

A HYBRID FUZZY-PI BASED IMPROVED IUPQC CONTROLLER TO SUPPLY EXTRA GRID-VOLTAGE REGULATION AS A STATCOM

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Abstract-This paper presents an improved controller for the dual topology of the unified power quality conditioner (iUPQC) with the usage of fuzzy logic controller extending its applicability in power-quality compensation, as well as in micro-grid applications. Here we are using fuzzy logic controller instead of using other controllers. 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. 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. Simulation results are provided by using the MATLAB/SIMULINK software to verify the new functionality of the equipment.

Index terms –iUPQC, micro-grids, power quality, static synchronous compensator (STATCOM), unified power quality conditioner (UPQC), Fuzzy logic.

I.INTRODUCTION

The power circuit of a UPQC consists of a combination of a shunt active filter and a series active filter connected in a back-to-back configuration. This combination allows the simultaneous compensation of the load current and the supply voltage, so that the compensated current drawn from the grid and the compensated supply voltage delivered to the load are kept balanced and sinusoidal. The dual topology of the UPQC, i.e., the iUPQC, where the shunt active filter behaves as an ac-voltage source and the series one as an ac-current source, both at the fundamental frequency. This is a key point to better design the control gains, as well as to optimize the LCL filter of the power converters, which allows improving significantly the overall performance of the compensator.

Certainly, power-electronics devices have brought about great technological improvements. However, the increasing number of power-electronics-driven loads used generally in the industry has brought about uncommon power quality problems. In contrast, power-electronics-driven loads generally require ideal sinusoidal supply voltage in order to function properly, whereas they are the most responsible ones for abnormal harmonic currents level in the distribution system. In this scenario, devices that can mitigate these drawbacks have been developed over the years. In, 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 has to determine and synthesize accurately the harmonic voltage and current to be compensated. Some of the solution sin values a flexible compensator, known as the unified power quality conditioner (UPQC) and the static synchronous compensator (STATCOM).

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. This means that it is not necessary to determine the harmonic voltage and current to be compensated, since the harmonic voltages appear naturally across the series current source and the harmonic currents flow naturally into the shunt voltage source. In actual power converters, as the switching frequency increases, the power rate capability is reduced. Therefore, the iUPQC offers better solutions if compared with the UPQC in case of high-power applications, since the iUPQC compensating references are pure sinusoidal waveforms at the fundamental frequency. Moreover, the UPQC has higher switching losses due to its higher switching frequency.

The STATCOM has been used widely in transmission networks to regulate the voltage by means of dynamic reactive power compensation. Nowadays, the STATCOM is largely used for voltage regulation, whereas the UPQC and the iUPQC have been selected as solution for more specific applications. 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.

This paper proposes an improved controller, which expands the iUPQC functionalities. This improved version of iUPQC controller includes all functionalities of those previous ones, including the voltage regulation at the load-side bus, and now providing also voltage

regulation at the grid-side bus, like aSTATCOM to the grid. Experimental results are provided to validate the new controller design.

This paper is organized in five sections. After this introduction, in Section II, the iUPQC applicability is explained, as well as the novel feature of the proposed controller. Section III presents the proposed controller and an analysis of the power flow in steady state. Finally, Sections IV and V provide the experimental results and the conclusions, respectively.

II. APPLICABILITY OF EQUIPMENT

In order to clarify the applicability of the improved iUPQC controller, Fig. 1 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 micro-grid. Bus B is a bus of the micro-grid, 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.

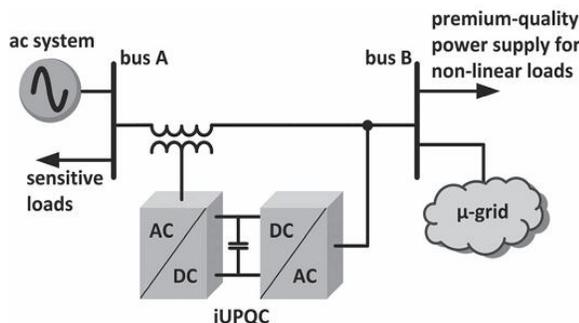


Fig.1. Example of applicability of iUPQC

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, aUPQC 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. Note that the modified iUPQC serves as an intertie between buses A and B. Moreover, the micro-grid connected to the bus B could be a complex system comprising distributed generation, energy management system, and other control systems involving micro-grid, as well as smart grid concepts [22]. In summary, the modified iUPQC can provide the following functionalities:

- “Smart” circuit breaker as an intertie between the grid and the micro-grid;
- Energy and power flow control between the grid and the micro-grid (imposed by a tertiary control layer for the micro-grid);
- Reactive power support at bus A of the power system;
- Voltage/frequency support at bus B of the micro-grid;
- 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.

