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Design and Simulation of Fuzzy Controller Based iUPQC to Improve Power Quality

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Abstract: In this paper Fuzzy based Interline Unified Power Quality Conditioner (iUPQC) for power quality enhancement. A Fuzzy Logic Controller (FLC) is based on fuzzy sets and fuzzy rules with their membership functions of inputs and outputs. A control technique of two active filters is to control the sinusoidal reference. In iUPQC; Series Active Filter (SAF) works as a current source and Parallel Active Filter (PAF) works as a voltage source and due to these there is a high and low impedances occurs which is indirectly compensates the harmonics and disturbances of the grid voltage and load current and also impedance path is low harmonic at load current. To deal with sinusoidal reference for well-known frequency spectrum, a technique of pulse width modulation (PWM) is used. By using this controller, beyond the conventional UPQC power quality features, including voltage sag/swell compensation, the iUPQC will also provide reactive power support to regulate not only the load-bus voltage but also the voltage at the grid-side bus. In other words, the iUPQC will work as a static synchronous compensator (STATCOM) at the grid side, while providing also the conventional UPQC compensations at the load or micro grid side. The proposed concept is implemented to Fuzzy logic controller by using Mat lab/Simulink software.

Keywords: iUPQC, Microgrids, Power Quality, Static Synchronous Compensator (STATCOM), Unified Power Quality Conditioner (UPQC).

I. INTRODUCTION

Nonlinear loads always reduces the power quality at electrical grid and contain a high harmonic which effect the critical loads. To overcome such problems we are using UPQC is low distortion of harmonic to regulate voltage from the loads and undistorted the current from the utility grid. In UPQC they are two types of filters SAF and PAF, PAF is a current source and SAF is a voltage source both of them are a non-sinusoidal reference and also compensate the harmonic in grid voltage and load current. It is a complex method to solve such problems we are using active filters to control the harmonics and to eliminate harmonics fuzzy controller [1-3]. Its conditioner consists of two single-phase current source inverters where the SAF is controlled by a current loop and the PAF is controlled by a voltage loop both of them are interconnected to fuzzy controller and grid current and load voltage are sinusoidal, and therefore, their references are also sinusoidal. This concept is called “dual topology of unified power quality conditioner” (iUPQC), and the control schemes use the p−q theory, for a real time of positive sequence. The aim of this paper is to propose Fuzzy based Interline Unified Power Quality Conditioner for power quality enhancement to eliminate the harmonic from source to load [4-6]. In ABC reference the proposed control scheme is developed for the classical control theory is without the need for coordinate transformers and digital control implementation. The references to both SAF and PAF with fuzzy logic controller is a pure sinusoidal, dispensing the harmonic extraction from the grid current and load voltage [7].

Dynamic reactive power compensation that means of the STATCOM has been used widely in transmission networks to regulate the voltage. Nowadays, the STATCOM is largely used for voltage regulation [8], whereas the UPQC and the iUPQC and fuzzy logic control have been selected as solution for more specific applications [9]. Moreover, these last ones are used only in particular cases, where their relatively high costs are justified by the power quality improvement it can provide, which would be unfeasible by using conventional solutions. By joining the extra functionality like a STATCOM in the iUPQC device, a wider scenario of applications can be reached, particularly in case of distributed generation in smart grids and as the coupling device in grid-tied micro grids [10]. In [11], the performance of the iUPQC and the UPQC was compared when working as UPQCs. The main difference between these compensators is the sort of source emulated by the series and shunt power converters. In the UPQC approach, the series converter is controlled as a non sinusoidal voltage source and the shunt one as a non sinusoidal current source. Hence, in real time, the UPQC controller and fuzzy logic controller has to determine and synthesize accurately the harmonic voltage and current to be compensated. On the other hand, in the iUPQC approach, the series converter behaves as a controlled sinusoidal current source and the shunt converter as a controlled sinusoidal voltage source.

