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Influence of Grid Integration of UPQC with Solar Power on Power Quality

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Abstract

To satisfy the expanding usage of power electronics in grid-integrated applications, an unified power quality conditioner (UPQC) is regarded as an effective power tool contributing to power quality issues. Voltage interruption problems remain unresolved even if UPQC handles current harmonics and voltage sag/swell. This study proposes a solar energy-based UPQC to export active power to the grid. The suggested method utilizes photovoltaic (PV) power for power quality management and a boost converter to send the remaining active power back into the grid. The PV-UPQC configuration's operation is simulated using MATLAB/Simulink. The PV-UPQC system can compensate for resultant harmonics, correct voltage sags, swells, and the maintenance of load voltage at its nominal value in addition to actively supplying the power grid. A considerable decline is observed in the THD of the load current from 104.66% to 2.56%. Conversely, a 97.55% decrease in load current THD is achieved.

Keywords: power quality, PV system, unified power quality conditioner (UPQC), fuzzy logic controller (FLC), maximum power point tracking (MPPT)

1. Introduction

Renewable energy sources are perceived to be the quintessential solutions for clean energy in modern society. Among multifarious selections of clean energy, photovoltaic (PV) solar energy is particularly exceptional due to its versatility and simplicity in establishing and maintaining. Consequently, well-implemented PV system examples are profusely accessible for commercial and technical research purposes [1-2]. By concentrating on power grid integration, PV-based solar energy experiments have been further refined.

However, researchers are becoming increasingly worried about the abrupt growth in the application of nonlinear loads in distribution systems. Specifically, the main source of the present disruptions in the distributed system is the sophisticated semiconductor technology-based systems. Furthermore, anomalies and malfunction in nonlinear loads will inevitably exhibit with voltage fluctuations. Thus, the awareness of power quality enhancement applications using power conditioners or other power quality improvement equipment has been gradually increased [3-5].

The term "power quality" has garnered impressive replies from researchers in recent decades, particularly in the field of electrical engineering. To preserve energy efficiency, power quality issues are frequently investigated and discussed to ensure uninterrupted electrical energy generation and promote grid decarburization. Meanwhile, care must be taken to manage the voltage and current disturbances that these power electronics-based nonlinear loads bring to the power system [6-8]. Among several techniques, phase-locked loop (PLL) and active power filter (APF) are power quality conditioners developed at different operating levels; however, more sophisticated conditioners like the unified power quality conditioner (UPQC) have been accentuated to a greater extent. In addition to the benefits of traditional conditioners, UPQC even possesses manifold

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additional features [9]. Devices for flexible AC transmission systems, as stated above, are crucial to the power system's power quality and correction. Functionally, to compare and distinguish UPQC and unified power flow controller (UPFC), the difference lies in the applications, i.e., UPQC is specifically designed to be used in the distribution side of the power system.

Concerning APFs, shunt APFs, and series APFs are the two forms of active filters [10-11]. A shunt APF can reduce the harmonics, which is a product of load current. On the other hand, the series APF compensates for voltage disturbances, such as voltage swell and sag. Meanwhile, back-to-back connections between the shunt and the series APF enable energy exchange through coupling with a DC-link capacitor. The components of UPQC include a control circuit and a power circuit, in which the power circuit is inclusive of a series injecting transformer and dual voltage source converters that are coupled with a DC-link capacitor [12].

The main contribution of this study is enumerated as follows:

(1) power quality management under grid integration and load side fluctuations are attained by combining PV and UPQC systems.

(2) the effectiveness of the PV-supported UPQC system has been determined under different dynamic operating conditions, such as the side effects of voltage sag/swell, distorted grid voltage, and total harmonic distortion (THD) on nonlinear loads.

The current research paper is organized as briefed herein. Section 2 expounds on modeling the PV systems using maximum power point tracking (MPPT) and system controls. In Section 3, the proposed PV-UPQC model is discussed while the simulation outcomes are detailed in Section 4. Finally, Section 5 concludes the research paper with major findings and recommendations.

2. The Photovoltaic Panels' Model and Characteristics

PV systems are rather desirable for energy supply even with their high initial prices because of their extended lifespan, excellent dependability, less dependence on maintenance, and stability with non-rotating modules. Given its attributes, PV systems are applicable to isolated areas.