The functionalities (d)–(f) previously listed were extensively explained and verified through simulations and experimental analysis, whereas the functionality (c) comprises the original contribution of the present work. Fig. 2 depicts, in detail, the connections and measurements of the iUPQC between bus A and bus B.

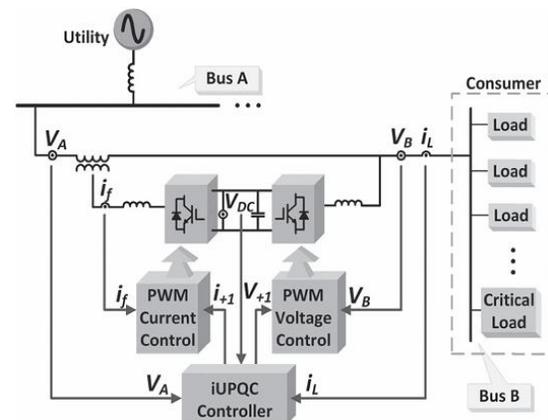


Fig.2. Modified iUPQC configuration.

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 freedom in 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.

III. IMPROVED IUPQC CONTROLLER

A. Main Controller

Fig. 2 depicts the iUPQC hardware and the measured units of a three-phase three-wire system that are used in the controller. Fig. 3 shows the proposed controller.

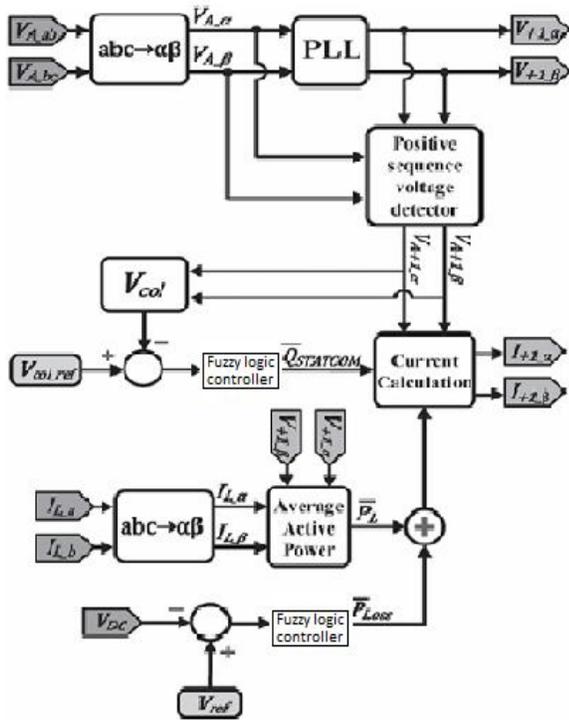


Fig.3. Novel iUPQC controller

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 $\alpha\beta$ -reference frame can be calculated as

$$\begin{bmatrix} V_{A,\alpha} \\ V_{A,\beta} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{A,ab} \\ V_{A,bc} \end{bmatrix} \quad (1)$$

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. There are many possible PLL algorithms, which could be used in this case. In the original iUPQC approach as presented, the shunt-converter voltage reference can be the PLL outputs or the fundamental positive-sequence component V_{A+1} of the grid voltage (bus A in Fig. 2). 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 PL plus the power Loss. The load active power can be estimated by

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

Where $i_{L,\alpha}$, $i_{L,\beta}$ are the load currents, and $V_{+1,\alpha}$, $V_{+1,\beta}$ are the voltage references for the shunt converter. A low-pass filter is used to obtain the average active power (PL).

The additional control loop to provide voltage regulation like a STATCOM at the grid bus is represented by the control signal Q STATCOM in Fig. 3. This control signal is obtained through a Fuzzy logic controller, in which the input variable is the error between the reference value and the actual aggregate voltage of the grid bus, given by

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

The sum of the power signals PL and PLloss composes the active-power control variable for the series converter of the iUPQC(p) described in Section II. Likewise, Q STATCOM is the active-power control variable q . Thus, the current references $i_{+1,\alpha}$ and $i_{+1,\beta}$ of the series converter are determined by

$$\begin{bmatrix} i_{+1,\alpha} \\ i_{+1,\beta} \end{bmatrix} = \frac{1}{V_{A+1,\alpha}^2 + V_{A+1,\beta}^2} \begin{bmatrix} V_{A+1,\alpha} & V_{A+1,\beta} \\ V_{A+1,\beta} & -V_{A+1,\alpha} \end{bmatrix} \times \begin{bmatrix} \bar{P}_L + \bar{P}_{Loss} \\ \bar{Q}_{STATCOM} \end{bmatrix} \quad (4)$$

B. Power Flow in Steady State

The following procedure, based on the average power flow, is useful for estimating the power ratings of the iUPQCconverters. 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.