It is not necessary to determine the harmonic voltage and current to be compensated, since the harmonic voltages appear naturally across the series currentsource and the harmonic currents flow naturally into the shunt voltage source. In this way, both grid current and load voltage are sinusoidal, and therefore, their references are also sinusoidal. Some authors have applied this concept, using voltage source inverters in uninterruptable power supplies and in UPQC. In [12], this concept is called "dual topology of unified power quality conditioner" (iUPQC), and the control schemes use the p−q theory, requiring determination in real time of the positive sequence components of the voltages and the currents. The aim of this project is to propose a simplified control technique for a dual three-phase topology of a unified power quality conditioner (iUPQC) to be used in the utility grid connection. The proposed control scheme is developed in ABC reference frame and allows the use of classical control theory without the need for coordinate transformers and digital control implementation. The references to both SAF and PAFs are sinusoidal, dispensing the harmonic extraction of the grid current and load voltage [13].

II. EQUIPMENT APPLICABILITY

In order to clarify the applicability of the improved iUPQC controller, depicts an electrical system with two buses in spotlight, i.e., bus A and bus B. Bus A is a critical bus of the power system that supplies sensitive loads and serves as point of coupling of a microgrid. Bus B is a bus of the microgrid, where nonlinear loads are connected, which requires premium-quality power supply. The voltages at buses A and B must be regulated, in order to properly supply the sensitive loads and the nonlinear loads. The effects caused by the harmonic currents drawn by the nonlinear loads should be mitigated, avoiding harmonic voltage propagation to bus A. The use of a STATCOM to guarantee the voltage regulation at bus A is not enough because the harmonic currents drawn by the nonlinear loads are not mitigated. On the other hand, a UPQC or an iUPQC between bus A and bus B can compensate the harmonic currents of the nonlinear loads and compensate the voltage at bus B, in terms of voltage harmonics, unbalance, and sag/swell. Nevertheless, this is still not enough to guarantee the voltage regulation at bus A. Hence, to achieve all the desired goals, a STATCOM at bus A and a UPQC (or an iUPQC) between buses A and B should be employed. However, the costs of this solution would be unreasonably high. An attractive solution would be the use of a modified iUPQC controller to provide also reactive power support to bus A, in addition to all those functionalities of this equipment, as presented. Note that the modified iUPQC serves as an intertie between buses A and B. Moreover, the microgrid connected to the bus B could be a complex system comprising distributed generation, energy management system, and other control systems involving microgrid, as well as smart gridconcepts.

In summary, the modified iUPQC can provide the following functionalities:

- "Smart" circuit breaker as an intertie between the grid and the microgrid;
- Energy and power flow control between the grid and the microgrid (imposed by a tertiary control layer for the microgrid);
- Reactive power support at bus A of the power system;
- voltage/frequency support at bus B of the microgrid;
- Harmonic voltage and current isolation between bus A and bus B (simultaneous grid-voltage and load-current active filtering capability);
- Voltage and current imbalance compensation.

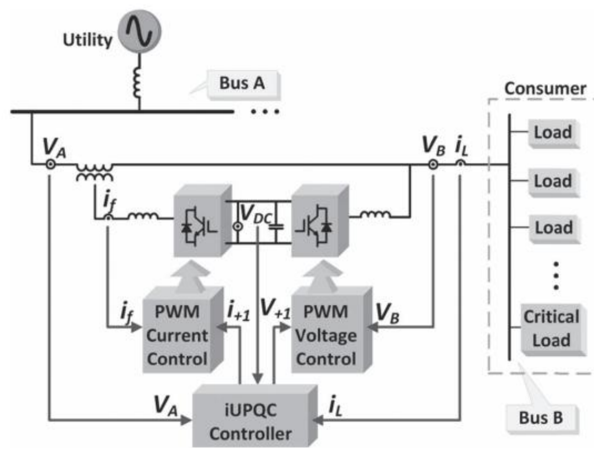

Fig.1. Modified iUPQC Configuration.

