, L_{NL}-30 mH
4	DC capacitor	V_{dc}-880 V, C_{dc}-1500 µF
5	VSI's filter	R_f-0.1 Ω, L_f-5 mH
6	Solar PV values	V_{pv}-400 V, I_{pv}-50 A, P_{pv}-20 KW
7	PI controller	K_p-18.3, K_i-4.3

4. RESULTS AND DISCUSSION

4.1. Power-quality enhancement using proposed fuzzy-logic controlled IRP-driven UAPQC device

For driving the non-linear imbalanced load, the 3-phase distribution network is powered by a supply with a 3-phase voltage of Vrms-415 V and a maximum frequency of Fs-50 Hz. The 3-phase diode-bridge rectifier with an uneven impedance of the load is regarded as an imbalanced non-linear load, introducing harmonic currents that are unbalanced and proliferate the current quality at the distribution system's PCC. Figure 5 depicts current harmonic mitigation in a 3-phase distribution network employing a fuzzy-logic-driven shunt VSI of a UAPQC device. The non-linear imbalanced load uses roughly 36 A of rated current, distorting the supply or PCC current and causing greater heat loss and damage to other adjacent connected loads at the PCC level. To reduce the harmonics of current at the PCC, a shunt VSI of a UAPQC device operated by a fuzzy-logic-based IRP controller was used. It injects the necessary in-phase compensatory currents to compensate for the distortions and imbalanced nature of the 38 A supply current. The shunt VSI of the UAPQC circuit therefore generates sinusoidal in form, simple, fundamental necessities, and a balanced supply or PCC current. As seen in Figure 6, the supply or PCC current is in phase with the supply voltage, resulting in a power factor of unity at the supply or PCC level. As shown in Figures 7 and 8, the observed total harmonic distortion (THD) of non-linear imbalanced load current is 21.77% and the observed THD of supply current is 2.38%, indicating that the THD values of supply current are within IEEE-519/2014 norms.

