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Improving Power Quality with Intelligent Control in Electrical Energy Systems

Abstract: - As the proliferation of sensitive electronic devices continues, the importance of maintaining high power quality in energy systems has become increasingly critical. Electrical disturbances within the energy system can lead to both technical and financial damages and can degrade the quality of power supplied. The Unified Power Quality Conditioner (UPQC) has emerged as a highly effective solution to mitigate these dilemmas. Key factors affecting power quality include voltage sags, swells, harmonics, non-linear loads, unbalanced loads, and voltage stability dilemmas. To address these challenges, a new intelligent control system based on a TS-fuzzy algorithm is proposed. This system is designed to enhance power quality by effectively managing various disturbances. The proposed controller's performance is evaluated through simulations using MATLAB/Simulink software, focusing on conditions such as voltage sags, swells, nonlinear loads, and unbalanced loads. Compared to a traditional Proportional Integral (PI) controller, the TS-fuzzy algorithm significantly reduces total harmonic distortion (THD) and stabilizes DC bus voltage. The proposed controller achieves THD levels of 2.43% for nonlinear loads and 1.6% for unbalanced loads, demonstrating superior performance over conventional methods.

Keywords: Power Quality (PQ), Unified power quality conditioner (UPQC), TS-Fuzzy Algorithm, Total Harmonic Distortion (THD), Electrical Disturbances

I. INTRODUCTION

An electrical energy system is designed to provide reliable and efficient power to ensure that various electrical devices can function properly. As the demand for electrical energy escalates, it is imperative to maintain that the power quality delivered aligns with the increasing power quantity requirements. One of the primary objectives in power grids has always been to uphold the quality of electrical power, which is essential for their effective operation [1].

The power system takes part in a crucial role in providing the electrical energy that is necessary for our everyday activities. However, power quality problems can crop up within the power system. Ensuring that the power transfer system operates efficiently requires meeting the prescribed power quality standards, such as IEEE 519 and IEEE 1159. Meeting these standards is crucial to guarantee the effectiveness and reliability of the power system [2-3]. As the use of testing equipment has become more prevalent, there has been a growing awareness and concern regarding power quality issues in recent years. This is because the proper functioning of these sensitive devices is heavily reliant on consistent and reliable power quality, and any deviations or disturbances can have a significant impact on their performance. The use of advanced electronic equipment has increased as a result of the growth of industrial and technical development. However, the operation of these devices has led to several issues in the electrical grid, such as the appearance of excessive harmonics, which can cause distortion in the supply voltage waves. Power quality (PQ) issues have become a significant challenge for modern electric power systems. Power quality issues pose significant challenges to modern electric power systems, with voltage sag, voltage swell, transient frequency deviation, flicker, voltage and current harmonics, and zero sequence currents being the most prevalent concerns. Power quality issues are deviations in voltage, current, or frequency that significantly depart from the ideal sinusoidal waveform and may cause failure or malfunction of customer equipment. Power quality refers to a power system's ability to maintain sinusoidal waveforms of voltages and currents on the distribution bus at their rated magnitude and frequency, with minimal deviation or distortion. Power electronic devices, such as Switch Mode Power Supplies (SMPS), current regulators, frequency converters, and others, can contribute to power quality issues. These devices may introduce harmonic distortions, voltage fluctuations, and other irregularities, impacting the overall stability and reliability of the power system. All power electronic devices are also classified as non-linear loads. Due to usage of non-linear loads harmonics, voltage sag, voltage swell all kind of distortion generated for which power quality issues generated and the consumer does not get the desired power.

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The power quality issues can be mitigated through the implementation of an electronics-based strategy. This equipment is a constructive solution for power quality issues. Conventionally different type of procedures has been taken to control the problem that is related to power quality. We used a static capacitor to compensate the reactive power in the grid. There is also other equipment such as thyristor switched capacitor (TSC), static VAR compensators (STATCOM), and thyristor-controlled reactors (TCR) have been implemented to offer greater flexibility in managing reactive power compensation [4].

In this paper, a unified power quality conditioner which is known as UPQC is used to address above issues. UPQC is the combination of a series active filter and a shunt active filter which are used to discard the high frequency current ripples and voltage distortion. Filters can be categorized into two distinct types: active filters and passive filters. In addition to this, active filtering is also categorized into shunt, series, and hybrid filters. The shunt active filter is specifically linked in parallel and addresses issues such as elevated harmonics [5]. Series active filters are essential for addressing voltage-related power quality disturbances by integrating in series with the power distribution system [6]. The hybrid composition of both series and shunt is capable to remove both types of problems. In UPQC we used a hybrid composition of both series and shunt converter with some noble control strategies. Active power filters (APFs) possess the capability to mitigate a variety of significant power quality issues. Previously, in conjunction with UPQC, PI control strategies were employed to effectively mitigate harmonics, voltage sag, voltage swell, and distortion. However, to enhance the performance of the UPQC and achieve improved results, this work has implemented a TS-fuzzy controller. The proposed controller was investigated under voltage sag, voltage swell and harmonic distortion. The suggested approach can be validated within the MATLAB/Simulink environment.

STATE OF THE ART:

In terms of custom power devices, it is important to understand that each device offers unique benefits and limitations that should be taken into consideration when selecting a device for a specific power system application. After extensive research, it can be concluded that the Unified Power Quality Conditioner (UPQC) is a highly efficient and effective remedy for diminishing power quality problems in power systems that have high-capacity loads, which are susceptible to voltage and current fluctuations and imbalances. There are many more reasons that proved why UPQC is preferred over others. In devices, most of the devices either correct current or voltage disruptions but UPQC does both tasks simultaneously and hence multiple tasks can be done by UPQC [7].

