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Power Quality Improvement in Solar Integrated Power Systems Using Fuzzy-Based MMC UPQC

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Abstract: Fuzzy-based MMC-UPQC in solar-integrated power systems to enhance power quality is proposed in this work. Due to power electronic switches in solar integration systems and in the nonlinear loads, harmonics and voltage sag and swells will impact other equipment and other consumers in the power systems. The proposed work aims to suggest the adoption of a Modular Multilevel Converter (MMC) based Unified Power Quality Conditioner (UPQC) to improve the power quality of medium and high-voltage solar-connected power systems. The proposed MMC-UPQC is highly unified and has reduced DC-link voltage, effectively isolated harmonics, and improves voltage regulation in the main system. To explain this work establishes the switching strategy of the MMC by examining how it suppresses harmonics and regulates the voltage. Based on this analysis, the paper designs a compound control strategy that combines a series and shunts hybrid active power filter and a synchronous method using SGDFT (Sliding-Mode Generalized Discrete Fourier Transform) filtered PLL (Phase Locked Loop). A fuzzy controller is adopted as DC voltage regulator due to its capability to manage uncertainties and nonlinearities in the system. The system utilizes a collection of fuzzy rules that enable the mapping of input signals to the output signal, thus rendering it appropriate for deployment in situations where the system dynamics are intricate. Finally, the paper validates the performance of the MMC-UPQC in a supply system using MATLAB/Simulink simulations. By analysing simulation results, the effectiveness of the MMC-UPQC in regulating control grid energy, suppressing load harmonic current, and compensating for immediate control is demonstrated.

Keywords: *Power Quality, Modular Multilevel Converter, Unified Power Quality Conditioner, Discrete Fourier Transform, fuzzy logic, PV generation*

1. Introduction

Employing solid-state devices in a power system can potentially result in Voltage fluctuations, power surges, notches, spikes, flickering, voltage imbalance, and harmonics in the power delivered to end users. Ensuring a constant and uninterrupted sinusoidal voltage with balanced sinusoidal currents is the fundamental purpose of generation, transmission and distribution systems. For sensitive and critical loads, an uninterrupted, constant sinusoidal voltage with balanced currents, and consistent magnitude and frequency is essential [1]. Incompetence to provide such high-quality power may cause protection systems to malfunction, resulting in significant losses in data, time, product quality, and services. To ensure consistency in power quality, the International Electro technical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) have established clear power quality standards [2].

The use of Distributed Generation (DG) technologies, including wind turbines, solar power plants, fuel cells, and others, is experiencing rapid growth. DG offers various technical, environmental, and economic benefits. However, electric utilities face multiple challenges in integrating DG into their systems. Reactive power compensation is the primary control parameter for DG, frequently changing the energy consumption patterns of sizable loads can result in voltage sag and swell within the system, which can cause fluctuations in the actual power demand. Additionally, uncorrected reactive power can impact the efficiency, power factor (PF), and active power capacity of DG systems [3]. To ensure the secure operation of equipment and facilitate source switching, the utilization of Power Electronic Converters (PECs) is essential for connecting DG systems to the utility grid. However, this can result in various Power Quality (PQ) issues, this ambit covers a range of power quality concerns, including voltage and current harmonics, voltage sag/swell, as well as voltage and current imbalances, voltage flicker, reactive power loading, neutral current, impulse transients, and interruptions [4].

The widespread use of power electronics switching devices has given rise to numerous PQ problems associated to voltage and current in distribution systems. PQ issues in interconnected power systems can be categorized as either utility-related or customer-related issues including

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excessive reactive power demand, load imbalances, current harmonics, and a low power factor. In contrast, utility-related problems refer to issues such as unbalanced loads, voltage distortions, voltage sag/swell, notches, and flicker, among others [5]. PQ problems can significantly diminish. These PQ problems can lead to reduced power transmission efficiency and may also result in damage to equipment connected to the distribution system. Utilizing two primary Voltage Source Converters (VSCs) interconnected through a shared DC link to the Unified Power Quality Conditioner (UPQC) presents a practical solution for mitigating PQ disturbances. Different UPQC topologies are implemented in distribution networks to reduce power quality problems [6].

UPQC systems can accomplish series and parallel active power-line conditioning simultaneously, by utilizing a combination of Active Power Filters (APFs) [7]. An example of the practical implementation of UPQC topology in a 3-phase 4-wire distribution system was described in [8]. By utilizing a dual compensation approach, this configuration can be linked to distribution systems and implement active power-line conditioning. However, it should be noted that this implementation is only suitable for low-voltage systems. A brief regulating approach for a double 3-φ UPQC topology was proposed in [9], in which the SeAF was controlled as a sinusoidal current source and the ShAF was regulated as a sinusoidal voltage source. Although this method can handle a distinct frequency spectrum, it deviates from the conventional UPQC configuration.

Due to its adaptability and benefit adaptability, UPQC is a commonly researched and utilized technology for enhancing power quality. The implementation of UPQC in high-voltage grids can be challenging expected by the significant power magnitude of moderate and high-voltage grids. Luckily, the Multilevel Modular Converter (MMC) can be employed in moderate and high-voltage applications, thanks to its capacity to endure elevated voltages and operate at low switching frequencies [10]. Coordinated control allows the UPQC's series and shunt converters to have distinct responsibilities for restoring voltage and current quality, respectively. By utilizing MMC technology, the UPQC system can effectively restore power quality and ensure stable grid voltage operation. In situations where power grids are unbalanced, particularly in standard and high voltage scenarios, voltage and current deformations can worsen, making it difficult for MMC-UPQC to offer sufficient compensation [11].

Multiple investigations have been conducted to evaluate the optimal VAR function of UPQC and explore stability analysis and Optimal Power Flow (OPF) by utilizing the shunt and series converters at various phases of the DG framework. This includes the integration of a solar power generation system with UPQC. Additionally, the PAC strategy has been analyzed to achieve voltage stabilization in a grid-connected UPQC system [12]. A survey was conducted to investigate the use of UPQC in stabilizing power quality in complex networks. The conventional power system structure involves generating stations being linked to load sites through lengthy transmission and distribution lines. To enhance the efficiency of distribution networks, the idea of customized equipment has surfaced. UPQC is designed to regulate voltage distortions, while the use of FACTS equipment helps enhance power quality and ensure reliable electricity. According to [13], voltage distortions on the load side can have a notable influence on the power factor and source power. To connect the UPQC and DG system, a Proportional Integral (PI) switch is employed in this study. The appropriate selection of the switching angle can eliminate low-order harmonics, while the suppression of other converters can reject high-order harmonics by injecting an equal but opposite amplitude. The topology presented in this work suggests that, in rural or remote areas, only one power distribution system may be available for consumer applications due to economic limitations.