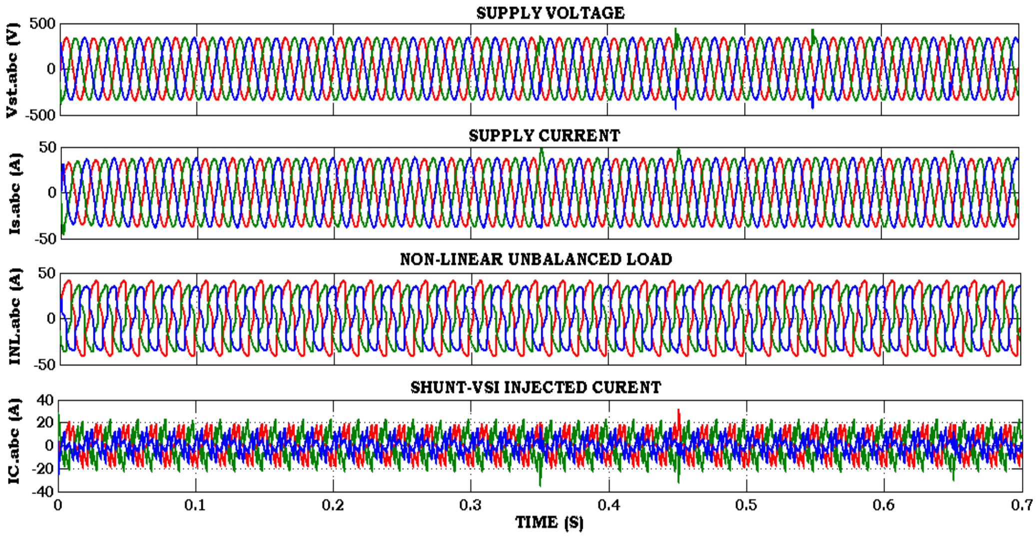


Figure 5. Mitigation of harmonic currents

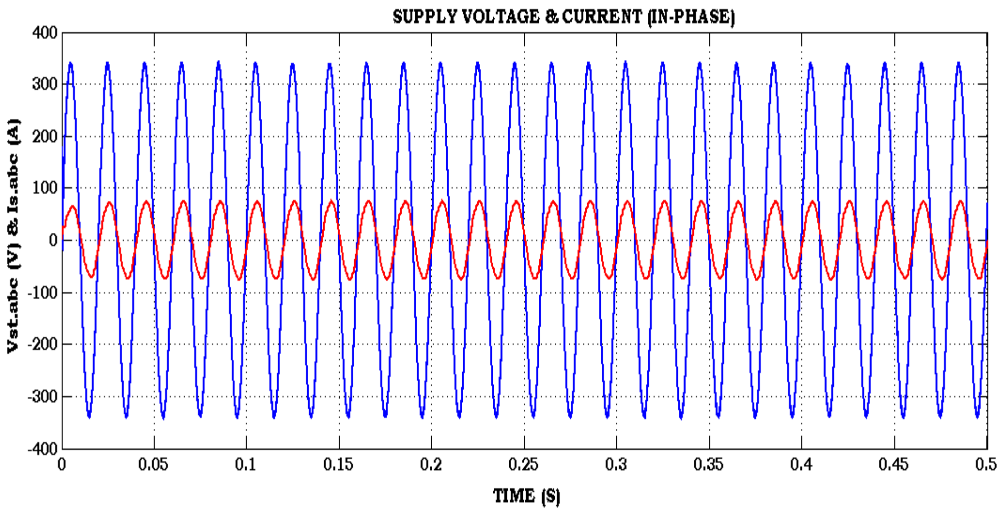


Figure 6. In-phase of supply voltage and current

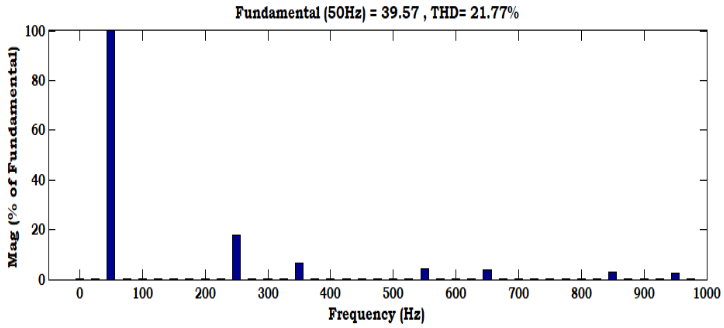


Figure 7. THD of non-linear unbalanced load current

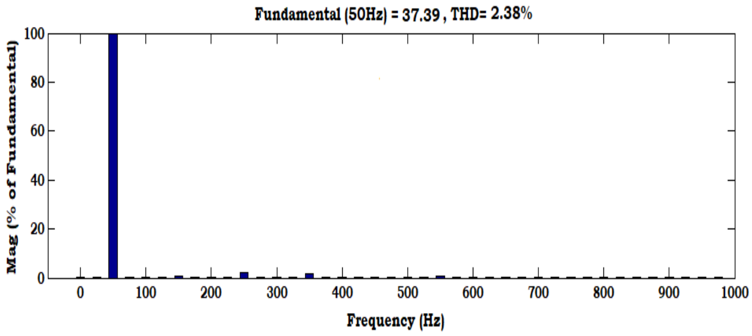


Figure 8. THD of supply current at the PCC level

The voltage sags-swells minimization is attained by employing series linked VSI of UAPQC device in the 3-phase distribution network as shown in Figure 9. For powering the non-linear imbalanced load, the 3-phase distribution network is powered by a 3-phase supply voltage of Vrms-415 V and a rated maximum frequency of Fs-50 Hz. In this circumstance, voltage sag-swells arise from the supply of the voltage across it, influencing the imbalanced nonlinear load and propagating the voltage quality at the distribution system's PCC. To relieve voltage sag-swells, the series VSI of the UAPQC device balances the sag-swells in load voltage, resulting in a well-balanced steady, and sinusoidal in-form load or PCC voltage. When the time t-(0<t<0.35 sec) is believed to be the pre-sag condition, the supply voltage is kept consistent at 340 V. At the time t-(0.35<t<0.45 sec, the voltage-sag appears, and the supply voltage is dropped by 50%, compromising the uninterrupted functioning of the non-linear imbalanced load. In this time state, the series-linked VSI of the UAPQC equipment injects the required voltage of 170 V, causing the non-linear load voltage to remain constant at 340 V. At the time t-(0.55<t<0.65 sec), the voltage-swell appears, and the supply voltage is raised by 50%, disrupting the continual functioning of the non-linear imbalanced load. In this case, the UAPQC device's series-linked VSI recovers an additional voltage of 170 V, causing the non-linear load voltage to remain constant at 340 V.