2.1. Solar PV panels

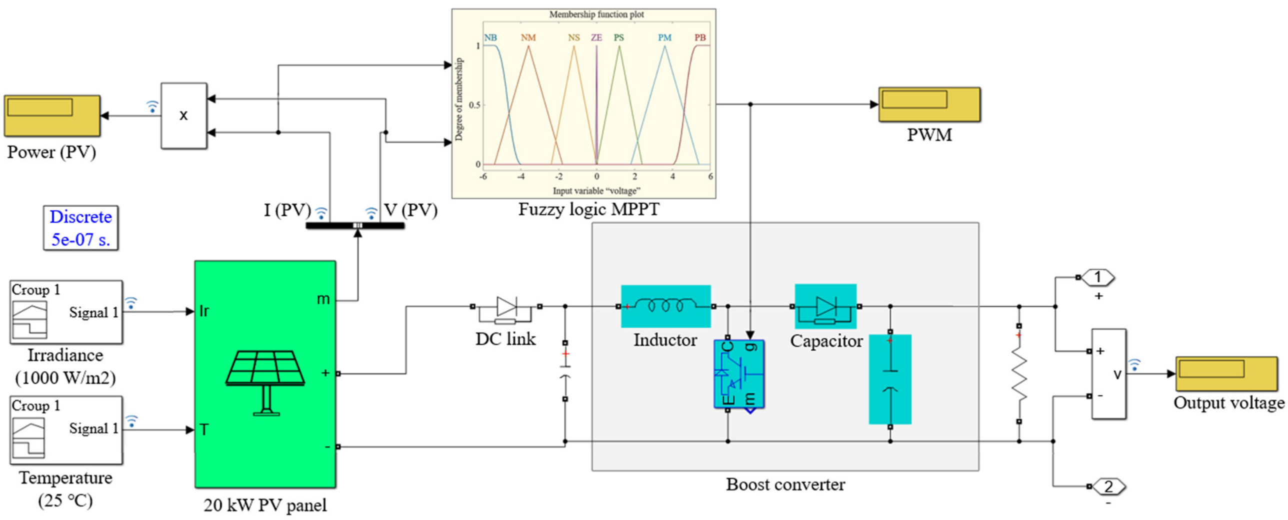


Fig. 1 PV system model with MPPT fuzzy logic controller in MATLAB/Simulink

Each cell in the module produces an exiguous amount of power per se. In this scenario, the PV cells are deployed as a combination of series and parallel modes to generate modules for applications requiring high power, while the modules comprise panels. Similarly, many panels are joined to one another using series and parallel connections to set up the PV array for the required output power [13]. The PV array block of the suggested system is made up of 8 parallel strings, each with 10 modules linked in series. The PV array can generate up to 20 kW of power. For the suggested system, Trina Solar TSM-250PDG5 is selected and receives two input signals: temperature (25 °C) and irradiance (1000 W/m^2). The PV system model is shown in Fig. 1.

2.2. MPPT controller

The PV system has a DC-DC converter to separate the load from the generator operating point (voltage and current). Such a power converter is arranged using the MPPT algorithm looking up the point of maximum power. MPPT designs consist of software (the MPPT algorithm) and hardware (the DC-DC converter). Both PV voltage and current are sent into the MPPT block [14]. In PV systems, the PV voltage is kept under control by the DC-DC converter by adjusting the duty cycle using the MPPT approach to keep the operating point of the PV panel at the maximum power point. In this work, a boost converter is used to perform two primary functions, i.e., managing the PV panel's varying input voltage and tracking the maximum power point through duty cycle adjustments [15].

2.3. MPPT control technique

To enable a PV system to function within its maximum power, the MPPT control technique is required to determine and sustain the peak power. These techniques identify either the current or voltage enabling the solar array to generate its maximum output power [16-17].

A. Incremental conductance (InC) algorithm

The renowned MPPT method, which is also known as the incremental conductance (InC) approach, is explained to assess the performance of the suggested fuzzy-MPPT controller. Moreover, the InC method has gained popularity with its simplicity of implementation. Since implemented, the controller can attain MPPT by changing the module voltage and monitoring the effect on the PV power output, which is subsequently compared with the PV power during the preceding perturbing cycle. Fig. 2 graphically shows the subsystem of the block utilized to determine the value of changes in the conduction angle generated from the PV module's input voltage and current [18-19].

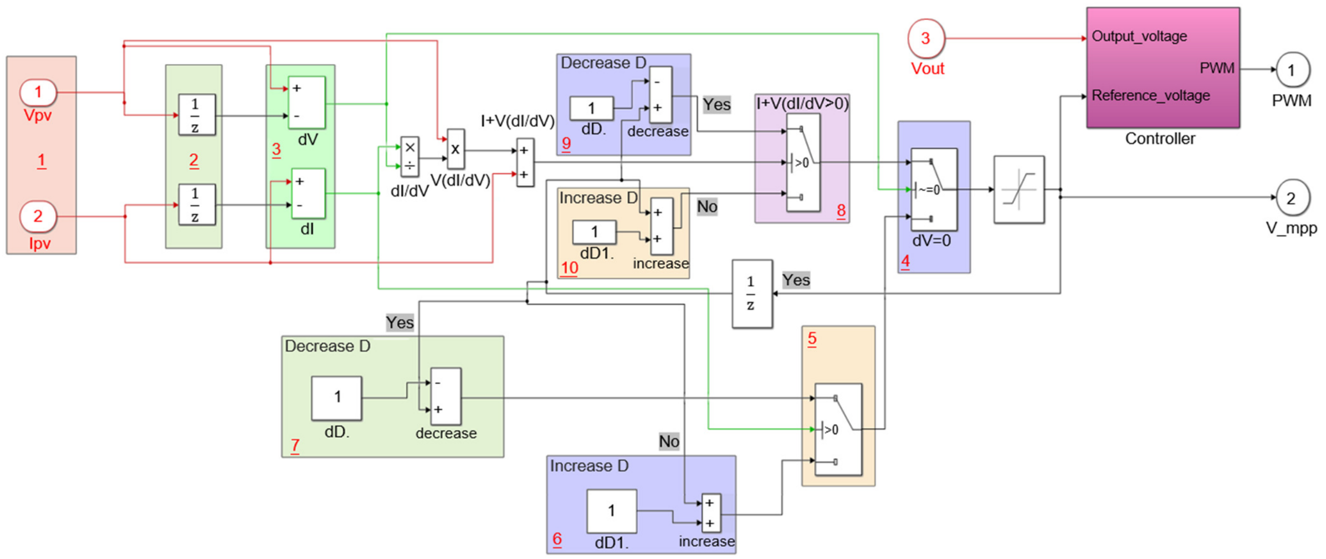


Fig. 2 MATLAB/Simulink model of InC algorithms

B. Fuzzy logic controller

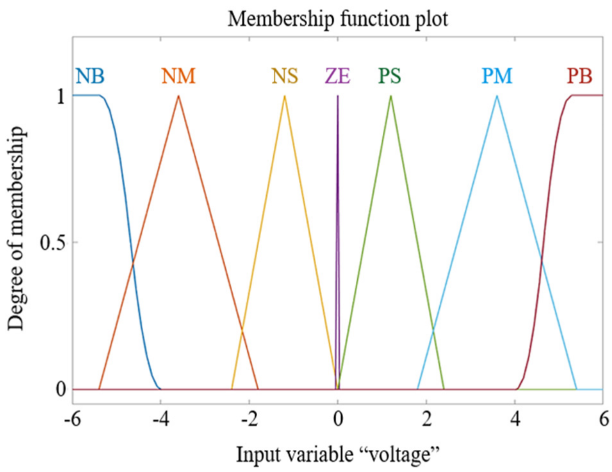
The research concerning PV systems on fuzzy logic controller (FLC)-based MPPTs has been widely investigated in recent years. Apropos linear and nonlinear systems, FLC, which does not mandate to have existing knowledge about precise PV module systems, is straightforward and efficient, even in the fast atmospheric variations [20]. The overall framework of a fuzzy logic-based controller algorithm can be segmented into three steps: fuzzification, rule basis, and defuzzification. Among these steps, the first step is the conversion of numerical input variables, via a membership function (MF), into language variables.