The Unified Power Quality Conditioner is a comprehensive solution that integrates two types of Active Power Filters (APFs) – shunt active power filters and series active power filters [8-10]. Shunt APFs are designed to counteract the current harmonics generated by non-linear loads, facilitating reactive power compensation and balancing of imbalance currents. On the other hand, series APFs primarily function as voltage regulators and harmonic isolators, ensuring a stable connection between non-linear loads and the utility grid. In modern-day distribution systems, there is an increasing demand for elevated levels of voltage quality and current stability. The UPQC addresses these requirements, making it a crucial component in today's power generation and distribution systems. The active power filters (APFs) have become increasingly relevant for practical implementation as they can effectively address issues related to voltage regulation and current stability by mitigating harmonic distortion and improving power factor in power systems. But it may not be cost effective if we install two separate devices individually.

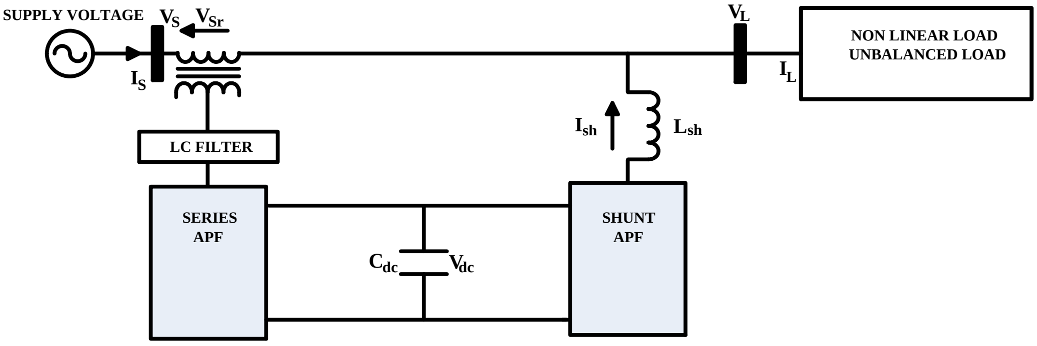


Fig.1. Configuration of UPQC

Moran [11] introduced a system configuration in which two separate systems were interconnected using a shared DC reactor. This particular configuration was referred to as a "line voltage regulator/conditioner." Additionally, the back-to-back inverter setup has been identified by several other names in the literature, including: Series-Parallel Converter [12], Unified Active Power Filter (UAPF) [13], Universal Active Power Line Conditioner [14-15], Universal Power Quality Conditioning System (UPQS) [16], Universal Active Filter [17].These various names highlight the versatility and applicability of the back-to-back inverter arrangement, as it serves as an effective solution for enhancing power quality, voltage regulation, and harmonic mitigation in electrical systems.

In configuration wise it can be said that the construction of UPQC is similar in nature to that of a unified power flow controller (UPFC) as both devices consists of power electronic components such as voltage source inverter (VSI), DC-link capacitors and transformers and utilize algorithms to regulate power flow and improve power quality in electrical power systems. Conversely, UPFC is capable of operating solely under balanced conditions. Due to its unique properties, the power transmission system is suited for the application of UPFC since it normally runs in a counterbalanced and wrapping out environment. Conversely, the power distribution system might encompass DC elements, along with voltage and current anomalies, as well as imbalances in voltage and current. Therefore, in this scenario, the UPQC is employed to address these issues effectively. Fig. 1 provides a visual representation of the UPQC system configuration, illustrating its components and how it is integrated into the power distribution system to lessen power quality problems and ensure stable and reliable operation.

The primary objective of a Unified Power Quality Conditioner (UPQC) is to address various voltage imbalances and power quality issues in electrical systems. These issues include voltage sags, swells, flicker, harmonics, reactive power, negative-sequence currents, and harmonics. To achieve this, the UPQC employs two inverters with specific functions: Shunt Active Power Filter: This inverter is connected across the load and serves as a shunt active power filter. Its purpose is to mitigate current harmonics generated by non-linear loads, thereby reducing reactive current in the load and improving power factor. Series Active Power Filter: line. It handles as a series voltage source inverter (VSI) and is used for utility supply. The series APF acts as a voltage source to counteract voltage disturbances, such as sags and swells, and helps in voltage regulation. By using both the shunt and series APFs, the UPQC effectively addresses a wide range of power quality issues, providing a more stable and reliable power supply to sensitive loads and improving overall system performance. In the system configuration shown in Figure (1), a common DC bus is formed using either a capacitor or an inductor. This DC-link is used to supply DC voltage to the two connected inverters. An LC filter is utilized as a passive low-pass filter (LPF) to reduce the amount of ripples in the system, thereby providing a smoother output. The shunt coupling inductor, denoted as Lsh, is employed to interface the shunt inverter with the power network. During the switching process, the ripples in the system are attenuated by the Lsh filter, contributing to improved performance and reduced harmonic content. A series injection transformer is used to connect the series inverter to the AC power line. This transformer allows the series inverter to interface with the power line effectively. Moreover, through the application of an authenticated turns ratio, there is often the potential to lessen the current or voltage capacity of the series inverter, making it more suitable for the application and enhancing system efficiency.

Due to the above-mentioned feature, the UPQC is used the new intelligent control strategy for decreasing the voltage sag, swell, harmonics, voltage instability etc. of the power system. The main contribution of the work is summarized below:

- To demonstrate that the proposed intelligent control strategy surpasses the traditional PI controller in terms of voltage and current harmonics. This validation provides evidence of the superiority of the intelligent control approach over the conventional method.
- The proposed intelligent control is tested under unbalanced condition and nonlinear loads. By examining the behavior of the system under such conditions, the paper highlights the robustness and adaptability of the proposed approach.
- To find the efficacy of the proposed controller, a comparative analysis between the FFT (Fast Fourier Transform) results of the suggested intelligent control strategy and the traditional control strategy is accomplished.
- To arbitrate the performance of the DC bus in terms of voltage utilizing both conventional and intelligent control techniques.