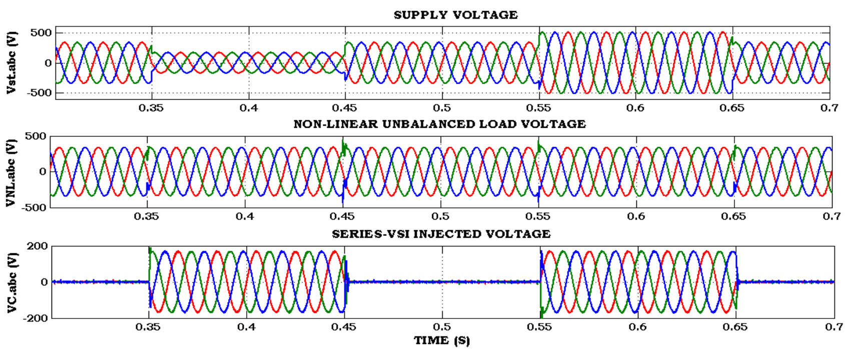
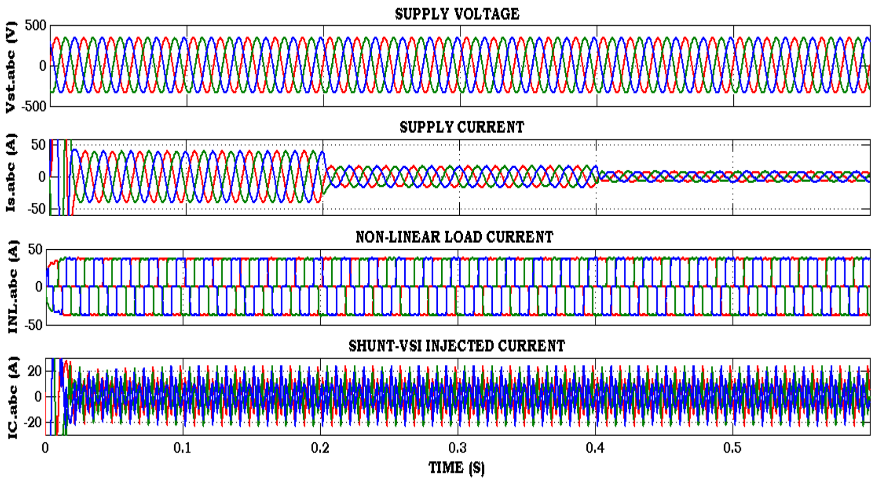


Figure 9. Mitigation of voltage sag-swells using series connected VSI of UAPQC device

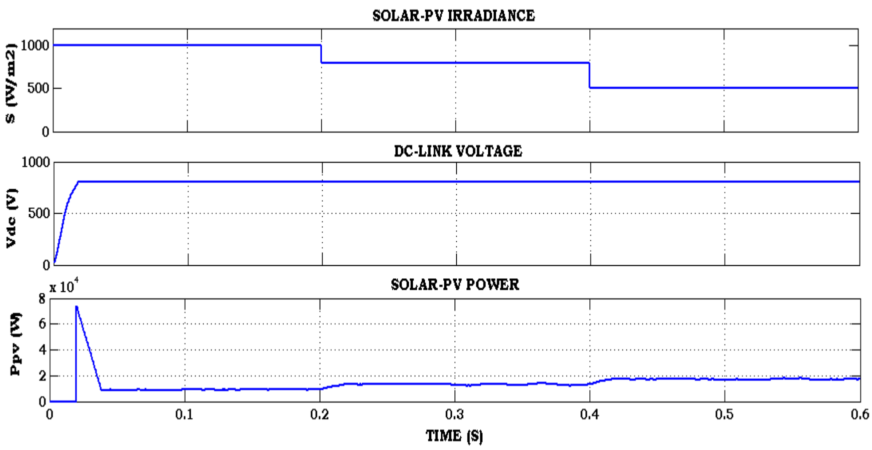
4.2. A solar PV integrated distribution system using proposed fuzzy-logic controlled IRP driven UAPQC device