The inputs for the fuzzy logic MPPT controller in the PV system are interpreted to include changes in voltage and power. typically, a block facilitates the computation of error (E) and error change (dE) at sampling instants k, while E and dE signals are the two inputs, and the duty cycle output (D) of FLC is determined via processing the aforementioned variables. The fuzzy logic toolbox is simulated using Simulink/MATLAB's fuzzy control [21-24].

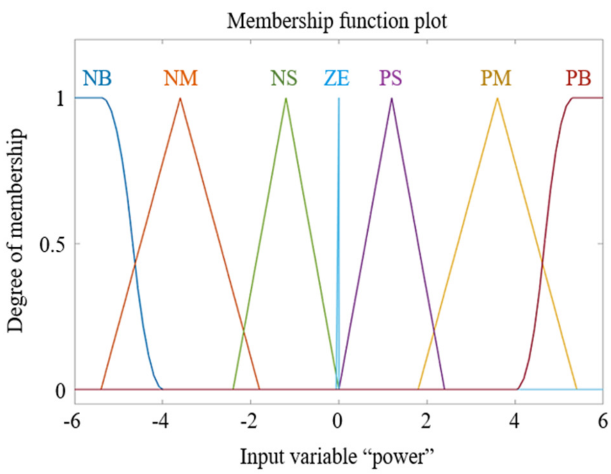
$$E(i) = \frac{\Delta P}{\Delta V} = \frac{P(i) - P(i-1)}{V(i) - V(i-1)},\ \Delta E(i) = E(i-1) \tag{1}$$

where the variable $V(i)$ represents the terminal voltage of the PV module, whereas $P(i)$ represents the power provided by the module.

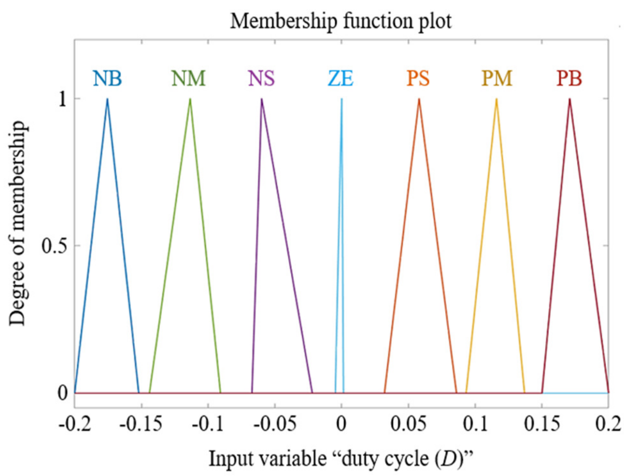
The linguistic variables listed herein are used by the MPPT fuzzy controller: positive medium (PM), negative medium (NM), positive small (PS), negative small (NS), positive big (PB), negative big (NB), and zero (Z). Based on user experience, the MFs of these variables are generated. The $E(k)$ and d$E(k)$ variables for addressing ongoing maximum power point issues have been established following many experiments conducted [25]. Fig. 3 lists the seven MFs. The logical operators MIN and MAX from the Mamdani type of inference rules are opted for the MPPT fuzzy controller. To ensure the controller optimizes for its output d, a total of 49 rules are presented in Table 1, and Fig. 4 shows the subsystem of the block FLC.



(a) Error (E)



(b) Error change (dE)



(c) Duty cycle output (D)

Fig. 3 Characteristics of fuzzy logic controller's MF

Table 1 FLC rule

E/dE	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	ZE	NB	NB	NB	NB
NM	ZE	ZE	ZE	NM	NM	NM	NM
NS	NS	ZE	ZE	NS	NS	NS	NS
ZE	NM	NS	ZE	ZE	ZE	PS	PA
PS	PA	PS	PS	PS	ZE	ZE	ZE
PM	PM	PM	PM	ZE	ZE	ZE	ZE
PB	PB	PB	PB	ZE	ZE	ZE	ZE

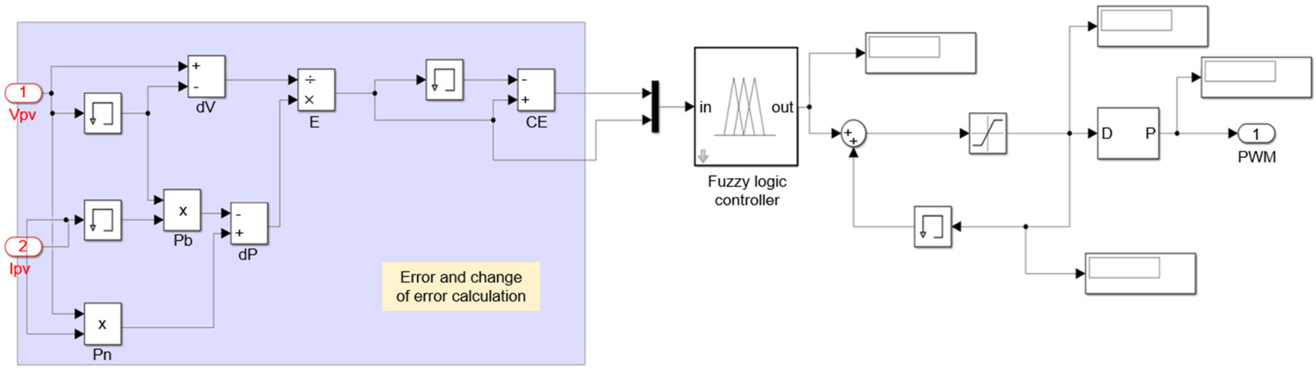


Fig. 4 Using MATLAB/Simulink to model FLCs

Finally, considering the two methods used during this research, as shown in Fig. 5, the fuzzy controls extract the maximum power of 20 kW with a proper stabilization time of 0.0782 s, whereas the InC method takes 0.1385 s to stabilize at the start of the simulation, indicating FLC reaches optimal MPPT in less time than the traditional approach.