Hysteresis current control is a popular strategy for controlling MMC due to its rapid response time. However, in the model phase, the slope of the sampling period is substituted for the slope of the current, leading to imprecise control and significant errors [14], [15]. Work in [16] and [17] proposed coordinated control techniques to regulate power quality and grid voltage balance, and the results were satisfactory. In [18], the proposal of an MMC-UPQC for enhancing power quality was hindered by the extensive number of Sub-Modules (SMs) present in the system, which resulted in the requirement to regulate a significant number of switches. Consequently, the precision and efficiency of the fuzzy control techniques in power quality issues were presented in [19].

The literature on MMC-UPQC research has identified several limitations. Firstly, many studies only consider voltage sags and swells, neglecting common scenarios in unequal networks such as load switch and consonant injection. Secondly, although extensive research has been dedicated to managing while controllers for shunt-side currents and harmonics have been developed, the progress of voltage quality controllers on the series side is still in its initial phases. Moreover, conventional control approaches like PI control, SMC, and PBC may not be suitable for accommodating varying structure limitations and achieving desirable device functioning in the presence of significant fluctuations and harmonics generated by renewable energy devices. To address these limitations, this paper aims to make the following contributions to the field of fuzzy-based MMC-UPQC research.

1. Fuzzy controlled MMC-UPQC for PV integrated grid system to improve power quality in the line by mitigating harmonics injected by nonlinear loads and PV system converters.

2. The focus of this study is to model a phase detection system based on the Synchronous Grid Frequency Detection Technique for grid synchronization in the presence of altered grid circumstances. The proposed method aims to accurately detect the grid voltage signal's phase angle, even in the presence of non-sinusoidal and distorted waveforms.

3. Maintaining the system to be stable during sudden unbalanced or sudden load change conditions. By adopting this approach by using this approach, it is possible to decrease the harmonic distortion rate of load voltage on the series side and grid current on the shunt side to below 5%, thereby restoring their quality.

2. Modular Multilevel Converter

MMC, a kind of multi-cell converter, offers promising topologies and can be widely employed in various applications. In high-voltage scenarios, MMC reduces the necessity for a unique DC source and transformer. The system voltage is achieved by connecting submodules in a series configuration, which generates a good multilevel voltage waveform. Each submodule of MMC is shaped in various forms using IGBTs, diodes, and capacitors. The application in which the converter is used, IGBT rating, and operating voltage decide the number of submodules to be connected to design MMC. For instance, 3 to 25 submodules are required for a variable frequency motor drive with a voltage rating of 1kV to 11 kV. For HVDC transmission system with a voltage rating of 500 kV require 300 to 600 submodules.

Fig. 1 depicts a three-phase MMC that converts DC to AC. In the MMC, in this configuration, the DC link is linked to the positive and negative terminals of the three legs, while the midpoint of each leg of MMC is linked to a three-phase AC system. This midpoint divides each leg into two parts called the positive arm and the negative arm. Every part involves series-associated submodules and a current-limiting inductor. As the difference between instantaneous voltages between the arms increases the circulating current, it is necessary to use an inductor as a current-limiting device. MMC can scale voltage and power ratings across the submodules due to the modular construction. MMC can convert unidirectional DC voltage into bidirectional stepped voltage with less *dv/dt* ratio, low THD, and reduced current ripples. MMC can be controlled at a low switching frequency and it's possible to achieve fault-tolerant operation due to series-connected submodules.

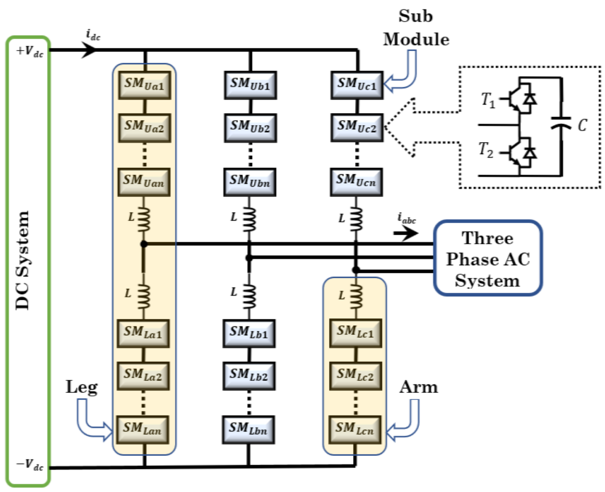
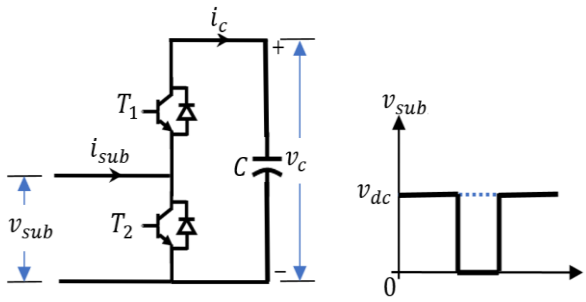


Fig. 1. Modular multilevel converter.

A submodule (SM) is a simple unidirectional voltage to bidirectional voltage conversion circuit using low voltage switching devices. Unidirectional or DC voltage can be applied to the submodule by using a capacitor. The following submodule types are commonly used: Modular Multilevel Converters (MMC) can use several types of submodules, including Half-Bridge (HB), Full-Bridge (FB), Flying Capacitor (FC), and Cascaded Half-bridge (CH), Double Clamp (DC) submodules.

The configuration of a half-bridge submodule with two IGBTs, two anti-parallel diodes, and a capacitance. The complementary operation of two IGBT switches, $T_1 T_1$ and $T_2 T_2$, is utilized to regulate the DC capacitor voltage, v_c, such that when one switch is on, the other is off, and vice versa is shown in Fig. 2 (a).



(a) (b)

Fig. 2. Switching states of MMC.

The capacitor voltage v_c is given as

$$v_c = \frac{1}{C}\int_0^t i_c(\tau)d\tau, \text{ where } i_c(\tau) = T_1 i_{sub}$$

Capacitor current i_c of the submodule on the DC side is equal to i_{sub} when T_1 switch is switched on and 0 when switched off. As indicated in Fig. 2 (b) two energy points are possible at the AC side of the submodule either v_{dc} or 0. AC side voltage v_{sub} is identical to capacitor voltage v_c when T_1 is switched on. While the current i_c flows in a positive direction, the capacitor voltage v_c increases, whereas it decreases when i_c flows in a decreasing way. The AC side voltage v_{sub} is zero when T_1 is switched off, and in this condition, the capacitor voltage v_c stays stable. The Table 1 illustrates the switching states of the half-bridge submodule.