II. PRINCIPLE AND OPERATION OF UPQC SYSTEM

Indeed, the Unified Power Quality Conditioner (UPQC) is based on the principle of combining both shunt and series Active Power Filters (APFs) to create a hybrid solution. The placement of a DC-link between the shunt and series APFs allows these two individual systems to function as one integrated system, making the UPQC a cost-effective solution for power quality improvement. The shunt inverter in the UPQC is operated using a current control mode, where it regulates the load current to match the reference value. The control algorithm ensures that the actual delivered current closely follows the set reference current, thereby achieving the desired performance of the UPQC. Additionally, the shunt APF performs another critical role by preserving the DC bus voltage within the system. By effectively domineering the DC bus voltage, the UPQC ensures the smooth function of the shunt and series APFs and helps to regain the stability and reliability of the entire system. Shunt inverter injects current to mitigate the harmonics that is generated from non-linear load. The detailed is given in Fig. 2.

The injected current can be governed from the below equation.

$$i_{Sh}(wt) = i_S^*(wt) - i_L(wt) \tag{1}$$

where, $i_{Sh}(wt)$, $i_S^*(wt)$ and i_L(wt) depicts the currents flowing through the shunt inverter, reference source, and load, respectively.

The series inverter of the UPQC is typically operated in voltage control mode. Its primary purpose is to generate and inject voltage in series with the power line to maintain a balanced and sinusoidal point of common coupling (PCC). By inserting the appropriate voltage in series with the line, the UPQC ensures that the power line remains free from distortions and voltage fluctuations, providing a stable and high-quality voltage supply at the load terminal. The equation below can be used to visualize the series inverter of the UPQC.

$$v_{Sr}(wt) = v_L^*(wt) - v_S(wt) \tag{2}$$

where, respectively, $v_{Sr}(wt)$, $v_L^*(wt)$ and $v_S(wt)$ represents the voltages injected into the series inverter, the reference voltage, and the actual source voltage.

During a voltage sag condition, the series inverter of the UPQC injects voltage to ensure that the voltage at the load terminal remains at the desired value. This injected voltage, denoted as v_{Sr} is compensates for the reduction in supply voltage caused by the sag. Maintaining the DC bus voltage is crucial for the UPQC to perform effectively. The DC-link feedback controller plays a significant role in this process. It needs to respond rapidly to any changes in the DC bus voltage and work efficiently to restore the DC bus voltage to the predetermined reference value. The controller should minimize any delays and overshooting to ensure the DC bus voltage is stabilized quickly and accurately. By efficiently managing the DC bus voltage and promptly compensating for voltage sags, the UPQC can effectively provide a stable and regulated voltage supply to the load, improving power quality and ensuring smooth operation of sensitive electrical equipment. Dynamic models that use the dq transformation, which converts sinusoidal signals to constants, are usually quite straightforward. This mapping, however, is precise and doesn't rely on any approximations. dq models represent a natural progression from time-varying phasor models and find widespread application in the study and characterization of rapid transient phenomena within power systems.

A more complex control approach is employed for shunt APFs because the precise regulation of current at the load connection point is critical to ensure the proper functioning and stability of the power system. Shunt APF's control strategy is based on a deviation between the current generated by the reference and the load. The transformation from abc to dq is used to create a reference current. The inputs for this transformation from abc to dq are the magnitude of the load current and the phase of the load voltage. To improve power factor and decrease the phase difference between current and voltage, the voltage phase is used as the reference phase for current. A PLL is placed and it reads the phase of load voltage. To extract the positive sequence current (d), negative sequence current (q), and zero sequence current (0) from the given references, they are multiplied by appropriate factors. The positive sequence current (d) is used to construct the amplitude of the reference current, which is then passed through a low pass filter to remove any signal variations. Subsequently, a dq to abc block is employed to create the desired 3-∅ phase current reference. Another current reference is generated by the shunt Active Power Filter (APF) to maintain the resemblance between the load current and its reference. This difference is then adjusted in the shunt APF's current. The hysteresis controller persistently observes the deviation between the present flow of current through the APF and its reference value, causing the controller's output to activate once the deviation surpasses a specific threshold. This output guides the APF to inject or withdraw current accordingly. To control the inverter's three arms, a complementary gate command is produced at the hysteresis controller's output, as each arm requires two gate commands.

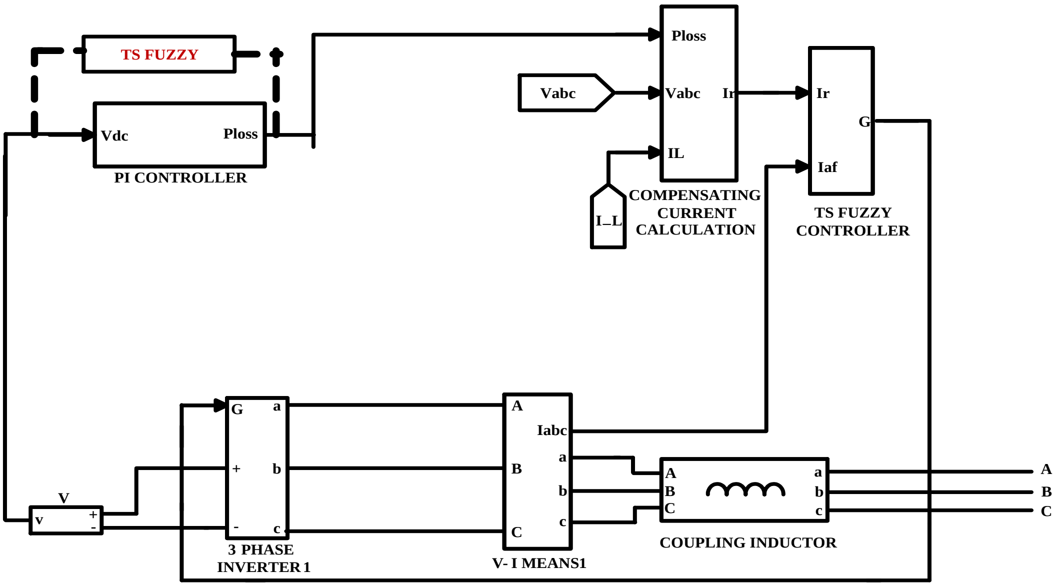


Fig.2. Shunt APF using PI controller and TS-fuzzy controller.