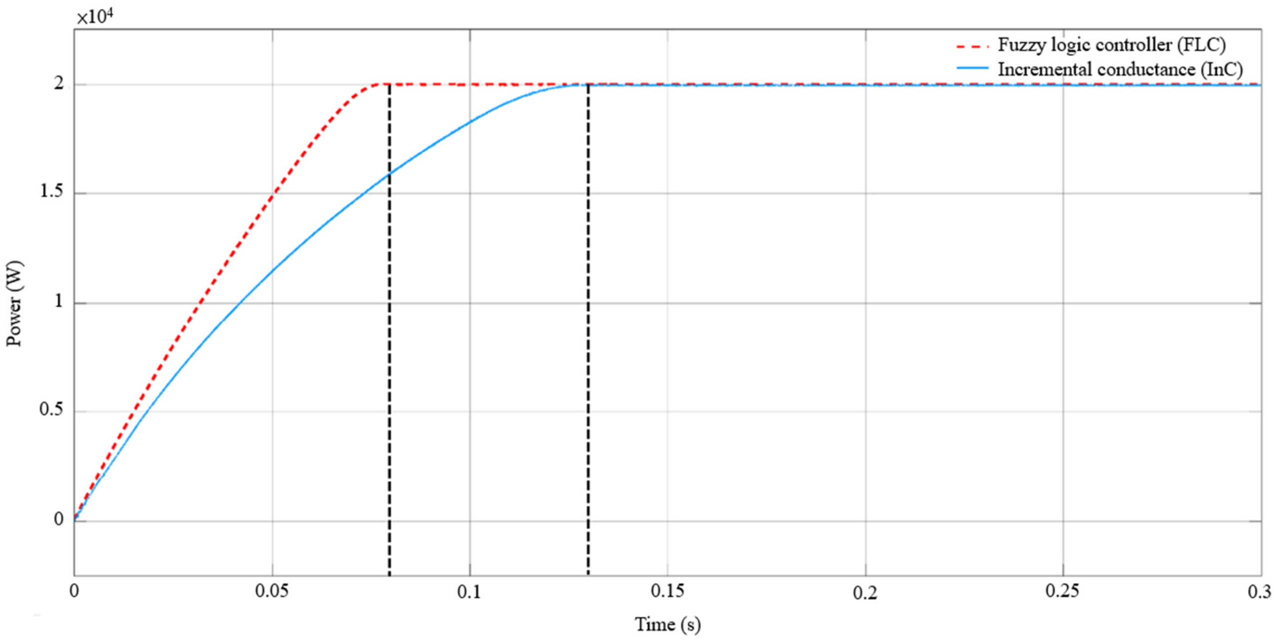


Fig. 5 PV system module's power output

3. System Design and Configuration of a PV-UPQC

The PV system is recommended to replace the DC-link capacitor to yield a continuous supply of DC voltage to the UPQC power circuit. Fig. 6 depicts the block diagram of the proposal for the integration of PV into the grid through the UPQC system. The UPQC control circuit is the second unit superintending the production of precise reference compensating voltage and current for the series and shunt APFs.

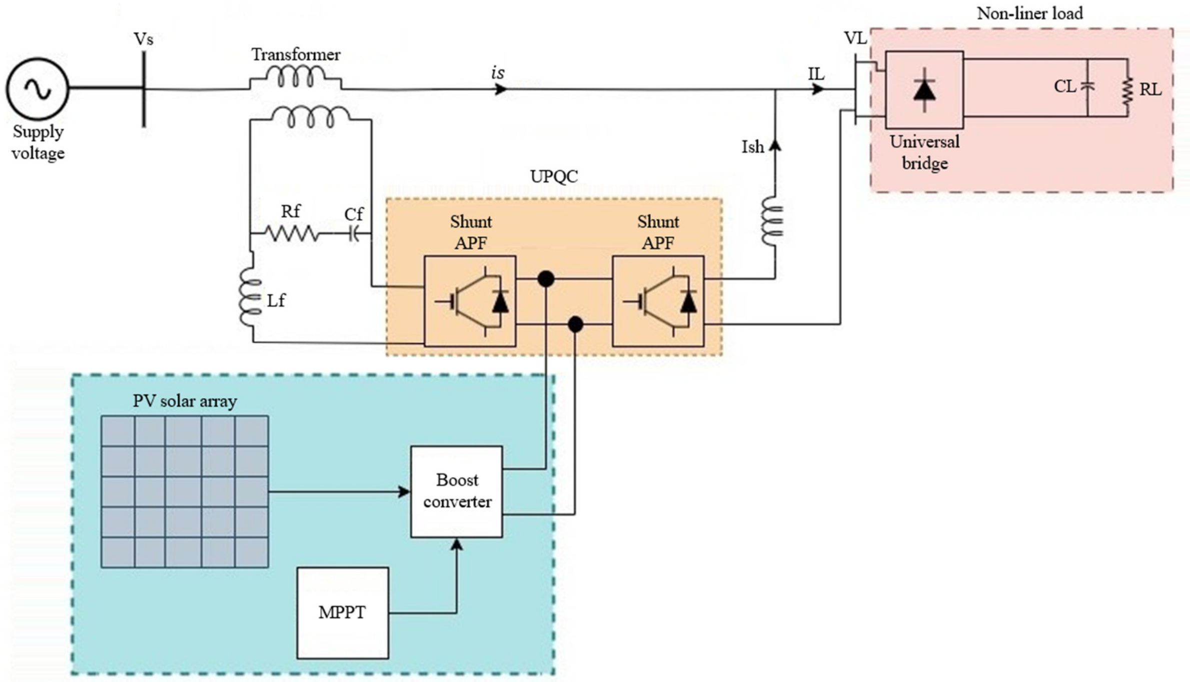


Fig. 6 PV-UPQC system block diagram

To eliminate grid voltage distortions, the management technique mentioned previously creates a reference load voltage and compares it with the real load voltage. Therefore, the load voltage is not distorted. With a PLL to measure the angle of the line voltage, the quadrature unit vector sin *wt* can be constructed by applying the sine function to the measured angle of the line voltage. Subsequently, the reference load voltage signal is generated through the multiplication of the desired amplitude value versus the sinusoidal waveform. Fig. 7 illustrates the Simulink model for this control approach.