Table 1. Changing States of half-bridge switching module

Switching state	T_1	T_2	v_{sub}	$i_{\text{sub}}>0$	$i_{\text{sub}}<0$
1	ON	OFF	v_c	v_c increases	v_c decreases
0	OFF	ON	0	v_c constant	v_c constant

Constant DC voltage is converted into bi-directional multilevel stepped voltage waveform by MMC using series connected similarly constructed submodules. The number of stages possible depend on the total of cascaded submodules connected in each leg of the arm. Let n number of submodules be connected in each leg with a rated capacitor voltage of v_c, then assume output voltage from submodules are termed as $v_{\text{sub1}}$$v_{sub1}$, $v_{\text{sub2}}$$v_{sub2}$, ⋯ v_{sub3}, $v_{\text{sub}n}$. With n number of submodules, n+1 amount of energy amounts which are equal to 0, v_c, 2v_c, $3v_c$ ⋯, nv_c. A voltage level of 0 can be achieved by turning off all submodule switches. Other voltage levels can be produced by combining redundant switching states of submodules. The capacitor voltage of each submodule is regulated or controlled by these switching states. Output voltage from each arm of MMC v_{arm} is equal to sum of voltages of submodule.

$$\begin{aligned} v_{\text{arm}} &= v_{\text{sub1}} + v_{\text{sub2}} + \cdots + v_{\text{sub}n} \\ &= S_1 v_{c1} + S_2 v_{c2} + \cdots S_n v_{cn} \end{aligned} \quad (1)$$

where S_1, S_2, ⋯, S_n are switching states (either 1 or 0) of submodules.

3. MMC Based UPQC

The structure of the system with nonlinear load, series and shunt converter and PV integrated DC link up is illustrated in Fig. 3. v_{dc} is the DC link voltage. v_{gabc} v_{gabc} and i_{gabc} i_{gabc} are source voltage and current, R_g and L_g are line resistance and inductance respectively, $v_{\text{ca}}$$v_{ca}$, v_{cb} and v_{cc} are series converter injected voltages trough series transformer, i_{cabc} i_{cabc} is compensator current injected by shunt converter, $v_{\text{labc}}$$v_{labc}$ and i_{labc} $i_{labc}$are load voltage and current. A series active filter (SeAF) is a series converter that connects to the line through a series transformer, while a shunt active filter (ShAF) is a shunt converter that connects in parallel with the line. Both the SeAF and ShAF use a boost converter to regulate the DC voltage and transfer additional power to the line from a photovoltaic (PV) source. Both SeAF and ShAF are comprised of modular multilevel converter with 8 submodules in each leg (i.e., 4 submodules for positive arm and 4 submodules for negative arm). A half bridge with two IGBTs, two anti-parallel diodes, and a DC capacitor is adopted as the submodule.

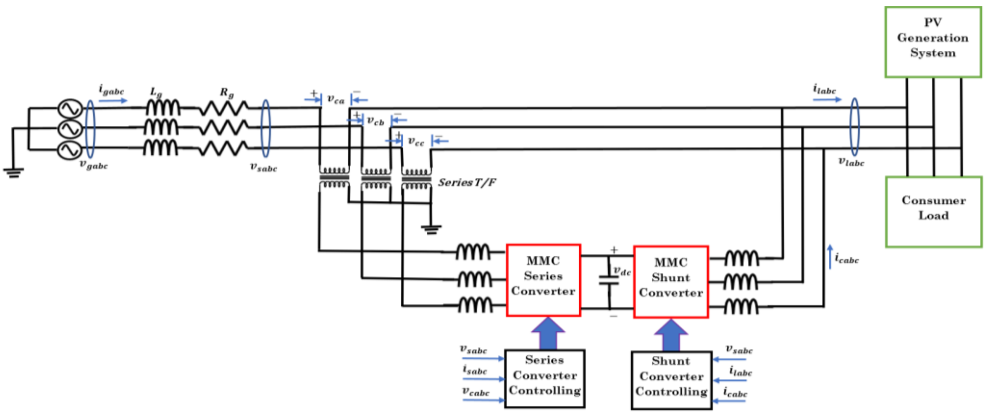


Fig 3. MMC based UPQC.

In each submodule, if switch T_1 is ON and T_2 is OFF then production voltage of submodule is equivalent to its capacitor current, if switch T_1 is OFF and T_2 is ON then output voltage of submodule is identical to its 0 and if both switches are in OFF condition, then submodule is in blocked state. In blocked state, capacitor is charged if its voltage is less than its respective submodule voltage, discharged if its voltage is more than respective submodule voltage.

The proposed model for improving power quality using MMC-based UPQC is depicted in Fig. 1. Specifically, each arm of the converter's output voltage comprises eight submodules, which can generate a nine-level output voltage. The proposed model features an MMC structure for the series filter and for the shunt filter to maintain sinusoidal harmonic currents and balance to regulate the voltage at the point of common coupling, a shunt filter is connected in parallel with the line, while a series filter that uses MMC is connected to the line through the series transformer. Harmonic filters are employed between the active filters and the line to mitigate fluctuations in the current and voltage that are injected into the line.

The initial stage in designing an MMC-UPQC for a PV-grid integrated system is to determine the appropriate sizes for the PV array, DC-link capacitor, and DC-link voltage level. The shunt compensator and series compensator must be sized correctly to handle the peak power output from both the PV array and grid, as well as to compensate for reactive power and current harmonics associated with the load current. The PV array must be sized to match the AC grid voltage at its maximum power point (MPP) voltage for it to connect to the grid through the MMC-UPQC.In normal circumstances, the PV array should be capable of providing the load's active power while also supplying power to the grid. Table 3 provides a detailed specification for the PV array, along with other design components such as interfacing inductors for the series and shunt compensators, as well as a series injection transformer for the series compensator. The series filter has a crucial role in delivering a nine-level output by providing a smooth and ripple-free voltage to the capacitor that connects between the shunt and series filters. Additionally, this system is capable of compensating for voltage sags and eliminating voltage harmonics that are produced within the system.