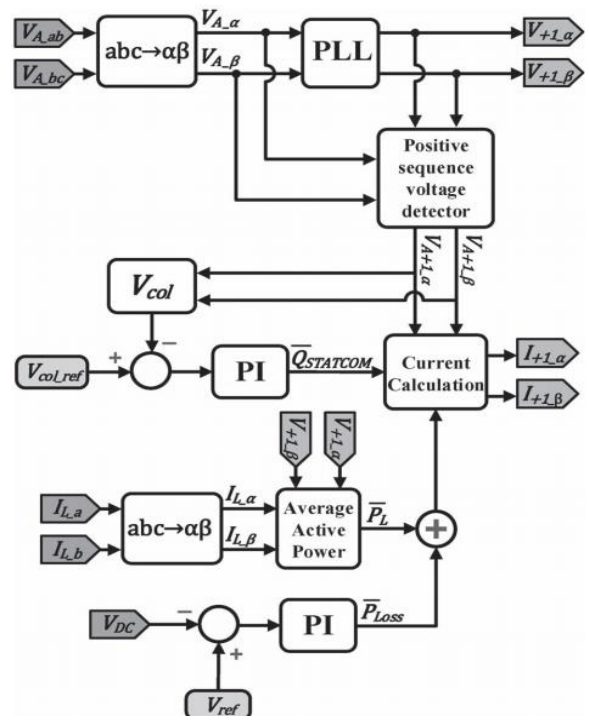

Fig.2. Novel iUPQC controller.

According to the conventional iUPQC controller, the shunt converter imposes a controlled sinusoidal voltage at bus B, which corresponds to the aforementioned functionality (d). As a result, the shunt converter has no further degree of freedomin terms of compensating active- or reactive-power variables to expand its functionality. On the other hand, the series converter of a conventional iUPQC uses only an active-power control variable p, in order to synthesize a fundamental sinusoidal current drawn from bus A, corresponding to the active power demanded by bus B. If the dc link of the iUPQC has no large energy storage system or even no energy source, the control variable p also serves as an additional active-power reference to the series converter to keep the energy inside the dc link of the iUPQC balanced. In this case, the losses in the iUPQC and the active power supplied by the shunt converter must be quickly compensated in the form of an additional active power injected by the series converter into the bus B. The iUPQC can serve as:

- "Smart" circuit breaker and as
- Power flow controller between the grid and the microgrid only if the compensating active- and reactive-power references of the series converter can be set arbitrarily. In this case, it is necessary to provide an energy source (or large energy storage) associated to the dc link of the iUPQC.

The last degree of freedom is represented by a reactive-power control variable $\bar{q}$for the series converter of the iUPQC. In this way, the iUPQC will provide reactive-power compensation like a STATCOM to the bus A of the grid. As it will beconfirmed, this functionality can be added into the controller without degrading all other functionalities of the iUPQC.

III. IMPROVED IUPQC CONTROLLER

A. Main Controller

Fig.1. depicts the iUPQC hardware and the measured units of a three-phase three-wire system that are used in the controller. Fig.2. shows the proposed controller. The controller inputs are the voltages at buses A and B, the current demanded by bus B (i_L), and the voltage v_{DC} of the common dc link. The outputs are the shunt-voltage reference and the series-current reference to the pulse width modulation (PWM) controllers. The voltage and current PWM controllers can be as simple as those employed, or be improved further to better deal with voltage and current imbalance and harmonics. First, the simplified Clark transformation is applied to the measured variables. As example of this transformation, the grid voltage in the αβ-reference frame can be calculated as

$$\begin{bmatrix} V_{A\_\alpha} \\ V_{A\_\beta} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{A\_ab} \\ V_{A\_bc} \end{bmatrix} \quad \textbf{(1)}$$