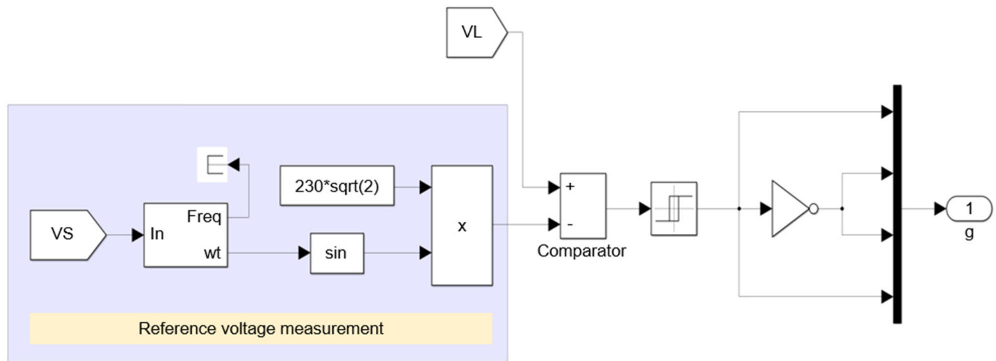


Fig. 7 Series APF control diagram

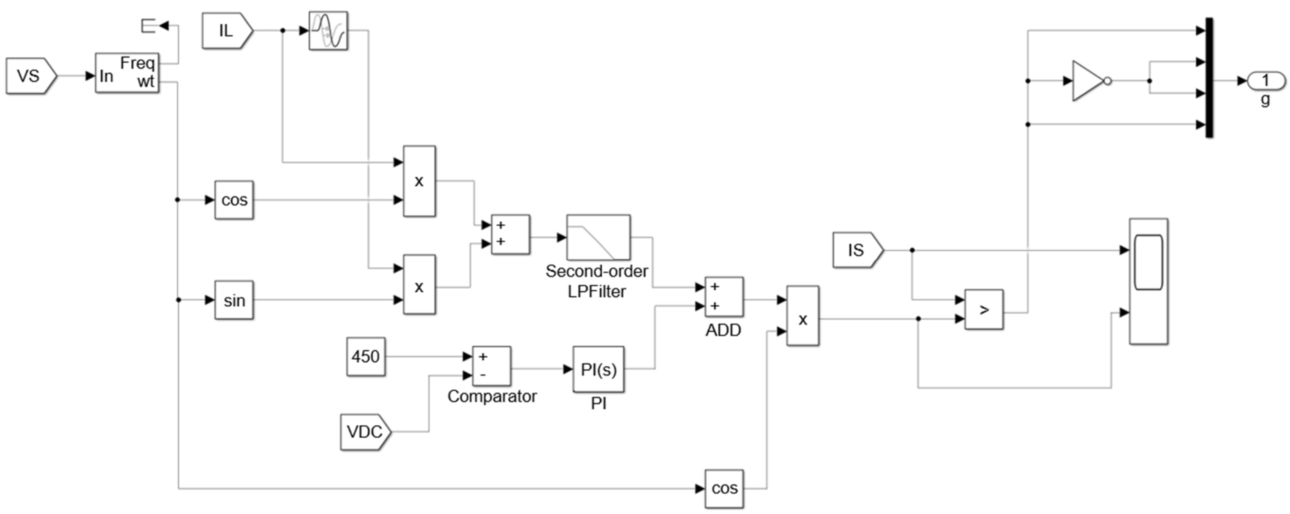


Fig. 8 Shunt APF control diagram

By producing the compensating current correctly, current compensation is given, and such a process is compatible with other methods. To retrieve the reference signal in this case, a controller based on synchronous reference frames is used. The rudimentary features of voltage or current a undergo transformation from a stationary reference frame (abc) to a revolving reference frame (dq- synchronous), in which the latter revolves at a synchronous pace. Fig. 8 visualizes the Simulink diagram for the single-phase synchronous reference frame control algorithm [26].

4. Simulation Results

With MATLAB/Simulink software, the suggested single-phase UPQC model, fed by the PV system in Fig. 9, is created to examine the performance of this system in mitigating THD, distorted grid voltage, and voltage sag/swell side effects on nonlinear loads. The details of PV-UPQC system parameters are given in Table 2.