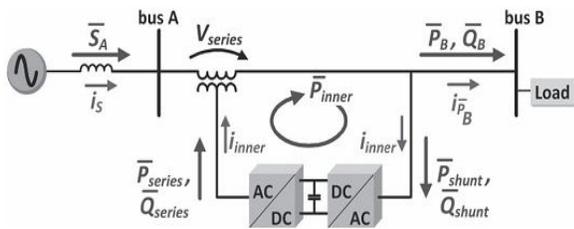


Fig.4. iUPQC power flow in steady-state

According to Fig. 4, 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 $V_A \neq V_B$. Moreover, V_{series} and i_{PB} in the coupling transformer leads to a circulating active power \bar{P}_{inner} in the iUPQC. 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

$$\bar{S}_A = \bar{P}_B \quad (5)$$

$$\bar{Q}_{shunt} = -\bar{Q}_B \quad (6)$$

$$\bar{Q}_{series} = \bar{Q}_A = 0 \text{ var} \quad (7)$$

$$\bar{P}_{series} = \bar{P}_{shunt} \quad (8)$$

Where S_A and Q_A are the apparent and reactive power injected in the bus A; P_B and Q_B are the active and reactive power injected in the bus B; P shunt and Q shunt are the active and reactive power drained by the shunt converter; P series and Q series are the active and reactive power supplied by the series converter, respectively.

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

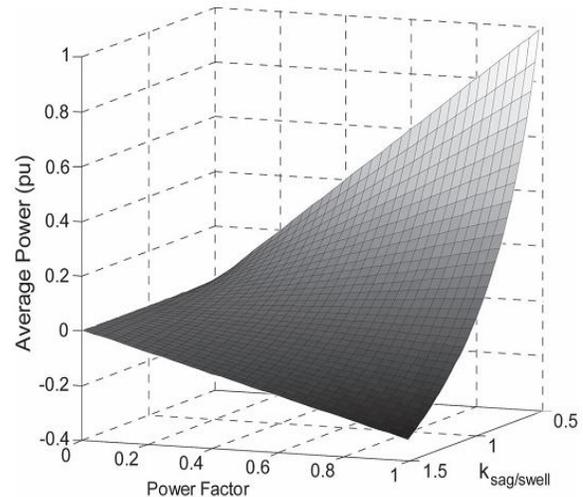
$$i_s = \frac{i_{PB}}{k_{sag/swell}} = i_{PB} + i_{inner} \quad (10)$$

$$i_{inner} = \left| i_{PB} \left(\frac{1}{k_{sag/swell} - 1} \right) \right| \quad (11)$$

The circulating power is given by

$$\begin{aligned} \bar{P}_{inner} &= \bar{P}_{series} = \bar{P}_{shunt} \\ &= 3(V_B - V_A)(i_{PB} + i_{inner}) \end{aligned} \quad (12)$$

Fig. 5 depicts the apparent power of the series and shunt power converters. In these figures, the 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 P inner arises and high rated power converters are necessary to ensure the disturbance compensation. It is important to highlight that, for each value, the amplitude of the apparent power is the same for capacitive or inductive loads.



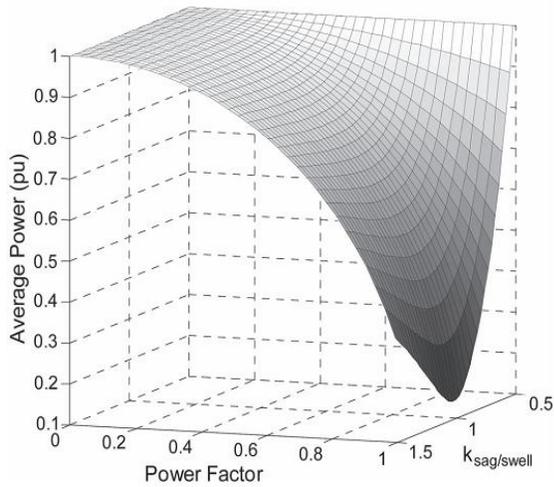


Fig. 5. Apparent power of the series and shunt converters, respectively

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, $V_A = V_B = V_N$, and then, the positive sequence of the voltage at the coupling transformer is zero ($V_{Series}=0$). Thus, instead of the y state, the power flow is determined by

$$\bar{S}_A = \bar{P}_B + \bar{Q}_{STATCOM} \quad (15)$$

$$\bar{Q}_{STATCOM} + \bar{Q}_{series} = \bar{Q}_{shunt} + \bar{Q}_B \quad (16)$$