The shunt converter imposes the voltage at bus B. Thus, it is necessary to synthesize sinusoidal voltages with nominal amplitude and frequency. Consequently, the signals sent to the PWM controller are the phase-locked loop (PLL) outputs with amplitude equal to 1 p.u. In the original iUPQC approach as presented, the shunt-converter voltage reference can be either the PLL outputs or the fundamental positive-sequence component V_{A+1} of the grid voltage (bus A in Fig.1.). The use of V_{A+1} in the controller is useful to minimize the circulating power through the series and shunt converters, under normal operation, while the amplitude of the grid voltage is within an acceptable range of magnitude. However, this is not the case here, in the modified iUPQC controller, since now the grid voltage will be also regulated by the modified iUPQC. In other words, both buses will be regulated independently to track their reference values. The series converter synthesizes the current drawn from the grid bus (bus A). In the original approach of iUPQC, this current is calculated through the average active power required by the loads $\bar{P}_L$plus the power$\bar{P}_{Loss}$. The load active power can be estimated by

$$P_L = V_{+1\_\alpha} \cdot i_{L\_\alpha} + V_{+1\_\beta} \cdot i_{L\_\beta} \quad \textbf{2)}$$

Where i_{L_α}, i_{L_β} are the load currents, and V_{+1_α}, $V_{+1_\beta}$are the voltage references for the shunt converter. A low-pass filter is used to obtain the average active power ($\bar{P}_L$).

The losses in the power converters and the circulating power to provide energy balance inside the iUPQC are calculated indirectly from the measurement of the dc-link voltage. In other words, the power signal $\bar{P}_{Loss}$ is determined by a proportional– integral (PI) controller (PI block in Fig. 2), by comparing the measured dc voltage VDC with its reference value. The additional control loop to provide voltage regulation like a STATCOM at the grid bus is represented by the control signal $\bar{Q}_{STATCOM}$ in Fig.2. This control signal is obtained through a PI controller, in which the input variable is the error between the reference value and the actual aggregate voltage of the grid bus, given by

$$V_{col} = \sqrt{V_{A+1\_\alpha}^2 + V_{A+1\_\beta}^2}. \quad \textbf{(3)}$$

The sum of the power signals $\bar{P}_L$ and $\bar{P}_{Loss}$ composes the active-power control variable for the series converter of the iUPQC ($\bar{p}$) described in Section II. Likewise, $\bar{Q}_{STATCOM}$ is the reactive-power control variable q. Thus, the current references i+1α and i+1β of the series converter are determined by

$$\begin{bmatrix} i_{+1\_\alpha} \\ i_{+1\_\beta} \end{bmatrix} = \frac{1}{V_{A+1\_\alpha}^2 + V_{A+1\_\beta}^2} \begin{bmatrix} V_{A+1\_\alpha} & V_{A+1\_\beta} \\ V_{A+1\_\beta} & -V_{A+1\_\alpha} \end{bmatrix} \times \begin{bmatrix} \bar{P}_L + \bar{P}_{Loss} \\ \bar{Q}_{STATCOM} \end{bmatrix}$$

B. Power Flow in Steady State

The following procedure, based on the average power flow, is useful for estimating the power ratings of the iUPQC converters. For combined series–shunt power conditioners, such as the UPQC and the iUPQC, only the voltage sag/swell disturbance and the power factor (PF) compensation of the load produce a circulating average power through the power conditioners. According to Fig.3, the compensation of a voltage sag/swell disturbance at bus B causes a positive sequence voltage at the coupling transformer ($V_{series} \neq 0$), since VA ≠VB. Moreover, V_{series} and i_{PB}in the coupling transformer leads to a circulating active power $\bar{P}_{inner}$ in theiUPQC.

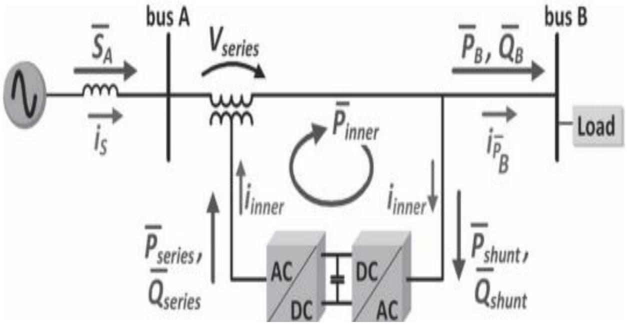

Fig.3. iUPQC power flow in steady-state.