III. Proposed Algorithm

Implementing a control strategy is crucial for enhancing the operational efficacy of the structure. In this work, the noble control approach and UPQC to address the power quality issue. Employed a control strategy for UPQC for sensing the signals of voltage and current. Compensating commands are used in terms of voltage or current levels. The characteristics and intended operation of a specific system are determined by the control strategy. The sole factor determining a UPQC's effectiveness is its control algorithm. The desired performance like switching instants of inverter switches can be achieved by the control strategy. Control strategy also determines the reference signal. There is different type of control strategy that are applied on UPQC. In this paper, the three-phase d-q theory is used.

Its adaptability to an extensive range of gain variations allows the TS-fuzzy linguistic rules to remain flexible, enabling effective management of intricate control challenges. As a result, it successfully improves the power system's stability in the face of demand fluctuations and weather changes [18-20]. It also monitors system uncertainties. Nevertheless, an exploration is conducted to assess whether the TS-fuzzy controller, across diverse operational scenarios, could potentially surpass the performance of the PI controller in cases characterized by nonlinearity and uncertain system conditions [18-20]. Thus, the goal of this work is to enhance the energetic execution of the system by using the proposed intelligent controller.

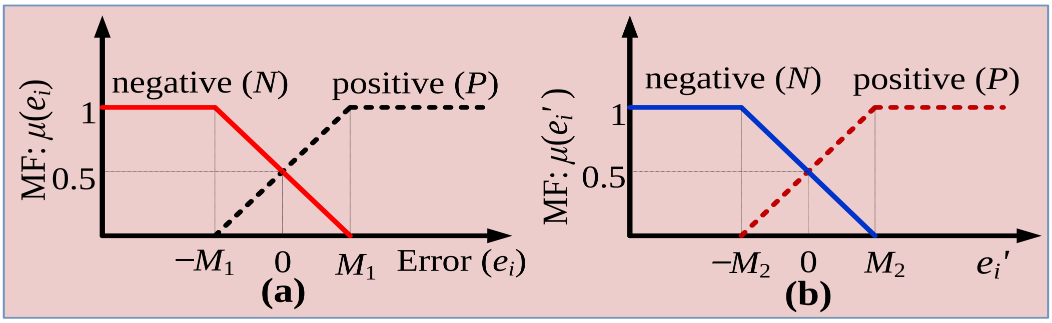


Fig.3. Membership used in: (a). Error in voltage (e_i) and (b). Voltage error derivative (e_i')

For the purpose of building the TS-fuzzy controller (Fig. 3), the variations in the voltage error (e_i) and its derivative (e_i') are used as the fuzzy control's input variables. Utilizing the information presented in Figure 3, two linguistic membership functions (MFs) are applied to transform the error voltage at input and its derivative into fuzzy representations: one for positive (P) and one for negative (N) values. The mathematical representations of these membership functions are given as follows:

$$\mu_P(e_i) = \begin{cases} 0, & e_i < -M_1 \\ \dfrac{e_i + M_1}{2M_1}, & -M_1 \le e_i \le M_1 \\ 1, & e_i > M_1 \end{cases} \text{ and } \mu_N(e_i) = \begin{cases} 1, & x_i < -M_1 \\ \dfrac{-e_i + M_1}{2M_1}, & -M \le x_i \le M_1 \\ 0, & e_i > M_1 \end{cases} \tag{3}$$

$$\mu_P(e_i^{'}) = \begin{cases} 0, & e_i^{'} < -L_2 \\ \dfrac{e_i^{'} + M_2}{2M_2}, & -M_2 \le e_i^{'} \le M_2 \\ 1, & e_i^{'} > M_2 \end{cases} \text{ and } \mu_N(e_i^{'}) = \begin{cases} 1, & e_i^{'} < -M_2 \\ \dfrac{-e_i^{'} + M_2}{2M_2}, & -M \le e_i^{'} \le M_2 \\ 0, & e_i^{'} > M_2 \end{cases} \tag{4}$$

The four fuzzy rules below are condensed to represent the TS-fuzzy controller:

Case-1: If $e_i(\kappa)$ is N and $e_i'(\kappa)$ is N, then $L_1 = b_1 e_i'(\kappa) + b_2 e_i'(\kappa)$.

Case-2: If $e_i(\kappa)$ is N and $e_i'(\kappa)$ is P, then $L_2 = b_3 L_1$.

Case-3: If $e_i(\kappa)$ is P and $e_i'(\kappa)$ is N, then $L_3 = b_4 L_1$.

Case-4: If $e_i(\kappa)$ is P and $e_i'(\kappa)$ is P, then $L_4 = b_5 L_1$.

The above controller's result is represented by L1, L2, L3 and L4 in the rules above, where k is the kth sampling instant. The ambiguous constants are b1, b2, b3, b4 and b5. The fuzzy constants' values as well as parameters of PI-controller are mentioned in Table 1. The coefficients (K_p, K_i) of the PI-controllers are designed on the integral-square-error (ISE) criterion [19].

The generalized defuzzifier is used to produce the output of the TS-fuzzy controller (Y), which is evaluated as follows:

$$Y = \frac{\left(S_1 \times L_1 + S_2 \times L_2 + S_3 \times L_3 + S_4 \times L_4\right)}{\left(L_1 + L_2 + L_3 + L_4\right)} \tag{5}$$

where, $S_1 = \min.\{\mu_P(e_i), \mu_P(e_i')\}$, $S_2 = \min.\{\mu_P(e_i), \mu_N(e_i')\}$

$S_3 = \min.\{\mu_N(e_i), \mu_P(e_i')\}$, $S_4 = \min.\{\mu_N(e_i), \mu_N(e_i')\}$

Through dynamic adaptation of the 'Y' value using the intelligent controller, enhancements are achieved in the power system's stability during various system contingencies.

TS-fuzzy controller uses time series data as input to create predictions. To create models that can represent the dynamic behavior of complex systems, time series analysis techniques are integrated with fuzzy logic in TS-fuzzy systems. A PI controller was also used before TS-fuzzy. A feedback control loop known as a PI controller uses output comparison to identify error signals in systems. The process variable's actual measured value is continuously compared to the desired set point value by the PI controller, which then takes remedial action based on the error signal.

