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GRID VOLTAGE REGULATION AS A STATCOM WITH AN IUPQC BY USING FUZZY

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ABSTRACT-This paper presents an improved controller for the dual topology of the unified power quality conditioner (iUPQC) extending its applicability in power-quality compensation, as well as in microgrid applications. 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 microgrid side. 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 by using this controller. Simulation results are provided to verify the new functionality of the equipment.

Index Terms—iUPQC, microgrids, power quality, static synchronous compensator (STATCOM), unified power quality conditioner (UPQC).

INTRODUCTION

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. 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. Some of the solutions involve a flexible compensator, known as the unified power quality conditioner (UPQC) [1]–[7] and the static synchronous compensator (STATCOM) [8]–[13].

Power circuit of a UPQC consistsof the 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 fuzzy logic and dual topology of the UPQC, i.e., the iUPQC, was presented in [14]–[19], 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 [20].

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 [9], whereas the UPQC and the iUPQC and fuzzy logic control have been selected as solution for more specific applications [21]. 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 microgrids.

In [16], 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 current source and the harmonic currents flow naturally into the shunt voltage source.

As the switching frequency increases, the power rate capability is reduced in actual power converters. 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. An 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 a STATCOM to the grid. Simulation results are provided to validate the new controller design.

EQUIPMENT APPLICABILITY

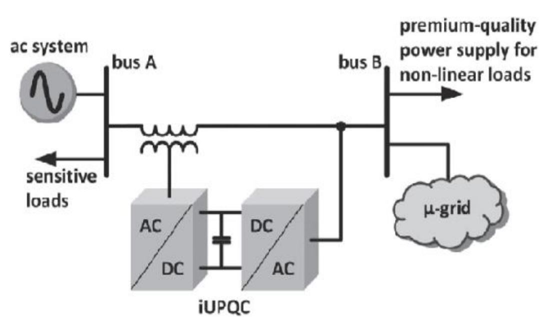

Fig. 1. Example of applicability of iUPQC.

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 microgrid, in order to clarify the applicability of the improved iUPQC controller. Bus B is a bus of the micro grid, nonlinear loads are connected to the bus B, 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 voltage regulation at bus A is not enough because the harmonic currents drawn by the nonlinear loads are not mitigated by use of a STATCOM. 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.

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, involving microgrid, as well as smart grid concepts. 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. In summary, the modified iUPQC can provide the following functionalities:

a) "smart" circuit breaker as an intertie between the grid and the microgrid;

b) Energy and power flow control between the grid and the microgrid (imposed by a tertiary control layer for the microgrid);

c) Reactive power support at bus A of the power system;

d) Voltage/frequency support at bus B of the microgrid;

e) Harmonic voltage and current isolation between bus A and bus B (simultaneous grid-voltage and load-current active filtering capability);

f) Voltage and current imbalance compensation.

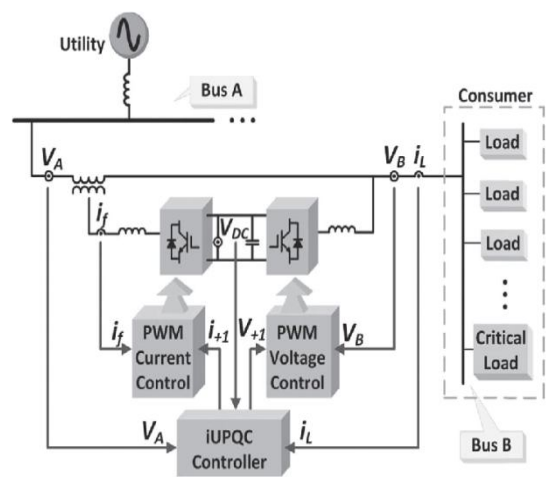

Fig. 2. Modified iUPQC configuration.

Fig. 2 depicts, in detail, the connections and measurements of the iUPQC between bus A and bus B.The functionalities (d)–(f) previously listed were extensively explained and verified through simulations analysis [14]–[18], whereas the functionality (c) comprises the original contribution of the present work.

Using fuzzy 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.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. According to the conventional iUPQC controller, the shunt converter imposes a controlled sinusoidal voltage at bus B, which corresponds to the aforementioned functionality (d).