Figure 10 depicts the simulation findings of a solar PV integrated distribution network employing the suggested Fuzzy-Logic controlled IRP-driven UAPQC device. It consists of supply specifications for DG Integration, solar PV voltage, solar PV Power, and DC-link voltage, in that order. For powering the non-linear imbalanced load, the 3-phase distribution network is powered by a supply with a 3-phase voltage of Vrms-415 V and a rated operating frequency of Fs-50 Hz. In this case, the solar PV power is provided to the distribution network via a shunt-VSI of the UAPQC module for active-power interchange under block-outs and grid-isolation mode. It also reduces current supply usage when there is sufficient solar PV energy, as demonstrated in Figure 10(a). The produced solar PV power is amplified to a high voltage by a DC-DC boost converter controlled by the INC-MPPT regulator.

The INC-MPPT method calculates the optimum solar PV power under changeable temperature and irradiance circumstances. At the time instant t-(0<t<0.2 sec). the irradiance level varies significantly from 1,000 W/m2 to 800 W/m2. Also varies from 800 W/m2 to 500 W/m2 at the time instant t-(0.2<t<0.4 sec). As a result, the acquired solar PV energy changes with varying irradiance, as does the current that is injected into the distribution system's PCC, but the DC-link voltage remains constant at 880 V, as illustrated in Figure 10(b). THD observation of non-linear imbalanced load and supply currents of standard PI-IRP and designed fuzzy-IRP controlled UAPQC circuit are shown in Figure 11 and Table 3. Compared to standard PI-IRP control effectiveness, the suggested Fuzzy controlled IRP controller-driven UAPQC device has a superior harmonic reduction, which boosts stability and improves power-quality characteristics.



(a)



(b)

Figure 10. Simulation results of solar PV integrated distribution system using proposed fuzzy-logic controlled IRP driven UAPQC device (a) supply specifications during DG integration and (b) solar PV voltage, solar PV power, and DC-link voltage

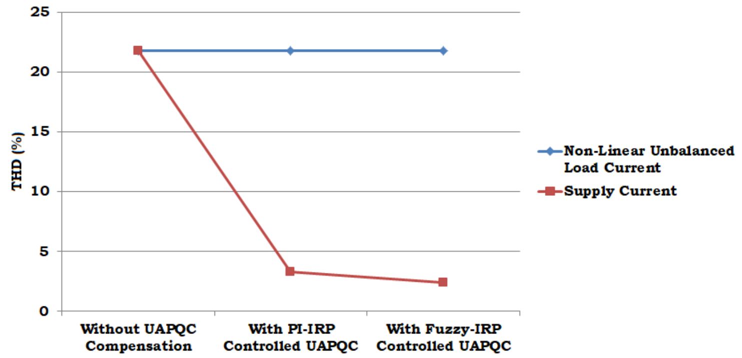


Figure 11. Graphical view of THD comparisons in conventional PI-IRP and proposed fuzzy-IRP controlled UAPQC device

Table 3. THD comparisons of non-linear unbalanced load current and supply currents of conventional PI-IRP and proposed fuzzy-IRP controlled UAPQC device

THD	Non-linear unbalanced load current (%)	Supply current (%)
Without UAPQC compensation	21.80	21.78
With PI-IRP controlled UAPQC	21.79	3.30
With fuzzy-IRP controlled UAPQC	21.77	2.38

5. CONCLUSION

In this work, an efficient solar PV powered DG connected distributed system for delivering the requisite load demand complying with enhanced power quality by using the proposed fuzzy-IRP controlled multi-functional UAPQC device. The fuzzy-IRP controlled UAPQC enhances voltage and current quality in a PCC distribution system with high stable performance and better compensation features in PQ mode. During abrupt load variations, block-outs, and grid-isolation mode, the UAPQC device's shunt-linked VSI exchanges both reactive and active power. It also reduces supply current use during DG mode; the needed load power is met by solar PV power. The observed THD of non-linear imbalanced load current is 21.77%, while the observed THD of supply current is 2.38%, indicating that the supply current THD values are within IEEE-519/2014 norms.

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