As was previously described, series APF uses a voltage control mechanism. To achieve this control, a 3-∅ sinusoidal wave should be generated with the desired amplitude and phase. Phase locked loops (PLL) read the input voltage's phase. Three nominal voltages are generated with appropriate phase alterations for each of the three phases. The output of the PWM generator provides the necessary control signals to the series APF. These control signals drive the power switches in the series APF to generate an acceptable compensating voltage on the output. The compensating voltage is designed to counteract voltage variations and harmonics present in the system, effectively improving the overall power quality. By following this voltage control mechanism, the series APF can effectively mitigate voltage fluctuations and harmonic distortions, contributing to a more stable and reliable power supply and enhancing the performance of the connected loads.

Table 1. The gain of different controllers

System	Proposed Controller	Conventional controller
UPQC	b_1=3.57, b_2 =2.8 b_3= –4.76, b_4 = 2.8 and b_5 = 27.008.	K_p =10, K_i =0.1

IV. SIMULATION RESULTS AND INFERENCES

Modelling and performance validation of the suggested control approach are both done using the MATLAB/Simulink platform. The trial-and-error method is commonly used by system operators to determine the gains of P/I/PI/PID-controllers. A model-based controller is needed for the majority of traditional control schemes, which can be challenging to execute when the configuration of the system changes (e.g., robust control, pole placement strategy, etc.) [21-22]. In order to eliminate the harmonics, a new control approach is employed called TS-fuzzy intelligent control. The detailed simulation model is given in Fig. 4. The following case studies are taken into consideration when discussing the simulation findings.

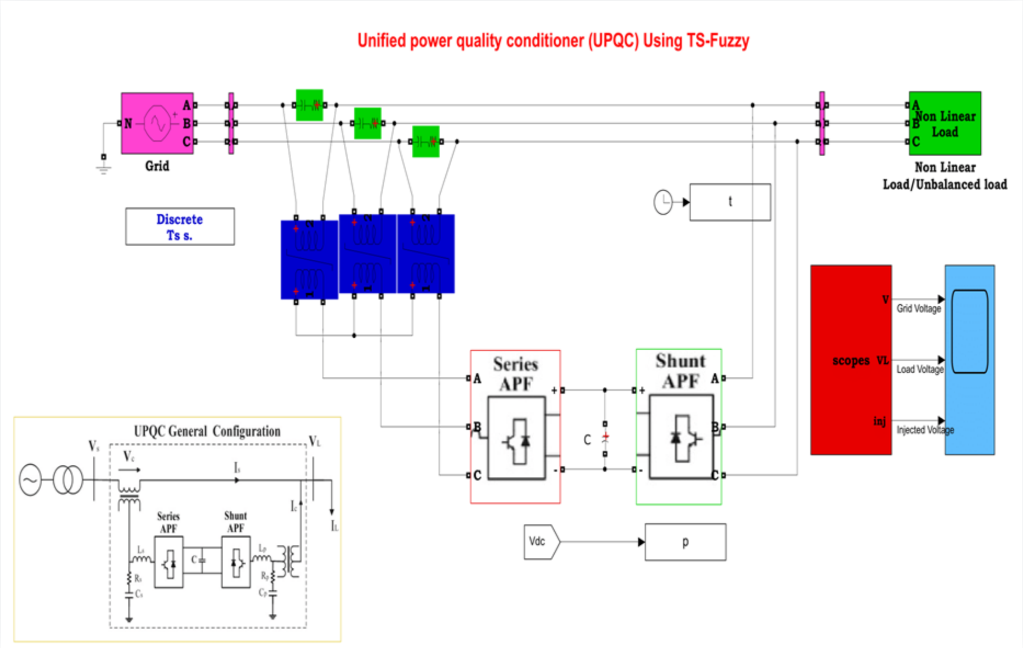


Fig.4. Simulation diagram of the studied system

A. *Case-1: Performance under voltage sag*

A voltage sag, often known as a "dip," is a momentary drop in the RMS line voltage that can range from 10% to 90% of the reference voltage. Its occurrence in power grids is inevitable due to changes in the quantity and nature of connected loads. It is observed in the graph that there is a voltage sag when the source voltage is taken into account under nonlinear load conditions. This is because the power system uses non-linear loads. The major goal is to upgrade the power quality of the electrical system and reduce voltage sag by utilizing the intended algorithm, so that any harm brought on by bad power quality will not affect the electricity supplied to the appliances. Voltage sag occurred between 0.9 and 1 seconds, according to the graph in Fig. 5(a). Fig. 5(b) shows the injected voltage, while Fig. 5(c) shows the voltage compensated and the sag decreased.

B. *Case-2: Performance under voltage swell*

In this case, a small rise in voltage levels over the range of normal operation is referred to as voltage swell. It stands in contrast to voltage sag, which describes a brief drop in voltage levels. Numerous things, including lightning strikes, power system problems, and abrupt increases in load demand, can result in voltage surges. Here, the algorithm also detects voltage swell in the graph when the source voltage is taken into account.