Additionally, the compensation of the load PF increases the current supplied by the shunt converter. The following analysis is valid for an iUPQC acting like a conventional UPQC or including the extra compensation like a STATCOM. First, the circulating power will be calculated when the iUPQC is operating just like a conventional UPQC. Afterward, the equations will include the STATCOM functionality to the grid bus A. In both cases, it will be assumed that the iUPQC controller is able to force the shunt converter of the iUPQC to generate fundamental voltage always in phase with the grid voltage at bus A. For simplicity, the losses in the iUPQC will be neglected. For the first case, the following average powers in steady state can be determined:

$$\overline{S}_A = \overline{P}_B \tag{5}$$

$$\overline{Q}_{\text{shunt}} = -\overline{Q}_B \tag{6}$$

$$\overline{Q}_{\text{series}} = \overline{Q}_A = 0 \text{ var} \tag{7}$$

$$\overline{P}_{\text{series}} = \overline{P}_{\text{shunt}} \tag{8}$$

Where $\overline{S}_A$ and $\overline{Q}_A$ are the apparent and reactive power injected in the bus A; $\overline{P}_B$ and $\overline{Q}_B$ are the active and reactive power injected in the bus B; $\overline{P}_{Shunt}$ and $\overline{Q}_{Shunt}$ are the active and reactive power drained by the shunt converter; $\overline{P}_{Series}$ and $\overline{Q}_{Series}$ are the active and reactive power supplied by the series converter, respectively.

Equations (5) and (8) are derived from the constraint of keeping unitary the PF at bus A. In this case, the current passing through the series converter is responsible only for supplying the load active power, that is, it is in phase (or counter phase) with the voltages V_A and V_B. Thus, (7) can be stated. If a voltage sag or swell occurs, $\overline{P}_{Series}$ and $\overline{P}_{Shunt}$ will not be zero, and thus, an inner-loop current (i_{inner}) will appear. The series and shunt converters and the aforementioned circulating active power ($\overline{P}_{inner}$) flow inside the equipment. It is convenient to define the following sag/swell factor. Considering VN as the nominal voltage

$$k_{\text{sag/swell}} = \frac{|\dot{V}_A|}{|\dot{V}_N|} = \frac{V_A}{V_N} \tag{9}$$

From (5) and considering that the voltage at bus B is kept regulated, i.e., VB = VN, it follows that

$$\sqrt{3} \cdot k_{\text{sag/swell}} \cdot V_N \cdot i_S = \sqrt{3} \cdot V_N \cdot i_{P_B}$$

$$i_S = \frac{i_{P_B}}{k_{\text{sag/swell}}} = i_{\overline{P}_B} + i_{\text{inner}} \tag{10}$$

$$i_{\text{inner}} = \left| i_{P_B} \left(\frac{1}{K_{\text{sag/swell}} - 1} \right) \right| \tag{11}$$

The circulating power is given by

$$\overline{P}_{\text{inner}} = \overline{P}_{\text{series}} = \overline{P}_{\text{shunt}} = 3(V_B - V_A)(i_{P_B} + i_{\text{inner}}) \tag{12}$$

From (11) and (12), it follows that

$$\overline{P}_{\text{inner}} = 3(V_N - V_A)\left(\frac{\overline{P}_B}{3V_N}\frac{1}{k_{\text{sag/swell}}}\right) \tag{13}$$

$$\overline{P}_{\text{inner}} = \overline{P}_{\text{series}} = \overline{P}_{\text{shunt}} = \frac{1 - K_{\text{sag/swell}}}{k_{\text{sag/swell}}}\overline{P}_B \tag{14}$$