Necessary to provide an energy source (or large energy storage) associated to the dc link of the iUPQC is follow the case .The iUPQC can serve as: a) “smart” circuit breaker and as b) 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 the last degree of freedom is represented by a reactive-power control variable 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 be confirmed, this functionality can be added into the fuzzy controller without degrading all other functionalities of the iUPQC.

III. IMPROVED IUPQC CONTROLLER

A. Main Controller

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

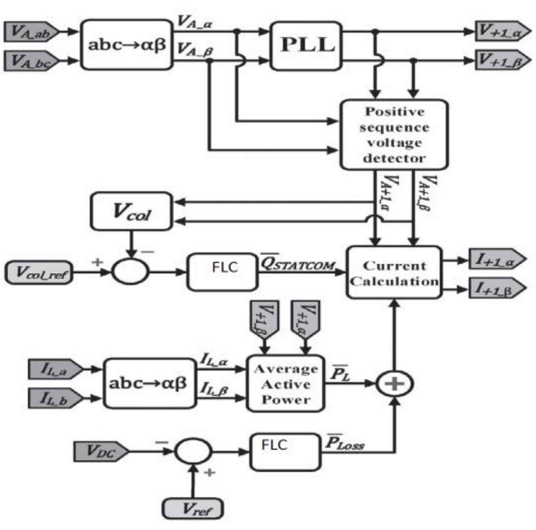

Fig. 3. Novel iUPQC controller.

The controller inputs are the voltages at buses A and B, the current demanded by bus B (iL), and the voltage Vdc 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 [11].

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

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

Consequently, the signals sent to the PWM controller are the phase-locked loop (PLL) outputs with amplitude equal to 1 p.u. The shunt converter imposes the voltage at bus B. Thus, it is necessary to synthesize sinusoidal voltages with nominal amplitude and frequency. There are many possible PLL algorithms, which could be used in this case, as verified in [29]–[33].In the original approach of iUPQC, this current is calculated through the average active power required by the loads PL plus the power PLoss. The series converter synthesizes the current drawn from the grid bus (bus A). 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 iL_α, iL_β are the load currents, and V+1_α, V+1_β are the voltage references for the shunt converter. A low-pass filter is used to obtain the average active power (PL).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 PLoss is determined by a fuzzy logic controller (fuzzy block in Fig. 3), by comparing the measured dc voltage VDC with its reference value.TheFig. 3 shows additional control loop to provide voltage regulation like a STATCOM at the grid bus is represented by the control signal QSTATCOM. 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 PLoss composes the active-power control variable for the series converter of the iUPQC (p) described. Likewise, QSTATCOM is the reactive-power control variable q. Thus, the current references i+1α and i+1β of the series converter are determined by

$$\begin{bmatrix} i_{+1\_\alpha} & i_{+1\_\beta} \end{bmatrix} = \frac{1}{v_{+1\_\alpha}^2 + v_{+1\_\beta}^2}\begin{bmatrix} v_{+1\_\alpha} & v_{+1\_\beta} \\ v_{+1\_\beta} & -v_{+1\_\alpha} \end{bmatrix} \times \begin{bmatrix} \bar{p}_L + \bar{p}_{Loss} \\ \bar{q}_{STATCOM} \end{bmatrix}. \quad (4)$$

A. 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.

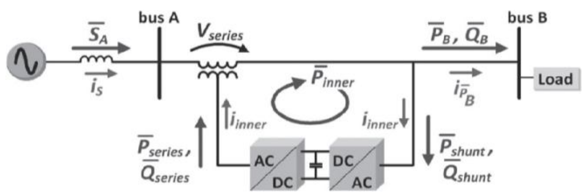

Fig. 4. iUPQC power flow in steady-state.

According to Fig. 4, the compensation of a voltage sag/swell disturbance at bus B causes a positive sequence voltage at the coupling transformer (Vseries 0), since VA VB. 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 [34], [35]. Moreover, Vseries and iPB in the coupling transformer leads to a circulating active power Pinner 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.