The recommended setup for managing MMC-UPQC involves utilizing the Synchronous Reference Frame (SRF) technique, which enables independent control of the SeAF and ShAF. To counteract harmonic currents and maintain the stability of the DC-link voltage, the ShAF utilizes a dual-loop feedback method along with a voltage feedforward mechanism. In contrast, the SeAF uses a voltage feedback mechanism and current feedforward approach to regulate the distorted load voltage. To ensure that both the SeAF and ShAF remain synchronized with the grid, it is necessary to use a control system that can handle non-ideal grid voltage conditions. Traditional Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) systems tend to perform poorly under such conditions. To address this issue, this article adopts the use of a pre-sorting SRF-PLL centred on the Sliding-Mode Generalized Discrete Fourier Transform (SGDFT) [20]. With the SGDFT-pre-filter in place, the SRF-PLL can operate effectively even when the grid voltage is seriously abnormal, provided that the PI gains are appropriately adjusted.

A. Control Design for ShAF

Fig. 4 illustrates the control block diagram of the ShAf, which comprises several modules such as reference current calculation, DC-link voltage control, output current control, voltage feedforward control, and SPWM. The required current is calculated using Symmetrical and Orthogonal Discrete Fourier Transform (SGDFT) applied to the load current. A fuzzy device normalizes DC link voltage to be equal to V_{dc}^{*} v_{dc}^{*} by generating a reactive current i_q. Active current i_d is assumed as 0 and by using Park transformation dq terms are transferred into abc (i_{2abc}) (i_{2abc}). Then reference currents can be calculated by

$$i^{*}_{rabc} = i_{2abc} + i_{labc} \tag{2}$$

The goal is to design a Proportional Resonant (PR) controller that follows the current reference. Using impulse variant method presented in [21] the transfer function for G_{idq} is evaluated. The basic idea behind G_{idq} as proportional resonant controller is to combine two control techniques - proportional control and resonant control - in order to achieve better performance and stability. Proportional control uses a feedback loop to adjust the output of a system depending on the variation between the desired value and the actual value. This is done by multiplying the error signal by a constant, named the proportional gain.

Resonant control, on the other hand, focuses on reducing the effects of harmonic disturbances or noise that can affect the system. It uses a filter to attenuate specific frequencies and amplify others. In G_{idq}, the proportional control is used to regulate the steady-state behaviour of the system, while the resonant control is used to dampen oscillations and attenuate harmonic disturbances. This control combines these two techniques by incorporating a resonant filter into the feedback loop of the proportional controller. The resonant filter is designed to attenuate disturbances at a specific frequency, called the resonant frequency, while amplifying signals at a slightly higher frequency. By adjusting the parameters of the filter and the proportional gain, a G_{idq} can be tuned to provide the desired response characteristics. Overall, this controller provides a more robust and efficient control solution for systems that are subject to harmonic disturbances or oscillations.

The impulse invariant method is a technique for designing digital filters based on an analogy filter's impulse response. This method is commonly used in signal processing applications where an analogy filter's characteristics need to be transferred to a digital filter. The basic idea behind the impulse invariant procedure is to sample the impulse response of the filter at a high rate and then use these samples to design the digital filter. To do this, the continuous-time impulse response of the analogy filter is first sampled at regular intervals to obtain a discrete-time sequence. The sampling rate should be chosen high enough so that the resulting digital filter has a good approximation of the analogy filter's frequency response.

To obtain the frequency response of a digital filter from its discrete-time impulse response, it is necessary to convert the latter into a transfer function in the z-domain. This conversion can be achieved through the use of the Z-transform, which transforms the discrete-time sequence into a rational function of a complex variable. Once the transfer function is obtained, it can be utilized to implement the digital filter using methods like direct form or cascade form. The digital filter produced through this process will possess a frequency response that closely approximates that of the corresponding analogy filter. After evaluating G_{idq} G_{idq} can be expressed as

$$G_{idq} = K_{pi} + \sum_{h=6,12} \frac{2K_{ii}T_s\left[1 - z^{-1}\cos(\omega_h T_s)\right]}{1 - 2z^{-1}\cos(\omega_h T_s) + z^{-2}} \quad (3)$$

where K_{pi} K_{pi} is proportional gain, K_{ii} K_{ii} is integral gain, T_s is the sample interval,

To account for the dominant harmonic orders in the load current, the Proportional Resonant (PR) controllers in the dq domain corresponding to the 6th and 12th harmonic orders are utilized. Additionally, to counteract any grid voltage disruptions, a voltage feed-forward control approach is integrated. A SPWM technique is employed to produce the required pulses for the Modular Multilevel Converter (MMC) of the ShAF.

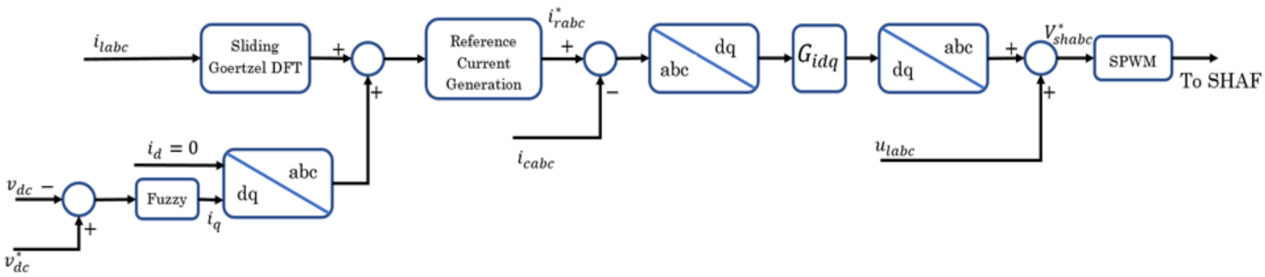


Fig 4. Control structure of ShAF.

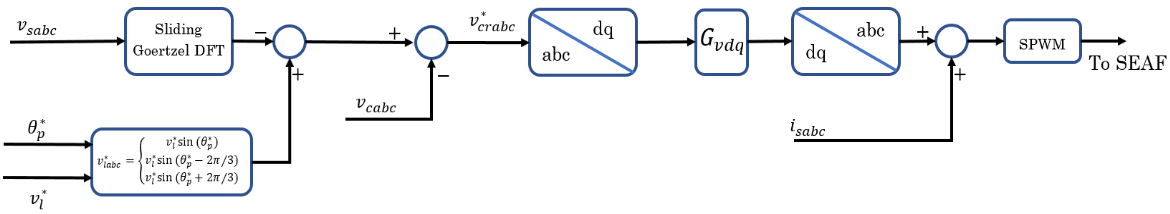


Fig 5. Control structure of SeAF

B. Control Scheme for SeAF

Fig. 5 illustrates the control architecture for the SeAF, which includes various elements such as reference voltage calculation, output voltage control, current feedforward control, and SPWM. Reference voltages are calculated from grid voltages v_{sabc} v_{sabc} and desired load voltages V^*_{labc}. Refence load voltages V^*_{labc} are calculated from fundamental phase sequence and minimal load phase voltage amplitude V^*_l v^*_l. Like the shunt HAPF's current control mechanism, the 6th and 12th Proportional-Resonant (PR) controllers represented as G_{vdq} (z) are adopted to trace the reference voltages in the sequence effective filter.