Thus, (14) demonstrates that $\overline{P}_{inner}$ depends on the active power of the load and the sag/swell voltage disturbance. In order to verify the effect on the power rate of the series and shunt converters, a full load system $\overline{S}_B = \sqrt{\overline{P}_B^2 + \overline{Q}_B^2} = 1$ p.u. withPF ranging from 0 to 1 was considered. It was also considered the sag/swell voltage disturbance at bus A ranging $k_{sag/swell}$ from 0.5 to 1.5. In this way, the power rating of the series and shunt converters are obtained through (6)–(8) and (14). The apparent power of the series and shunt power converters. In these figures, the $k_{sag/swell}$-axis and the PF-axis are used to evaluate the power flow in the series and shunt power converters according to the sag/swell voltage disturbance and the load power consumption, respectively. The power flow in the series converter indicates that a high power is required in case of sag voltage disturbance with high active power load consumption. In this situation, an increased $\overline{P}_{inner}$ arises and high rated power converters are necessary to ensure the disturbance compensation. Moreover, in case of compensating sag/swell voltage disturbance with high reactive power load consumption, only the shunt converter has high power demand, since $\overline{P}_{inner}$ decreases. It is important to highlight that, for each PF value, the amplitude of the apparent power is the same for capacitive or inductive loads. In other words, the same for $\overline{Q}_B$ capacitive or inductive.

If the iUPQC performs all original UPQC functionalities together with the STATCOM functionality, the voltage at bus A is also regulated with the same phase and magnitude, that is, $\dot{V}_A = \dot{V}_B = \dot{V}_N$, and then, the positive sequence of the voltage at the coupling transformer is zero ($\overline{V}_{series}$ =0). Thus, in steady state, the power flow is determined by

$$\overline{S}_A = \overline{P}_B + \overline{Q}_{\text{STATCOM}} \tag{15}$$

$$\overline{Q}_{\text{STATCOM}} + \overline{Q}_{\text{series}} = \overline{Q}_{\text{shunt}} + \overline{Q}_B \tag{16}$$

$$\overline{Q}_{\text{series}} = 0 \text{ var} \quad \textbf{(17)}$$

$$\overline{P}_{\text{series}} = \overline{P}_{\text{inner}} = 0 \text{ W} \quad \textbf{(18)}$$

Where $\overline{Q}_{STATCOM}$ is the reactive power that provides voltage regulation at bus A. Ideally, the STATCOM functionality mitigates the inner-loop active power flow ($\overline{P}_{inner}$), and the power flow in the series converter is zero. Consequently, if theseries converter is properly designed along with the coupling transformer to synthesize the controlled currents $I_{+1_\alpha}$and I_{+1_β}, as shown in Fig.3, then a lower power converter can be employed. Contrarily, the shunt converter still has to providethe full reactive power of the load and also to drain the reactive power injected by the series converter to regulate the voltage at bus A.

IV. FUZZY LOGIC CONTROL

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of compensator. The basic scheme of a fuzzy logic controller is shown in Fig 4 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

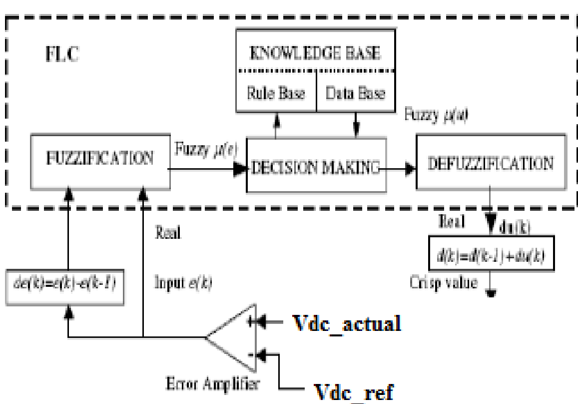

Fig.4.Block diagram of the Fuzzy Logic Controller (FLC) for proposed converter.

Rule Base: the elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse in-put/output variables; in the steady state, small errors need fine control, which requires fine input/output variables as shown in Fig.5. Based on this the elements of the rule table are obtained as shown in Table 1, with 'Vdc' and 'Vdc-ref' as inputs.

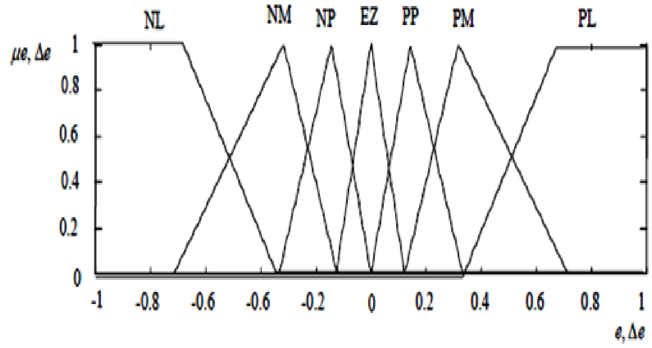

Fig.5. Membership functions for Input, Change in input, Output.