For simplicity, the losses in the iUPQC will be neglected to these follows. 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 the first case, the following average powers in steady state can be determined:

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

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

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

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

where SA and QA are the apparent and reactive power injected in the bus A; PB and QB are the active and reactive power injected in the bus B; Pshunt and Qshunt are the active and reactive power drained by the shunt converter; Pseries and Qseries are the active and reactive power supplied by the series converter, respectively.

The constraint of keeping unitary the PF at bus Aderivedto equations (5) and (8). 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 VA and VB. Thus, (7) can be stated. Consequently, the coherence of the power flow is ensured through (8).

If a voltage sag or swell occurs, Pseries and Pshunt will not be zero, and thus, an inner-loop current (Iinner) will appear. The series and shunt converters and the aforementioned circulating active power (Pinner) flow inside the equipment. It is convenient to define the following sag/swell factor. Considering VN as the nominal voltage

$$k_{\frac{sag}{swell}} = \frac{|\dot{V}_A|}{|\dot{V}_N|} = \frac{V_A}{V_N}. \quad (9)$$

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

$$\sqrt{3}.k_{\frac{sag}{swell}}.V_N.I_A = \sqrt{3}.V_N.I_{P_B}$$

$$I_A = \frac{I_{P_B}}{k_{\frac{sag}{swell}}} = I_{P_B} + I_{inner} \quad (10)$$

$$I_{inner} = \left|I_{P_B}\left(\frac{1}{k_{\frac{sag}{swell}}} - 1\right)\right|. \quad (11)$$

The circulating power is given by

$$\underline{P}_{inner} = \underline{P}_{series} = \underline{P}_{shunt} = 3(V_B - V_A)(I_{P_B} + I_{inner}). \quad (12)$$

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

$$\underline{P}_{inner} = 3(V_N - V_A)\left(\frac{P_B}{3V_N}\frac{1}{k_{\frac{sag}{swell}}}\right) \quad (13)$$

$$\square_{\square\square\square\square\square} = \square_{\square\square\square\square\square\square} = \square_{\square\square\square\square\square} = \frac{1 - \square_{\frac{\square\square\square}{\square\square\square\square\square}}}{\square_{\frac{\square\square\square}{\square\square\square\square\square}}} \square_{\square}. \quad (14)$$

In order to verify the effect on the power rate of the series and shunt converters, a full load system SB = P 2 B + Q 2 B = 1p.u. with PF ranging from 0 to 1 was considered. Thus, (14) demonstrates that Pinner depends on the active power of the load and the sag/swell voltage disturbance. It was also considered the sag/swell voltage disturbance at bus A ranging ksag/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 depicts to the Fig. 5. In these figures, the ksag/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.

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 = ˙VB = ˙VN, and then, the positive sequence of the voltage at the coupling transformer is zero (V Series = 0). Thus, in steady state, the power flow is determined by

$$\square_{\square} = \square_{\square} + \square_{\square\square\square\square\square\square\square} \quad (15)$$

$$\square_{\square\square\square\square\square\square\square} + \square_{\square\square\square\square\square\square} = \square_{\square\square\square\square\square} + \square_{\square} \quad (16)$$

$$\square_{\square\square\square\square\square\square} = 0 \; \square\square\square \quad (17)$$

$$\square_{\square\square\square\square\square\square} = \square_{\square\square\square\square\square} = 0 \; \square \quad (18)$$

Ideally, the STATCOM functionality mitigates the inner-loop active power flow (Pinner), and the power flow in the series converter is zero. Where, QSTATCOM is the reactive power that provides voltage regulation at bus A. Consequently, by using fuzzy control if the series converter is properly designed along with the coupling transformer to synthesize the controlled currents I+1_α and I+1_β, as shown in Fig. 3, then a lower power converter can be employed. Contrarily, the shunt converter still has to provide the 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. Ideally, the STATCOM functionality mitigates the inner-loop active power flow (Pinner), 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.