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

$$\bar{P}_{series} = \bar{P}_{inner} = 0 \text{ w} \quad (18)$$

Where $Q_{STATCOM}$ is the reactive power that provides voltage regulation at bus A. Ideally, the STATCOM functionality mitigates the inner-loop active power flow (P_{inner}), and the power flow in the series converter is zero.

IV. FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, interference engine and defuzzification.

The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

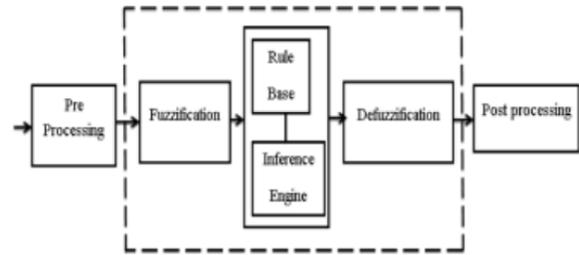


Fig.6 Fuzzy logic controller

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the shape of membership function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor

Table I Fuzzy Rules

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular $E(k)$ input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \quad (14)$$

$$CE(k) = E(k) - E(k-1) \quad (15)$$

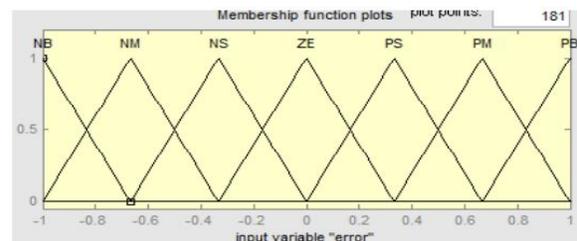


Fig.7 Membership functions

Inference Method: Several composition methods such as Max-Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum

operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height“ method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output.

The set of FC rules are derived from

$$u = -[\alpha E + (1-\alpha) * C]$$

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible.

Fuzzy PI hybrid control logic

PI controller

- Design a proportional controller to meet the transient response specifications, i.e. place the dominant closed-loop system poles at a desired location
- Add a PI controller with a zero
- Tune the gain of the system to move the closed-loop pole closer
- Check the time response and modify the design until it is acceptable.

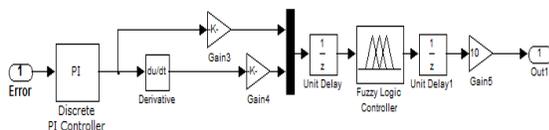


Fig 8. Fuzzy PI hybrid control

V. SIMULATION RESULTS

The improved iUPQC controller, as shown in Fig. 3, was verified in a 5-kVA prototype, whose parameters are presented in Table I. The controller was embedded in a fixed-point digital signal processor (TMS320F2812). In order to verify all the power quality issues described in this

paper, the iUPQC was connected to a grid with a voltage sag system, as depicted in Fig. 9.

TABLE I: IUPQC PROTOTYPE PARAMETERS

Parameter	Value
Voltage	220 V rms
Grid frequency	60 Hz
Power rate	5 kVA
DC-link voltage	450 V dc
DC-link capacitors	$C = 9400 \mu\text{F}$
Shunt converter passive filter	$L = 750 \mu\text{H}$ $R = 3.7 \Omega$ $C = 20.0 \mu\text{F}$
Series converter passive filter	$L = 1.0 \text{ mH}$ $R = 7.5 \Omega$ $C = 20.0 \mu\text{F}$
Sampling frequency	19440 Hz
Switching frequency	9720 Hz
PI controller (\bar{P}_{loss})	$K_p = 4.0$ $K_i = 250.0$
PI controller ($\bar{Q}_{STATCOM}$)	$K_p = 0.5$ $K_i = 50.0$

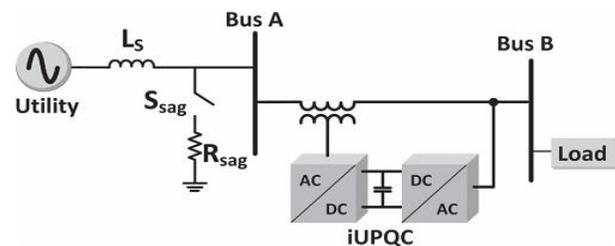


Fig. 9. iUPQC experimental scheme.