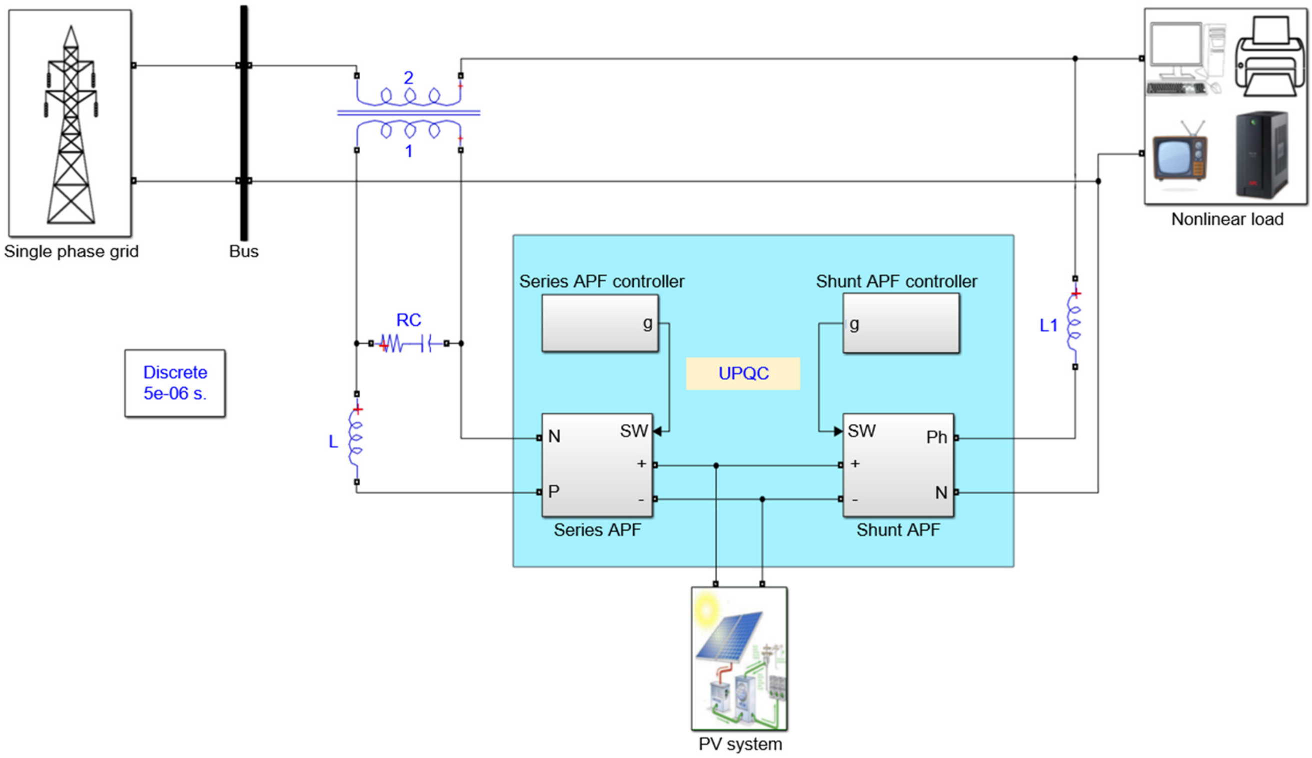


Fig. 9 Proposed PV-UPQC system using MATLAB/Simulink

Table 2 Simulation parameters

Parameters		Value
Single-phase grid voltage	Supply voltage (V_s)	230 V
	Frequency (F)	50 Hz
	Line impedance (R_s, L_s)	4.8 mΩ, 18.3µH
PV system	Parallel resistance (R_{sh})	288 Ω
	Series resistance (R_s)	0.2351 Ω
	Short circuit (I_{sc})	37.6 V
	Open circuit (Voc)	8.55 A
	DC output voltage of PVs	650 V
	MPP current (I_{MPP})	8.06 A
	MPP voltage (V_{MPP})	31 V
	P max	249.86 W
	Switching Frequency	10KHz
UPQC	Series APF (R, C, L)	0.1mΩ, 20µF, 1.5mH
	Shunt APF (L)	1.2 mH
Nonlinear load	Resistance	100Ω
	Inductance	4mH
	Capacitor	240 µF

4.1. *Performance under harmonics of load*

The performance of the PV-UOQC system with distorted load current is examined herein. Fig. 10 displays the waveforms of the supply current, the distorted load current, and the injected current via shunt APF-provided current. Fig. 11 illustrates the THD values for both load as well as supply currents. The shunt APF eliminates the harmonics generated by the load into the grid current. The suggested control method decreases the current THD from 104.66% to 2.56%, which complies with the IEEE 519 guidelines [27].

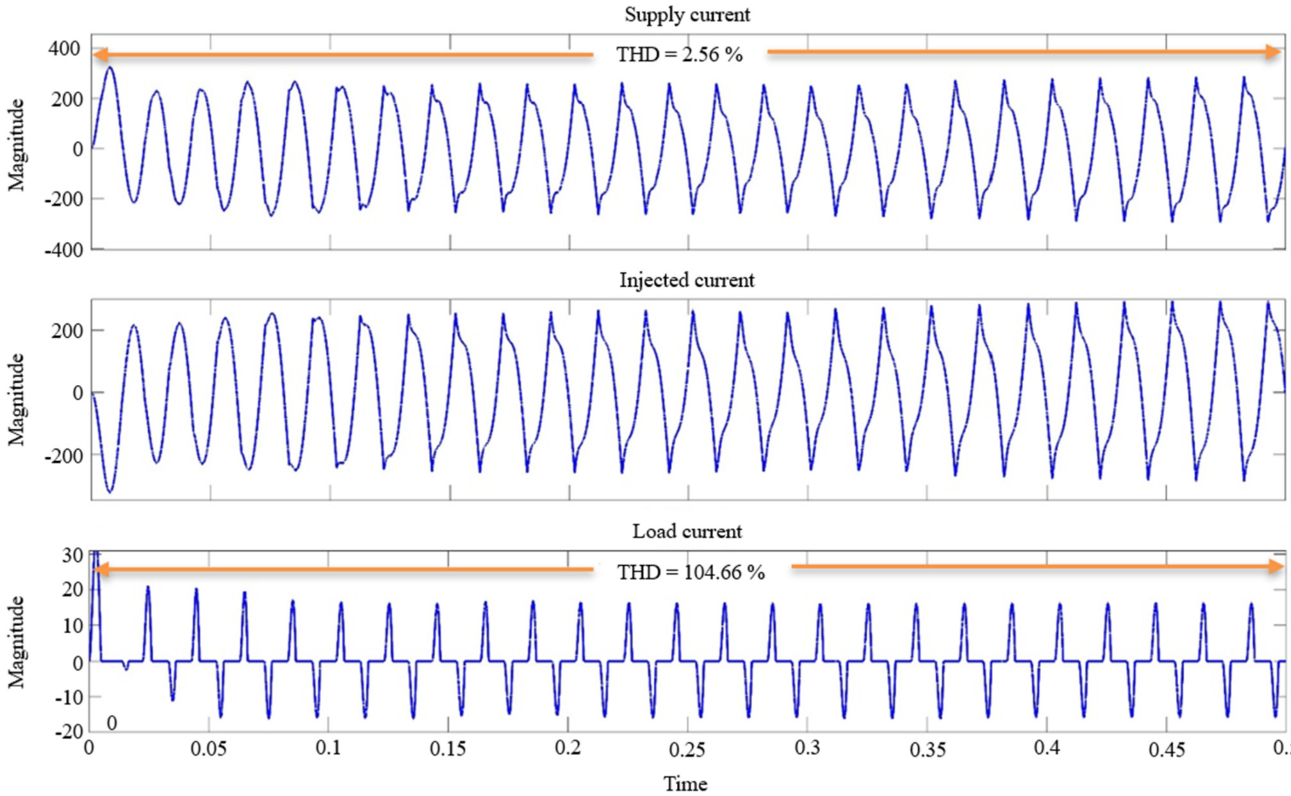
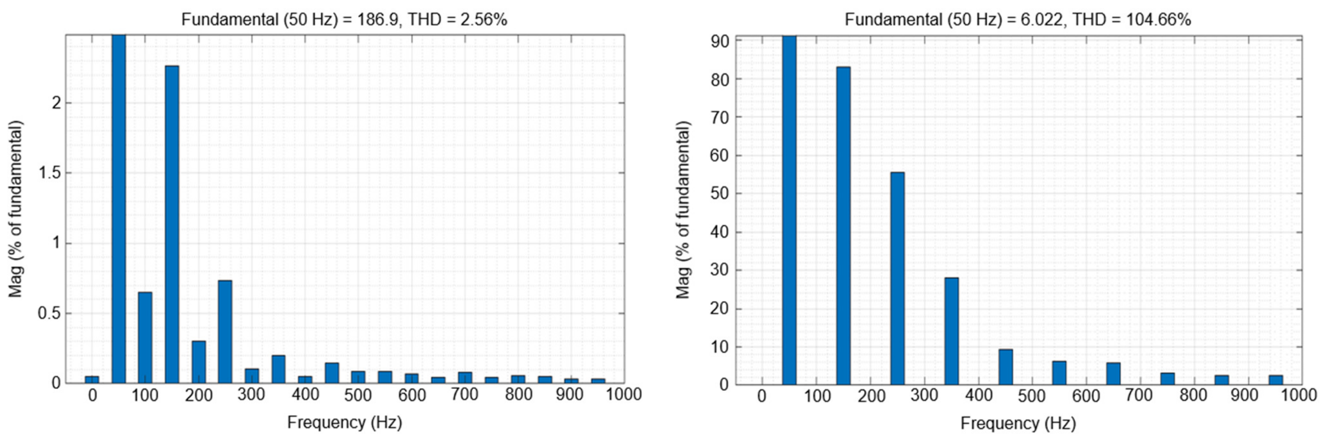