TABLE I: Rule Base

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

V. MATLAB/SIMULATION RESULTS

Simulation results of this paper is as shown in bellow Figs.6 to 11.

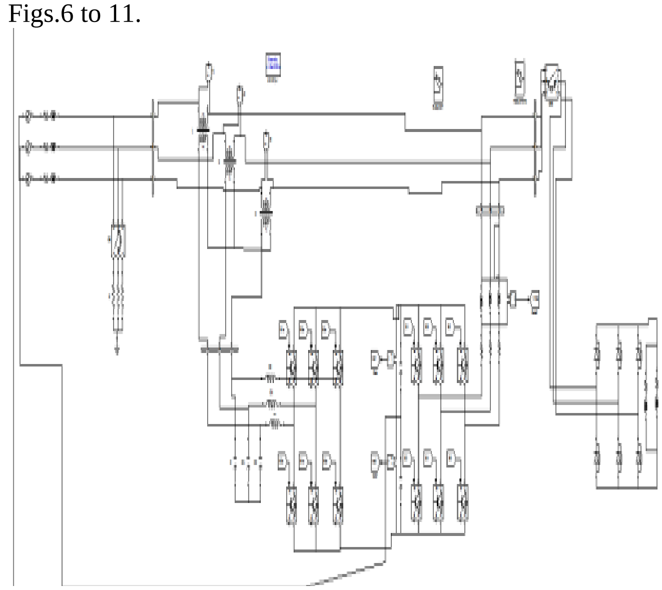

Fig.6. Matlab/simulation circuit for conventional method of iUPQC.

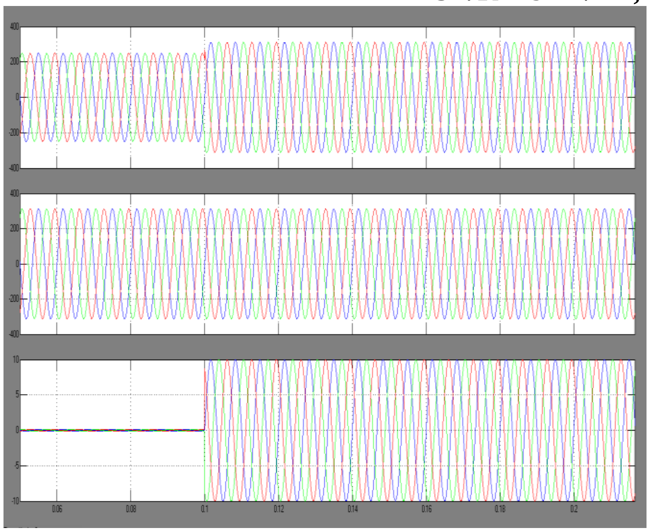

Fig. 7. iUPQC response at no load condition: (a) grid voltages VA, (b) load voltages VB, and (c) grid currents.

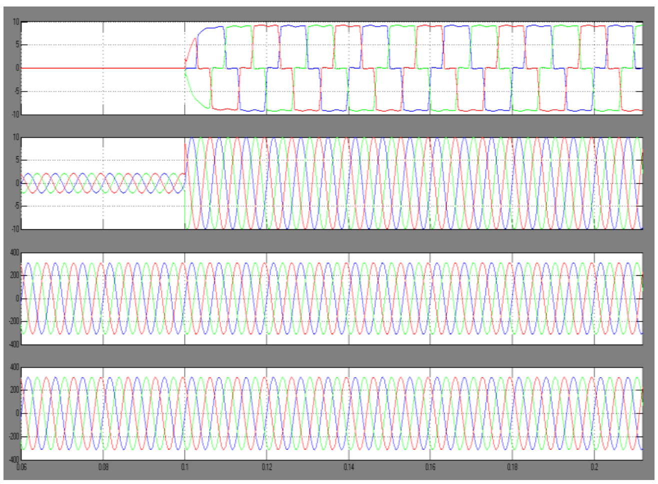

Fig. 8. iUPQC transitory response during the connection of a threephase diode rectifier: (a) load currents, (b) grid currents, (c) load voltages and (d) grid voltages.