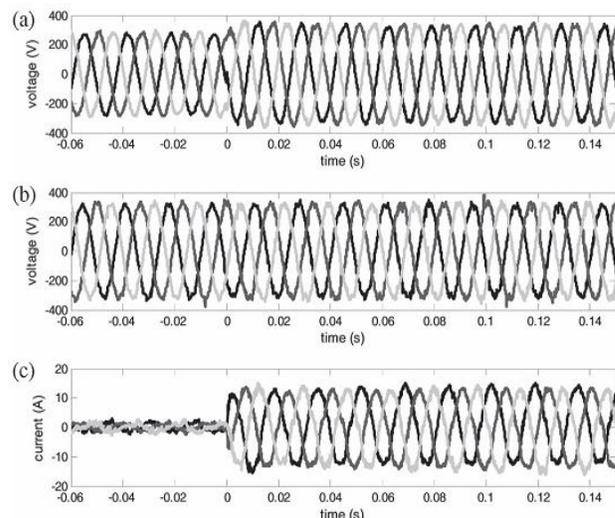


Fig. 10. iUPQC response at no load condition: (a) grid voltages VA, (b) load voltages VB, and (c) grid currents.

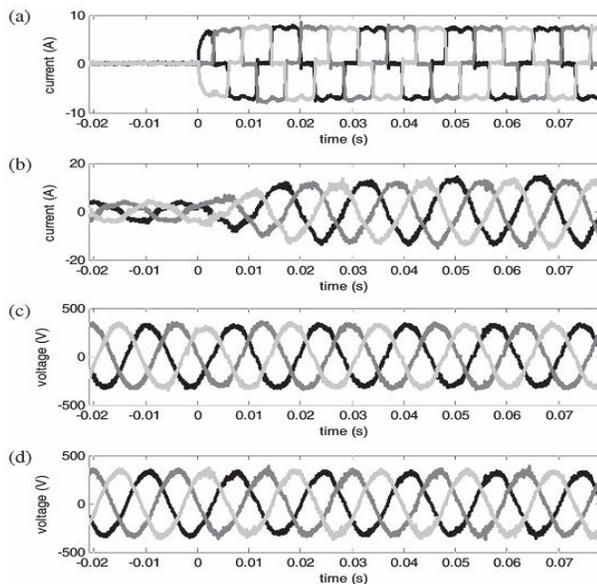


Fig. 11. iUPQC transitory response during the connection of a three phase diode rectifier: (a) load currents, (b) grid currents, (c) load voltages and (d) grid voltages.

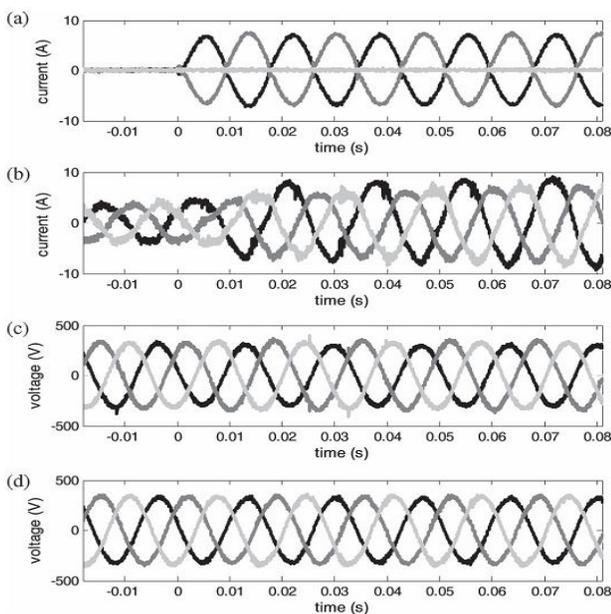


Fig. 12. iUPQC transitory response during the connection of a two-phase diode rectifier: (a) load currents, (b) source currents, (c) load voltages, and (d) source voltages.

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.

Here we are using fuzzy logic controller instead of using other controllers. In the improved iUPQC controller, the currents synthesized by the series converter are determined by the average active power of the load and the active power to provide the dc-link voltage regulation, together with an average reactive power to regulate the grid-bus voltage. The simulation results verified the improved iUPQC goals. The grid-voltage regulation was achieved with no load, as well as when supplying a three-phase nonlinear load. These results have demonstrated a suitable performance of voltage regulation at both sides of the iUPQC, even while compensating harmonic current and voltage imbalances.

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