Current feedforward control is employed to compensate for the current disturbances.

$$G_{vdq} = K_{pv} + \sum_{h=6,12} \frac{2K_{iv}T_s\left[1 - z^{-1}\cos(\omega_h T_s)\right]}{1 - 2z^{-1}\cos(\omega_h T_s) + z^{-2}} \quad (4)$$

where K_{pv} and K_{iv} K_{ii} are PI gains and T_s is the sample time.

C. Fuzzy Controller as DC Voltage Regulator

A fuzzy controller is a type of controller that uses fuzzy logic to make decisions based on input data that is imprecise or uncertain. It is a type of artificial intelligence that mimics the way humans make decisions by using linguistic variables, membership functions, and fuzzy rules to map input data to output data. In a fuzzy controller, the input data is first fuzzified, which means that it is transformed into a set of membership functions that represent the degree of membership of the input data to certain linguistic variables. Then, a collection of fuzzy rules is defined in Table 2 that maps the input data to the output data based on the linguistic variables and membership functions. The output data is then defuzzied, which means that it is transformed from the fuzzy set of membership functions to a crisp output value. Fuzzy controllers have been used in an extensive choice of uses, involving control systems for industrial procedures, robotics, and intelligent transportation systems. They are particularly useful in situations where traditional control methods may not be effective due to the imprecise or uncertain nature of the input data.

The paper proposes the use of a fuzzy controller to control the DC voltage, where the controller's inputs are the DC voltage error (E) and the error's rate of change (CE) as shown in Fig. 6 and Fig. 7 respectively. The controller's output (OUT) is utilized to modify the reactive current needed by the shunt converter of the MMC-UPQC as shown in Fig. 8.

Table 2. Fuzzy rules

E \ CE	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	PS	PM	PB	PB	PB	PB

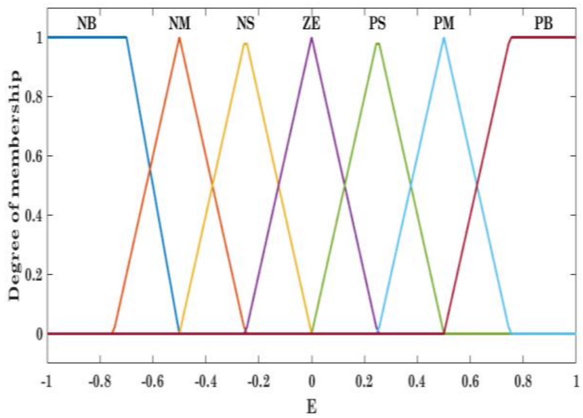


Fig. 6. Error response to the fuzzy controller.

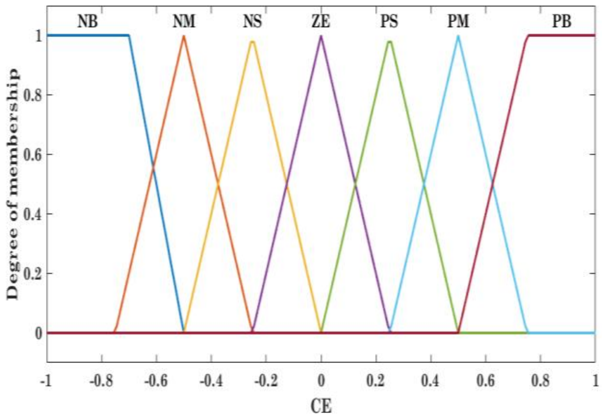


Fig. 7. Change in error input to the fuzzy controller.

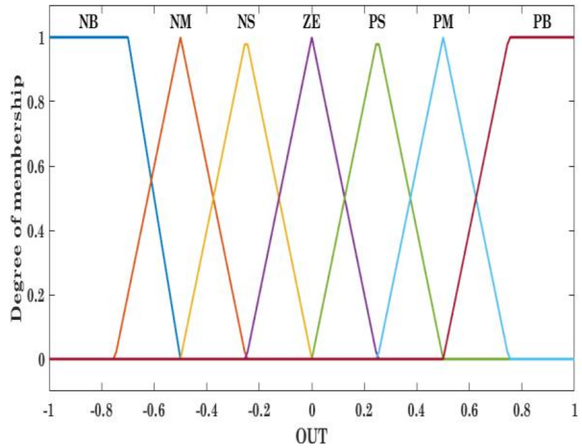


Fig. 8. Fuzzy controller output membership functions.

Table 3: System parameters

Grid voltage and frequency	440 V, 50 Hz
Line resistance and inductance	0.2 ohm and 0.5 mH
PV generation system	
Open Circuit Voltage	64.2 V
Short Circuit Current	5.96 A
MPP voltage	54.7 V
MPP Current	5.58 A
Parallel Strings	66
Series connected modules per string	5
Series Transformer	630 KVA 440/440 V
Series converter Filter	2mH, 20 µF
Shunt Converter Filter	1.35 mH, 215 µF
MMC	
No. of Sub Modules per leg	8
Capacitance of Sub Module	3.3 mF
DC Link Capacitance	9400

4. Simulation Results

This research conducted a performance analysis of the fuzzy controlled MMC-UPQC through simulations using MATLAB-Simulink software. A simulation setup was utilized, which consisted of a 3-φ diode bridge rectifier with an R-L load representing a nonlinear load. In this study, a simulation of a system with a nonlinear load was conducted using MATLAB-Simulink software. The load consisted of a three-phase diode bridge rectifier with R-L load, and the simulation considered different dynamic conditions such as sag and swell in PCC voltage. A solver step size of 1e-6s was used, and the simulation utilized the system parameters presented in Table 3. The study evaluates the effectiveness of the fuzzy controlled MMC-UPQC in a 440V distribution network with PV integration and compares the results with those of a conventional UPQC and a PI controlled MMC-UPQC. For the analysis, a resistive load with a diode bridge rectifier was utilized as a nonlinear load.

The impact of distorted grid voltages and nonlinear loads on the management of the intended fuzzy controlled MMC-UPQC is demonstrated in Case 1, as depicted in Fig. 9. The grid voltage was intentionally distorted, with characteristic harmonics of 5th, 7th, 11th, and 13th. The system also included a diode rectifier with RL load and a PV generation system. The distorted waveforms of the source voltage, load current, and the steady-sinusoidal load voltage and source current waveforms after MMC-UPQC activation are illustrated in Fig. 9 and Fig. 10, respectively. While Fig. 11 and Fig. 12 exhibit the improved compensation performance of the fuzzy controlled MMC-UPQC.