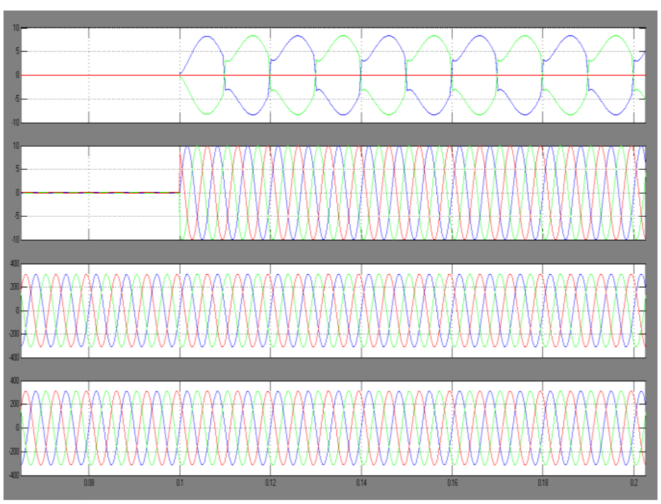

Fig. 9. iUPQC transitory response during the connection of a two phase diode rectifier: (a) load currents, (b) source currents, (c) load voltages, and (c) source voltages.

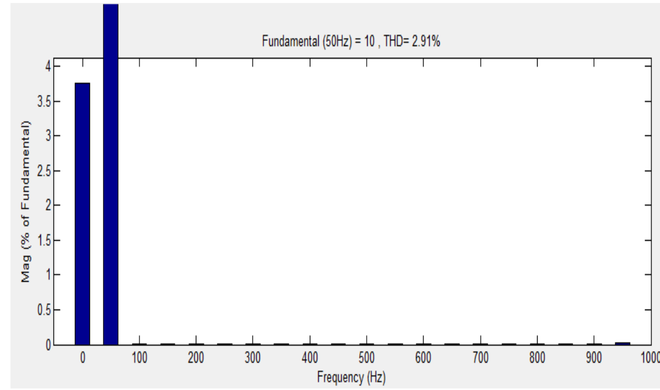

Fig.10.THD for PI Controller.

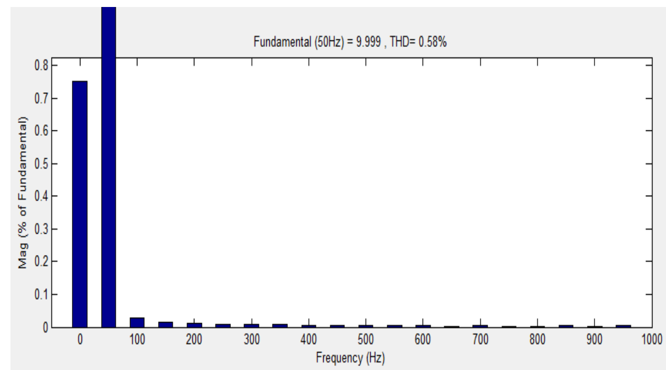

Fig.11.THD for Fuzzy logic Controller.

VI. CONCLUSION

In this manner, in addition to all the power-quality compensation features of a conventional UPQC or an iUPQC, this improved controller also mimics a STATCOM to the grid bus with the usage of fuzzy logic controller. This new feature enhances the applicability of the iUPQC and provides new solutions in future scenarios involving smart grids and micro-grids, including distributed generation and energy storage systems to better deal with the inherent variability of renewable resources such as solar and wind power. A proposed scheme of iUPQC using fuzzy controller in ABC reference frame of both the active filters and their control loops are generated by a digital signal processor (DSP) and to related to other proposed controls its utilization is better for a sinusoidal reference and to eliminate the harmonic from source to load.

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