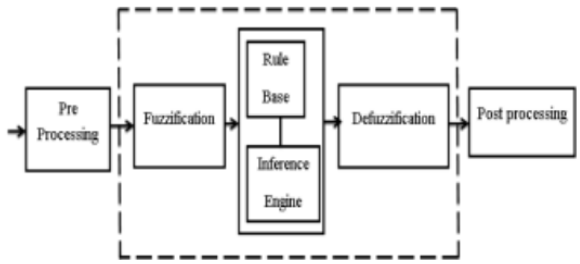

Fig.(8) Fuzzy logic controller

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 CE(k) E(k) 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

$$E(k) = \frac{\square_{\square\square}(\square) - \square_{\square\square}(\square - 1)}{\square_{\square\square}(\square) - \square_{\square\square}(\square - 1)} \qquad (14)$$

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

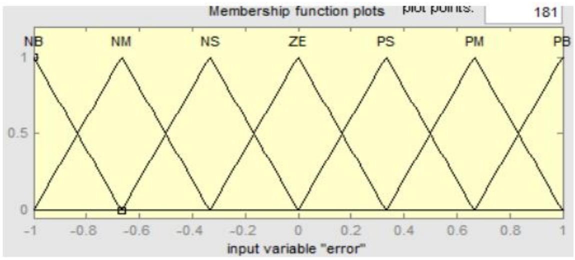

Fig.(b) Membership functions

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. set of FC rules is made using Fig. (b) is given in Table 1.

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.

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 µF
Shunt converter passive filter	L = 750 µH R = 3.7 Ω C = 20.0 µF
Series converter passive filter	L = 1.0 mH R = 7.5 Ω C = 20.0 µF
Sampling frequency	19440 Hz
Switching frequency	9720 Hz

In this paper in order to verify all the power quality issues described, the iUPQC was connected to a grid with a voltage sag system, as depicted in Fig. 6.

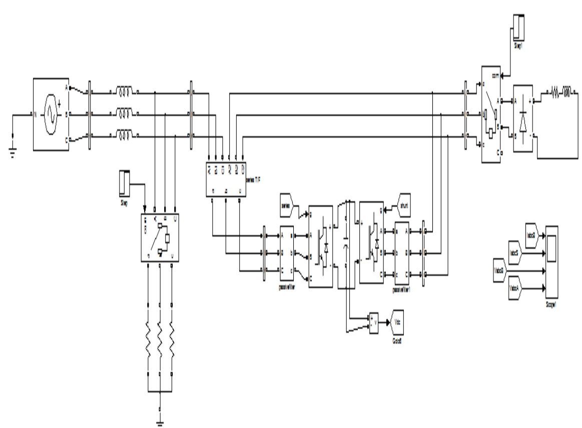

Fig. 6.Block diagram of simulation.

In this simulation case, LS = 10 mH, and RSag = 7.5 Ω To verify the grid-voltage regulation (see Fig. 7), the control of the QSTATCOM variable is enabled to compose (4) at instant t = 0 s.. As shown in Fig. 7 before the QSTATCOM variable is enabled, only the dc link and the voltage at bus B are regulated, and there is voltage sag at bus A. After t = 0s, the iUPQC starts to draw reactive current from bus A, increasing the voltage until its reference value. As shown in Fig. 7, the load voltage at bus B is maintained regulated during all the time, and the grid-voltage regulation of bus A has a fast response.

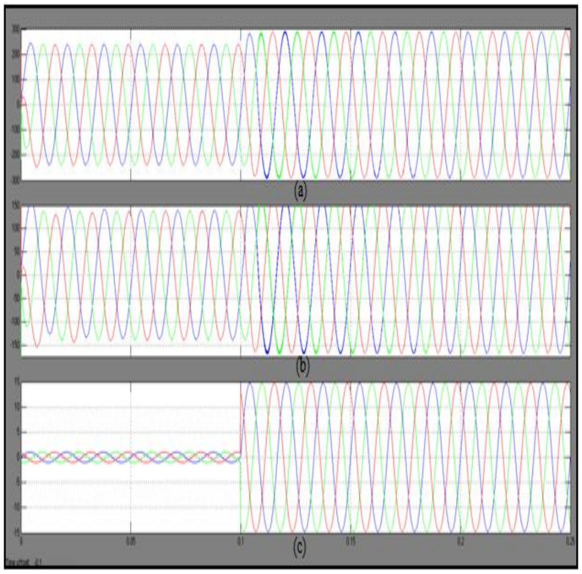

Fig. 7.iUPQC with fuzzy response at no load condition: (a) grid voltages VA, (b) load voltages VB, and (c) grid currents.