Corresponding to the FFT analysis, the fuzzy controlled MMC-UPQC successfully eliminated the 5th, 7th, 11th, and 13th harmonics. As a result, the load voltage THD and grid current THD considerably reduced from 11.66% to 1.52% and from 30.77% to 2.24%, respectively. The Fig. 13 exhibit the efficacy of the fuzzy control approach in regulating the DC link voltage at the desired reference value of 400V. Furthermore, the Fig. 14 shows the performance comparison between conventional UPQC, PI controlled MMC-UPQC, and fuzzy controlled MMC-UPQC. It indicates that the proposed fuzzy control strategy outperforms the other two methods in regulating the DC link voltage under various dynamic conditions.

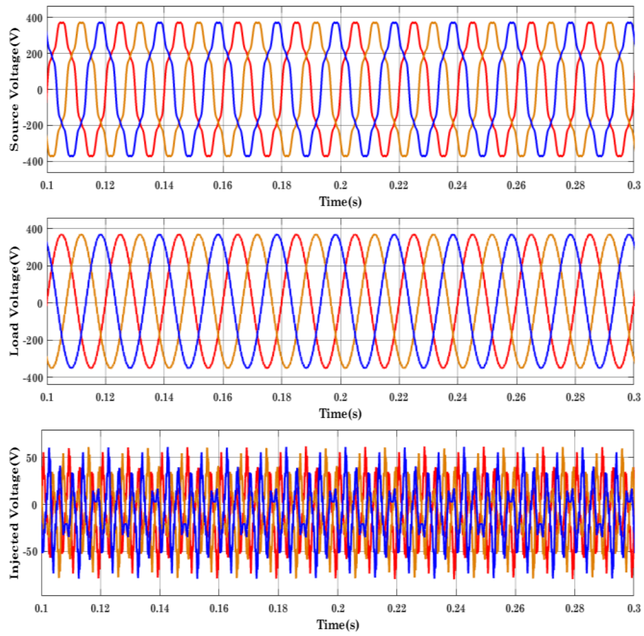


Fig. 9. Source voltage, load voltage and injected voltage by series converter

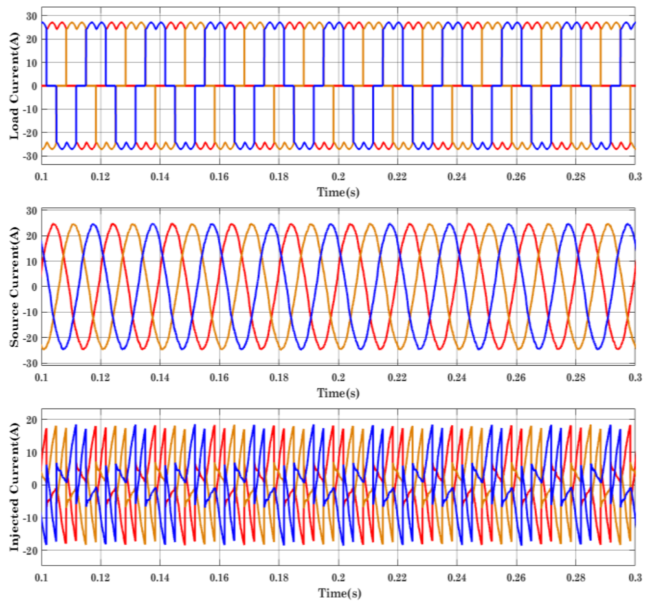


Fig. 10. Load current, source current and injected current by shunt converter.

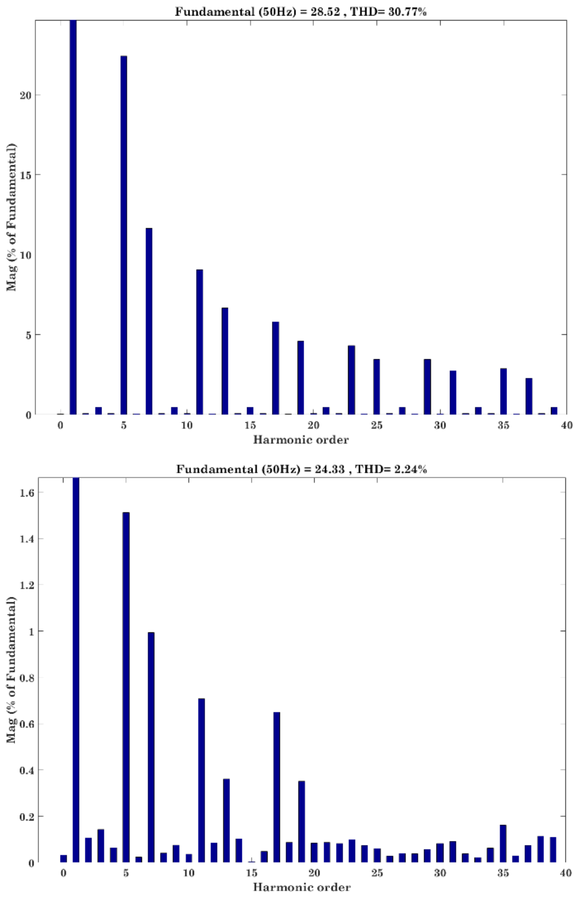


Fig. 11. Load current and source current THD

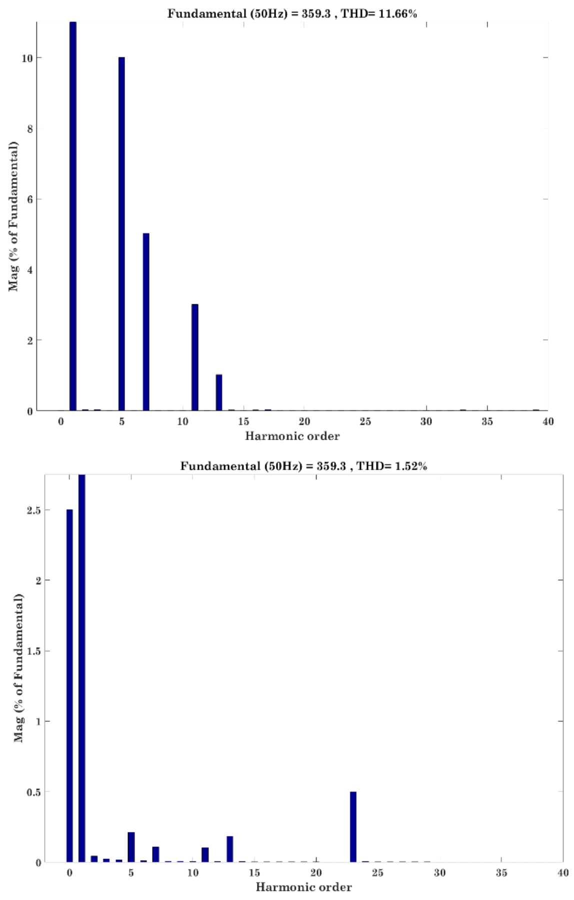


Fig 12. Source voltage and load voltage THD.