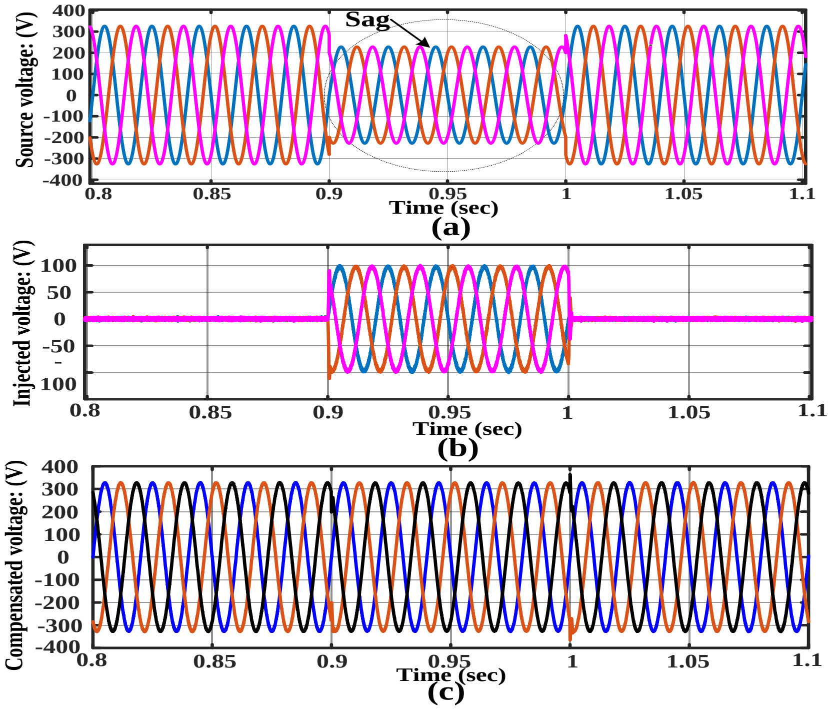


Fig.5. Performance of proposed controller during sag: (a) voltage at input, (b) voltage at injection, and (c) voltage during compensated

The cause of it is the power system's non-linear load. Absolutely, the power excellence in a power system can be significantly impacted by the use of certain types of loads. The voltage swells shown in Fig. 6(a) took place between the seconds of 1.6 and 1.7. The injected voltage is shown in Fig. 6(b), and the counterbalanced voltage is shown in Fig. 6(c) after the voltage swell has been decreased.

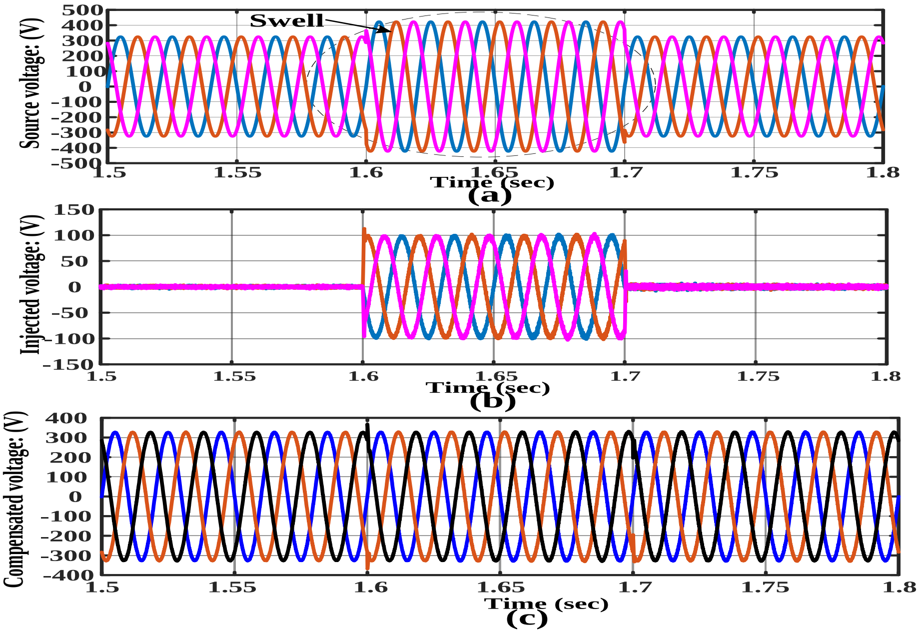
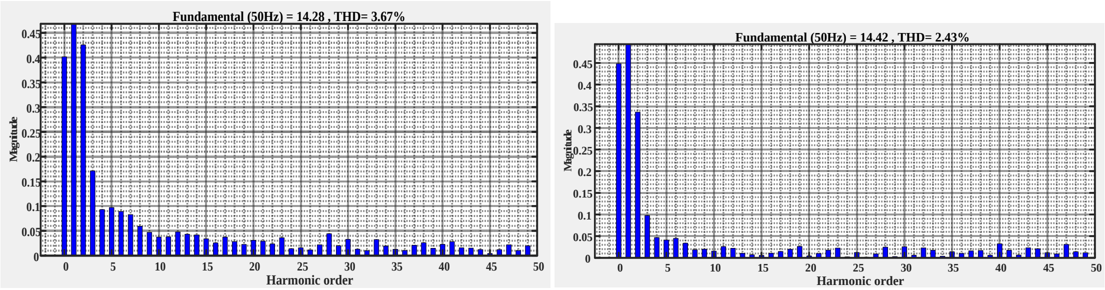


Fig.6. Performance of proposed controller during swell: (a) voltage at input, (b) voltage at injection, and (c) voltage during compensated.

C. *Case-3: Performance under nonlinear load*

Under nonlinear load situations, the proposed controller's performance is evaluated. Traditional PI controllers have a higher harmonic content than contemporary temporary control methods. The typical PI controller's overall harmonic distortion is 3.67%. The TS-fuzzy controller's overall harmonic distortion is 2.43%. Therefore, the novel intelligent control approach complies with IEEE 519 and IEEE 1159 [2,3]'s requirement that the total harmonic distortion be less than 5%. Here, it is observed that an intelligent control strategy produces superior outcomes. The THD using conventional control and proposed control is given in Fig. 7(a) and Fig. 7(b).



(a) (b)

Fig.7. Harmonic content of nonlinear load: (a) PI controller, (b) TS-fuzzy controller

D. *Case-4: Performance under unbalanced load*

By connecting three loads with differing values to one another, a three-phase load can be changed into an imbalanced load. Due to the imbalanced current drawn from each phase in this scenario, the voltage could become out of balance and endanger other grid-connected equipment. If the current drawn from the load is not constant and changes over time, an unbalance problem may also develop.