Fig. 10 Simulation waveforms of the supply current, injected current, and load current



(a) Load currents (b) Supply currents

Fig. 11 Total harmonic distortion

4.2. *Performance under grid voltage*

Fig. 12 portrays the distance concerning the effectiveness of series APF in the compensation of harmonics in the source voltage. The load voltage eliminates all harmonics, validating its suitability for nonlinear loads. In addition, the voltage's THD is lowered by the suggested control method from 11.68% to 1.51%, falling within the IEEE 519 guidelines [27].

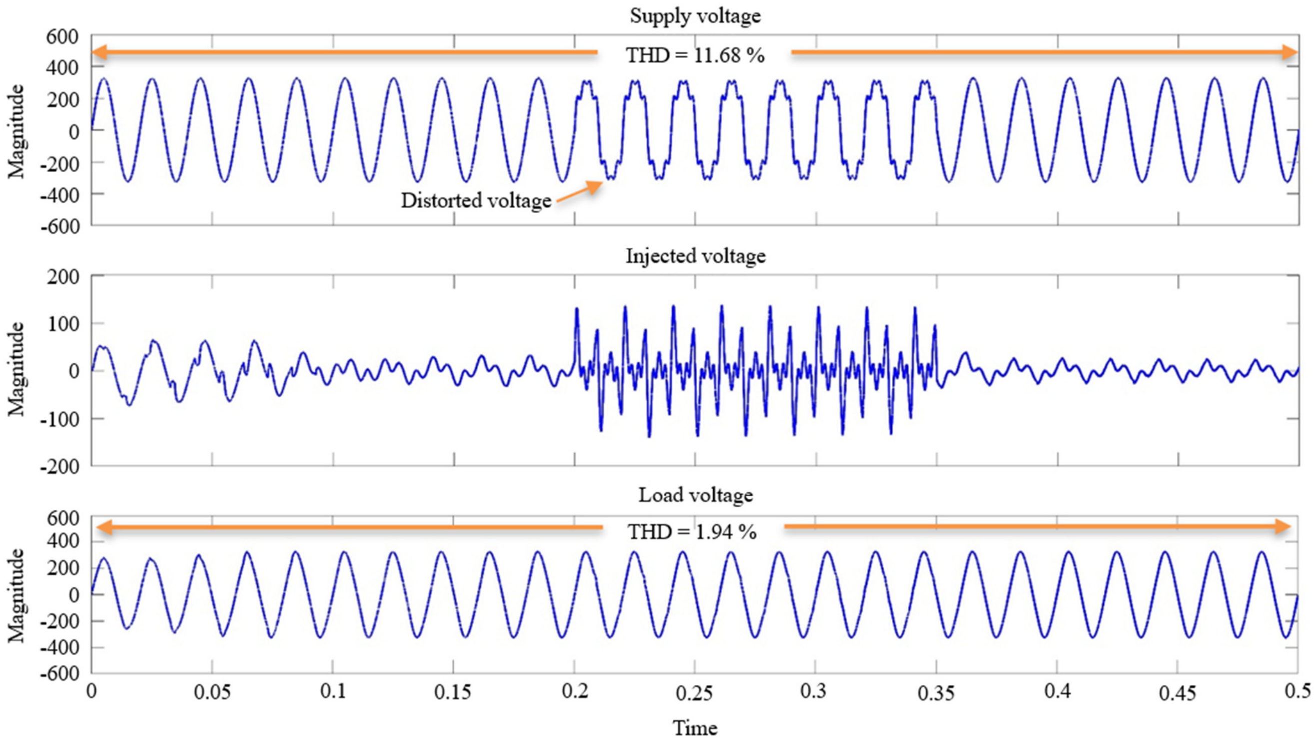


Fig. 12 Simulation waveforms of the supply voltage, injected voltage, and load voltage under grid voltage distortion