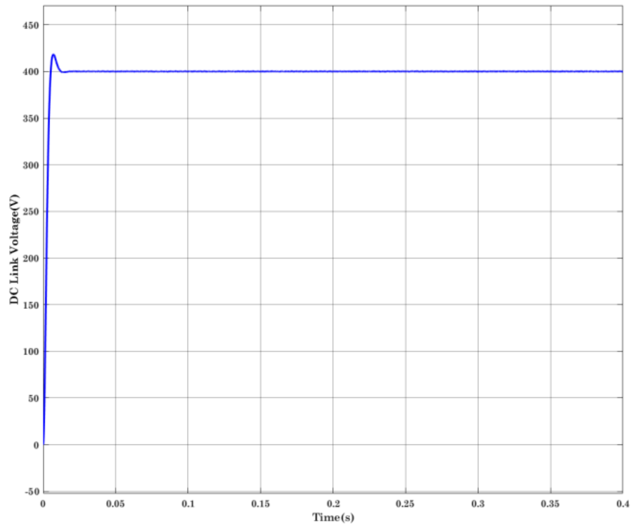


Fig 13. DC Link voltage regulation with fuzzy controlled MMC-UPQC

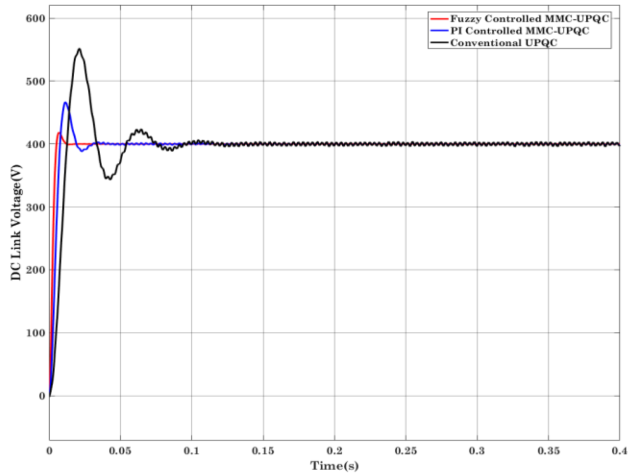


Fig 14. DC Link voltage comparison between conventional UPQC, PI controlled MMC-UPQC and fuzzy controlled MMC-UPQC.

Case 1. This case simulates voltage sag and voltage swell conditions using unbalanced grid voltages with varying percentages of sag/swell on different phases. The simulation considers a pure resistive load. To simulate a voltage sag, unbalanced grid voltages were introduced with a 40% sag on phase A, 30% sag on phase B, and 20% sag on phase C at 0.4s. To simulate a voltage swell, unbalanced grid voltages were introduced with a 60% swell on phase A, 30% swell on phase B, and 40% swell on phase C at 0.4s. Fig. 15 and Fig. 16 display the results of the evaluation of the different voltages using fuzzy controlled MMC-UPQC under sag and swell conditions, respectively. The figures demonstrate the simulation results reveal that the fuzzy controlled MMC-UPQC compensates for the voltage sag/swell conditions effectively by adding compensating voltages, which instantaneously regulate and balance the load voltages at their rated value. As a result, the system's performance concerning the source voltage and DC link voltage are improved under both conditions. The graphs corresponding to the imitation effects validate the ability of the regulator in maintaining the load voltages despite the severe voltage disturbances. Additionally, the DC link voltage is well-regulated at the reference value of 400 V with a maximum overshot of 4.5% within two cycles. These findings affirm the MMC-UPQC's ability to sustain load voltage under challenging voltage sag/swell conditions, thereby augmenting the system's overall stability and performance.

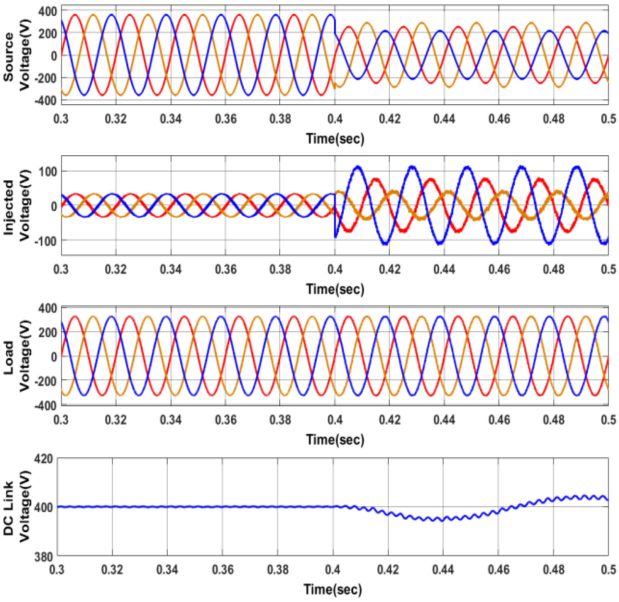


Fig 15. Source and injected voltage, load voltage and DC link voltage during sag condition

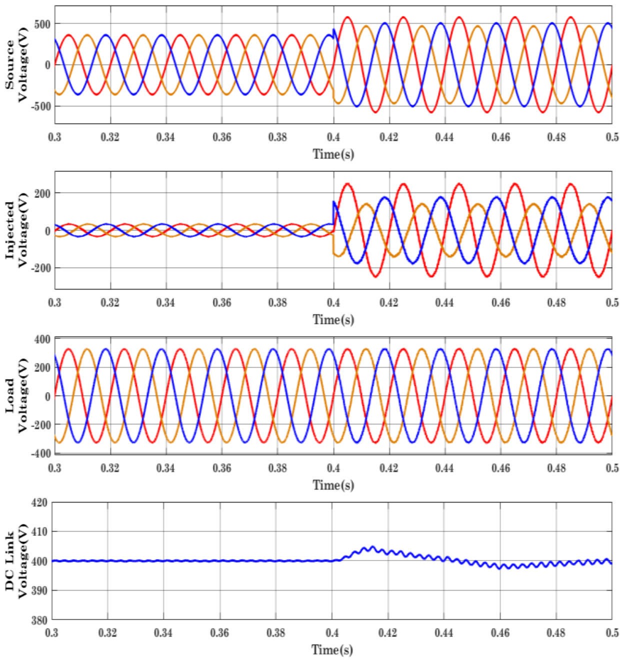


Fig 16. Source and injected voltage, load voltage and DC link voltage during swell condition