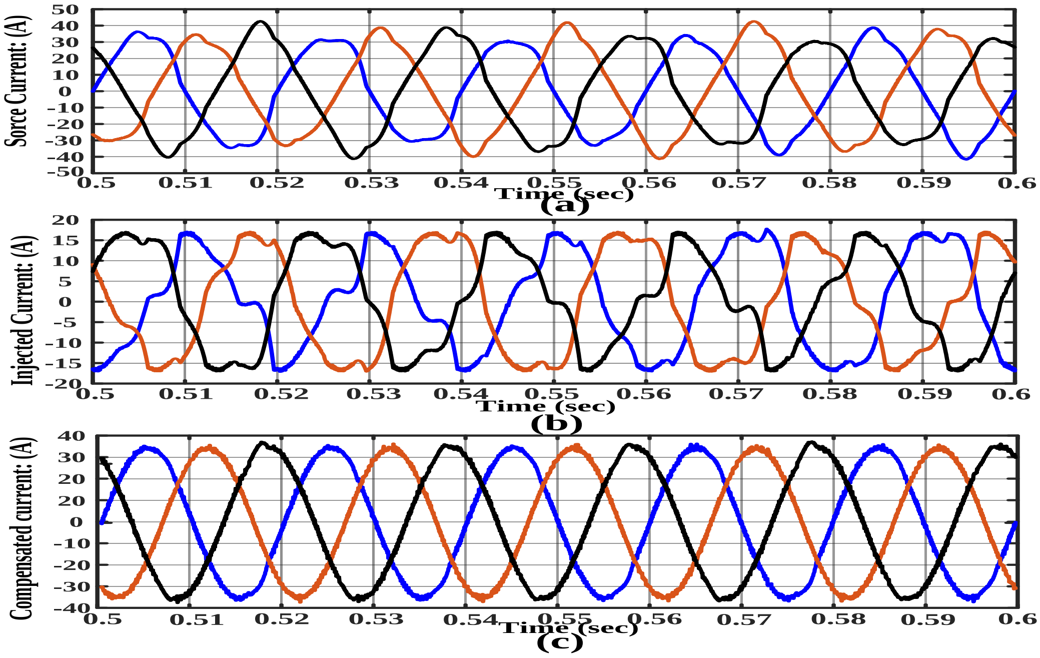


Fig.8. Performance of PI controller during Unbalanced load (a) Source Current, (b) Injected Current, (c) Compensated Current

In these circumstances, the UPQC can account for the current and voltage. Power systems are inherently unbalanced due to faults (i.e., the current in each phase is not the same due to an unbalanced load) and unbalanced switching action in each phase. Unbalanced loads have an unsupportable effect on the performance of the voltage stability of the power system. The voltage deviation arises from the asymmetrical voltage losses across the LC filter. In this instance, a three-phase load linked to the grid with various impedances is used to simulate an imbalanced load. The details current waveform using PI and proposed control method is given in Fig. 8 and Fig. 9, respectively.

Fig. 10 and Fig. 11 allow us to evaluate the overall harmonic distortion produced by conventional and intelligent controllers when the system is unbalanced. Here, we can observe that the overall harmonic distortion for the PI controller is 2.59%, while in TS-fuzzy controller is 1.60%. Therefore, it is concluding that TS-fuzzy provides higher performance than traditional control method.

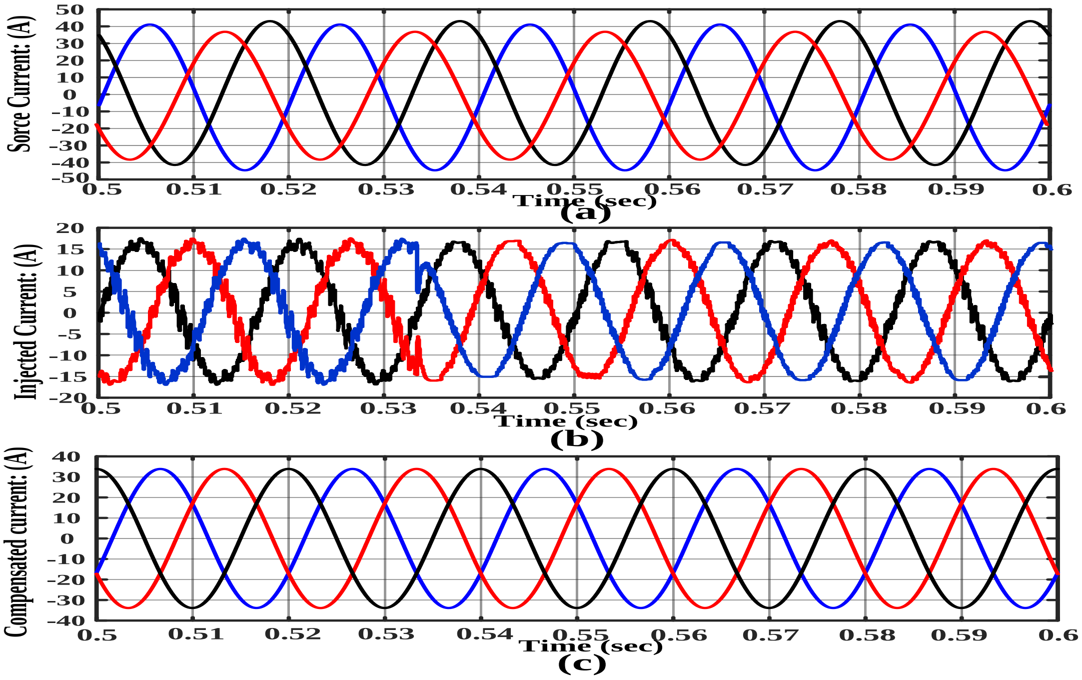


Fig.9. Performance of Unbalanced load using TS-fuzzy control :(a) Source current. (b)injected current. (c)Compensated current