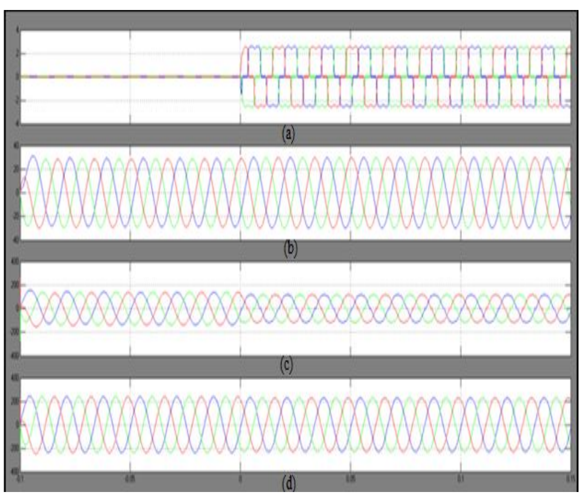

Fig. 8.iUPQC with fuzzy response during the connection of a three phase diode rectifier: (a) load currents, (b) grid currents, (c) load voltages and (d) grid voltages.

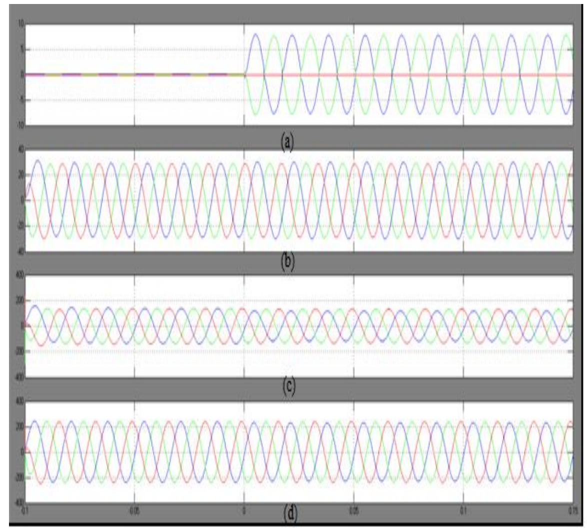

Fig. 9.iUPQC with fuzzy response during the connection of a two phase diode rectifier: (a) load currents, (b) source currents, (c) load voltages, and (d) source voltages.

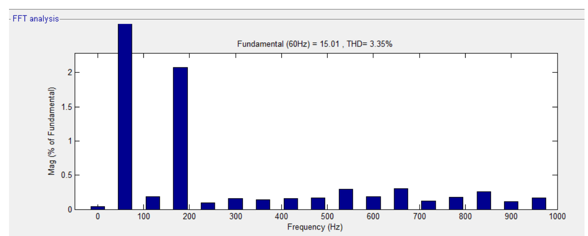

Fig. 10 THD value of grid current with fuzzy controller at no load.

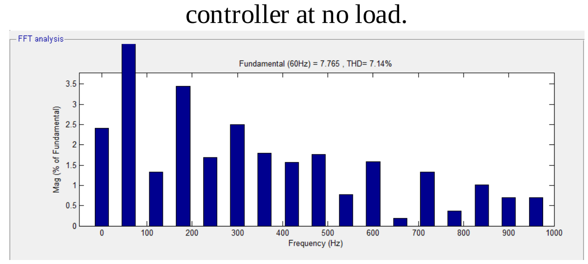

Fig. 11. THD value of grid current without fuzzy controller at no load.

CONCLUSION

In this paper, 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. This new feature enhances the applicability of the iUPQC and provides new solutions in future scenarios involving smart grids and microgrids, including distributed generation and energy storage systems to better deal with the inherent variability of renewable resources such as solar and wind power. Despite the addition of one more power-quality compensation feature, the grid-voltage regulation reduces the inner-loop circulating power inside the iUPQC, which would allow lower power rating for the series converter. Moreover, the improved iUPQC controller may justify the costs and promotes the iUPQC applicability in power quality issues of critical systems, where it is necessary not only an iUPQC or a STATCOM, but both, simultaneously. These results have demonstrated a suitable performance of voltage regulation at both sides of the iUPQC, even while compensating harmonic current and voltage imbalances. 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.

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