Case 2. This simulation aims to assess the dynamic response of the fuzzy controlled UPQC to abrupt load variations under demanding conditions, such as harmonic, unbalanced, and sag grid voltages, while a nonlinear load followed by an RL load as depicted in Fig.17. At 0.3s, the MMC-UPQC is activated, prior to 0.4s, the series active power filter maintains load voltages at their rated value without any distortion. The Fig. 18 illustrates that the shunt converter prevents harmonic currents from being injected into the grid. At the 0.4s mark, the sudden inclusion of a resistive load in parallel with the nonlinear load resulted in an escalation of the load current amplitudes notably, despite the escalating active power demand from the load, the MMC-UPQC output voltages and currents remained constant, indicating its ability to manage sudden load variations proficiently. The dynamic response of the fuzzy controlled MMC-UPQC to such abrupt load changes is explored, and the outcomes indicate that the system operates effectively even in demanding conditions, such as harmonic, unbalanced, and sag grid voltages.

At 0.4s, the addition of a resistive load causes an increase in load current amplitudes, despite the increase in load active power, the MMC-UPQC's output voltages and currents remain stable, with negligible changes observed in the grid current and DC-link voltage, with a maximum overshoot of 3% and a response time of 2 cycles, respectively, indicating the effective handling of sudden load changes by the Fuzzy controlled MMC-UPQC. The DC-link voltage remains stable throughout the simulation, indicating that the MMC-UPQC can maintain excellent compensation performance even with load changes, ensuring a smooth transition between different operating conditions.

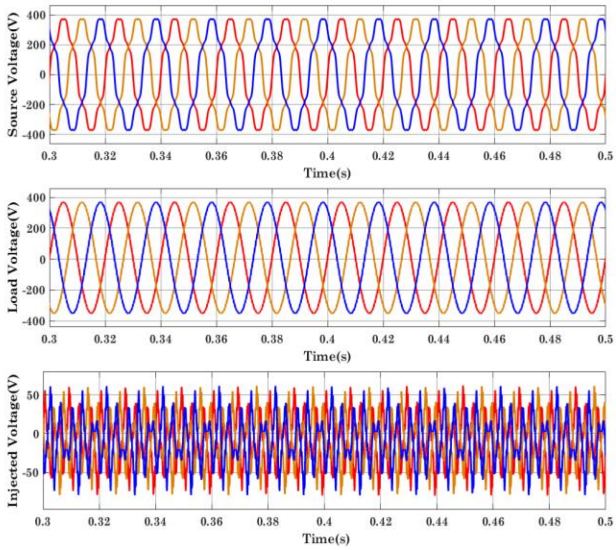


Fig 17. Source, injected and load voltage by series converter with abrupt load variations.

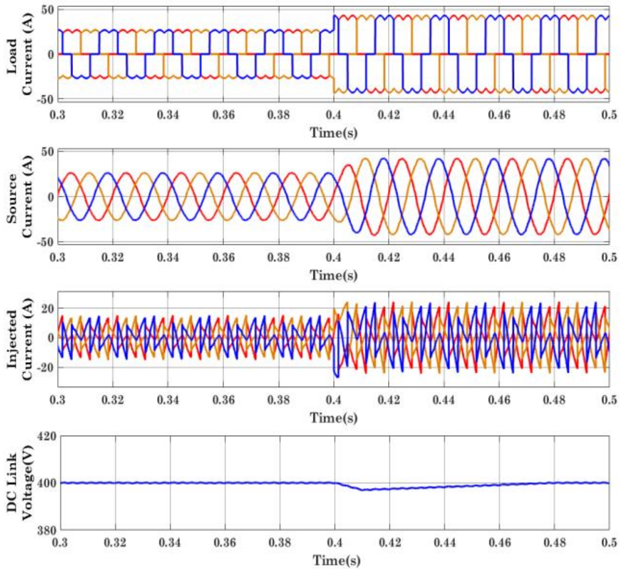


Fig 18. Load current, source and injected current, and DC link voltage by shunt converter with abrupt load variations.

5. Conclusion

The study suggests the use of fuzzy controlled MMC-UPQC as a viable option to improve power quality in solar integrated systems and to ensure high-quality power supply for Sensitive Nonlinear (NL) and Renewable Energy Generation (REG) sources. The main feature that sets the MMC-UPQC system apart from conventional UPQC systems is its integration of both ShAf and SeAF, which are constructed using modular multilevel converters. This integration helps to mitigate the harmful impact of harmonics on the solar system's other loads, ultimately leading to improved system stability.

The paper explains the implementation of control strategies and the design of main circuit components. To ensure that both the series and shunt HAPF remain synchronized with the grid, it is necessary to use a control system that can handle non-ideal grid voltage conditions. SRF-PLL systems may not perform well in challenging operating conditions. To address this problem, the proposed solution is to implement a pre-filtering SRF-PLL that utilizes the Sliding-Mode Generalized Discrete Fourier Transform (SGDFT). A fuzzy controller is adopted as DC voltage regulator due to its ability to handle uncertainties and nonlinearities in the system. It uses a set of fuzzy rules to map the input signals to the output signal, making it suitable for applications where the system dynamics are complex or not well understood according to the simulation outcomes, the presented MMC-UPQC system is highly effective in mitigating harmonics, compensating for reactive power in the vicinity of the harmonic source, and improving the power quality of the solar-integrated system.Additionally, the MMC-UPQC system can effectively address grid voltage harmonics, unbalance, and sag, resulting in a more efficient and reliable power system. This innovative approach has the potential to be applied to diverse fields, including industrial DC power supply systems, renewable energy generation systems, and HVDC transmission systems.

6. Future scope

A more sophisticated voltage regulation technique using adaptive neuro-fuzzy systems in the future could more precisely extract the voltage and current harmonics with a better understanding of simulation verification. Another direction is to study the effect of load variations and variations in the irradiation on the performance proposed MMC-UPQC.

Conflict Of Interest

The authors declare no conflict of interest.

Author Contributions

Under the supervision of Dr. S. Ramesh Kumar, and Dr. N. Karthik, Rajesh Garikapati conducted research and simulations. All the authors have approved the final version of paper.

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