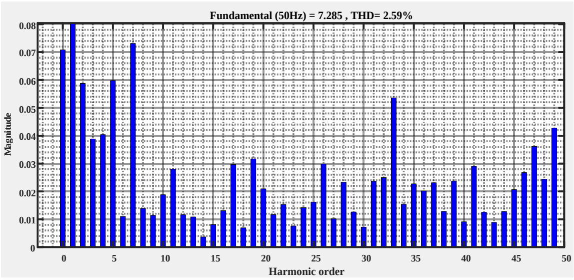


Fig.10. THD using PI controller

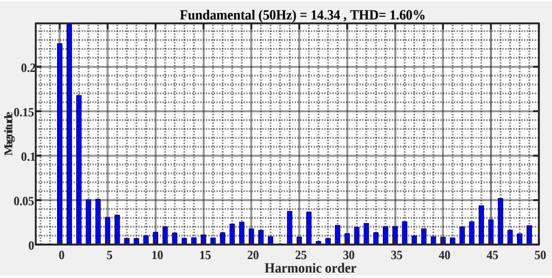


Fig.11. THD using TS-fuzzy controller

E. Case-5: Performance of proposed control strategy in DC bus voltage

The DC bus voltage (Vdc), voltage level that connects the various system components, can fluctuate when there is a power imbalance between the generation and the load in an electrical system. To regain the stability and smooth function of the system, it is crucial to synchronize the DC bus voltage at its nominal value. In a UPQC system, which consists of a series Active Power Filter (APF) and a Shunt APF, a cooperation control methodology is utilized for the purpose of controlling the DC bus voltage. The cooperation between these two components is essential for maintaining the permissible voltage level of DC bus. The DC bus voltage is a significant factor in determining the system's effectiveness. It serves as an indicator of the overall system health and the effectiveness of the control strategies employed. Monitoring the DC bus voltage allows operators to assess the system's ability to handle power mismatches, voltage sags, and voltage swells. From the given information, comparing the effectuality of the proposed controller and the conventional controller in different conditions provides some physical significance.

In a sag condition shown in Fig. 12, where the voltage drops below the nominal level, the TS-fuzzy controller manages to maintain a higher DC bus voltage (630V) compared to the traditional PI controller (600V). This physical significance indicates that the proposed controller effectively compensates for the voltage drop and helps stabilize the system during sag events. In a swell condition, where the voltage rises above the nominal level, the PI controller performs better by maintaining a lower DC-link voltage (790V) compared to the TS-fuzzy controller (700V). This physical significance suggests that the PI controller effectively handles the excessive voltage and prevents it from affecting the system's stability.

Overall, the physical significance of the comparison reveals that the TS-fuzzy controller excels in lessening voltage sags, while the PI controller performs better in mitigating voltage swells. These observations emphasize the importance of selecting the appropriate controller based on the specific operating conditions to regain the stability and performance of the UPQC system. To guarantee the secure functioning and safeguarding of both the DC-bus and power electronics components integrated within a micro-grid, it is essential to adhere to certain voltage limits for the DC bus voltage (Vdc) within limit of ±10% (i.e., ±0.1 p.u.) The IEEE 1547 and EN 50160 standards provide guidelines for these permissible variances in the DC-link voltage [23-24].

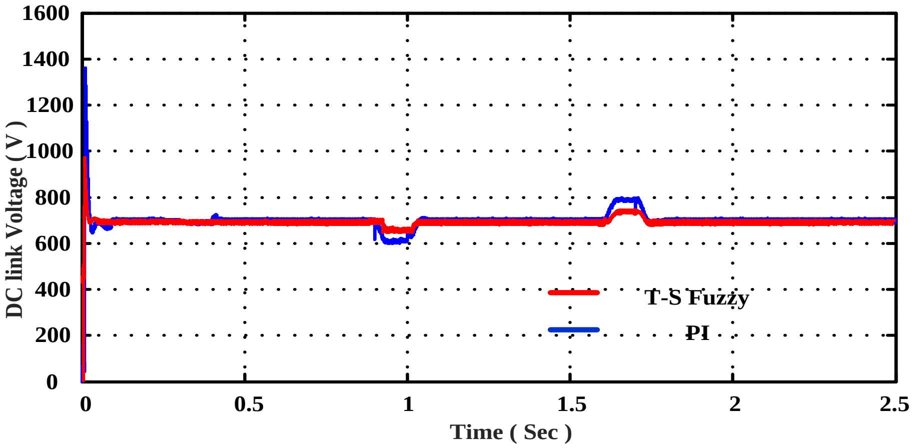


Fig.12. Comparative DC- link voltage: Proposed controller and conventional controller

V. CONCLUSION

In this paper, the performance of the Unified Power Quality Conditioner (UPQC) was investigated under two conditions: nonlinear load and unbalanced load cases. The UPQC consists of two voltage source inverters (VSIs) placed in series and shunt in the system. The traditional control strategy, which utilized a Proportional-Integral (PI) controller, was initially employed to mitigate power quality problem such as voltage sag, swell, and harmonics. However, the limitations of the PI controller were identified, prompting the adoption of a new intelligent control strategy known as the TS-fuzzy controller. Through simulations conducted in MATLAB, the effectiveness of the TS-fuzzy controller was evaluated under various scenarios including voltage sag, swell, harmonics, unbalanced load, and nonlinear load. The results demonstrated that the TS-fuzzy controller outperformed the PI controller in terms of power quality enhancement. Specifically, the TS-fuzzy controller effectively reduced voltage sag, swell, and total harmonic distortion, while also exhibiting less variation in the DC bus voltage based on the findings, it can depict that the proposed TS-fuzzy controller is a superior control algorithm for the UPQC system. It addresses the limitations of the traditional PI controller and offers improved performance in mitigating power quality problem. The utilization of the TS-fuzzy controller in UPQC systems can lead to enhanced power quality, ensuring a stable and reliable power supply for sensitive electronic devices.

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APPENDIX

Parameters of the system

For simulation	
Grid voltage (Line voltage)	400V
Frequency	50Hz
Transmission line capacitance	100µF
Transmission line Resistance	1Ω

Rated KVA	4
Rated V	380V
Frequency	50Hz
Resistance	0.02p.u.
Inductance	0.02p.u.
Filter resistance	0.4Ω
Filter Inductance	15mH
Coupling Inductor	10mH