4.3. Performance under voltage swell/sag

Fig. 13 exhibits the grid-side voltage sag and swell conditions. In this setup, 0.3 pu voltage sag could be observed in the range of 0.1 and 0.2 s, whereas 0.3 pu voltage swell could be observed in the range of 0.3 and 0.4 s. To generate a clean sinusoidal voltage possessing nominal magnitude near the load end, the required compensation voltage is generated by series APF properly for swell and sag in the voltage instantly for the extraction of fundamental components of grid voltage. The THD values of current and voltages are within the limits, as described in the IEEE 519 guidelines. Finally, Table **3** presents a comparison between the suggested approach and previous research in the area of enhancing UPQC performance when supported by a PV system.

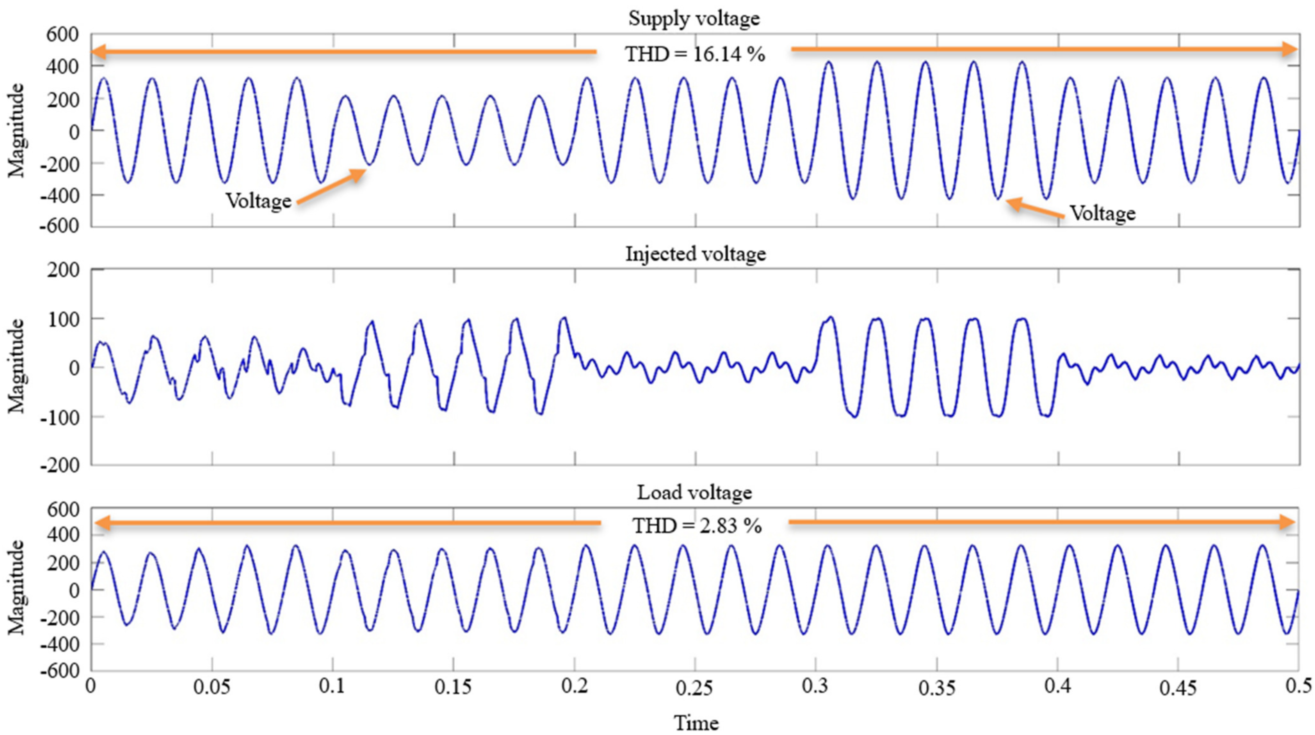


Fig. 13 Simulation waveforms of the supply voltage, injected voltage, and load voltage under voltage sag/swell condition

Table 3 A comparison between the suggested approach and published literature

Ref.	UPQC-control		PV-control	THD (%)
	Series APF	Shunt APF	MPPT technique	
[2]	unit vector templates	reactive power theory (d-q theory)	Perturb and observe (P&O)	3.86%
[6]	reference voltage management	d-q theory	Hybrid P&O	3.25%
Proposed	reference voltage management	synchronous reference frame	Fuzzy logic	2.56%

5. Conclusions

This paper presents an innovative UPQC powered by a PV system. A PV system with 20 kW of power, a boost converter, and an MPPT algorithm based on fuzzy logic is designed to determine and maintain active power. This active power is subsequently exported to the grid network by employing the shunt APF function designed in UPQC. Due to this setup, the PV system accomplishes two tasks: a regulated DC link ensured to the UPQC power circuit and active power supplied to the grid network. The system data can infer the presence of harmonics in both supply voltage and load current. On both the supply and load sides, the THD data was acquired for both voltage and current waveforms.

As a result, a huge decline was observed in the THD of the load current from 104.66% to 2.56%. Conversely, a 97.55% decrease in load current THD is achieved. Similarly, at the load side, the THD of supply voltage declines from 16.14% to 2.83%, yielding a reduction of 82.46% in supply voltage THD. The series APF ensures the load terminal voltage at the defined value to handle unprecedented changes in the grid voltage level (sag and swell). Solar power improves the UPQC performance, even though the load on the grid is lessened by providing the source with excess generated power given a load deficit. The PV system's active power contributes to the improved performance of the proposed UPQC model for voltage swells. Therefore, the overall performance of the system can be enhanced by implementing the suggested technique. In future work, developing the proposed system by using a three-phase system of PV-UPQC with Grid Integration is possibly attainable.

Conflicts of Interest

The authors declare no conflict of interest.

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