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A Fuzzy Controlled IUPQC for Grid Voltage Regulation as a STATCOM

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***Abstract*— This paper shows A improved controller for the dual topology of the unified power quality conditioner (iUPQC) broadening its relevance in power-quality pay, and additionally in microgrid applications. iUPQC will act as a static synchronous compensator (STATCOM) at the grid side, while giving likewise conventional UPQC pay at the load or microgrid side. Another control procedure with Fuzzy logic controller is given here. Past the conventional UPQC power quality highlights, including voltage sag/swell remuneration, the iUPQC will likewise give reactive power support to direct the load-bus voltage as well as the voltage at the grid-side bus by utilizing this controller. Expansion of Fuzzy controller gives low total harmonic distortions in the system. Simulation results are given to confirm the new functionality of the hardware.**

Keywords: **iUPQC, microgrids, power quality, static synchronous compensator (STATCOM), unified power quality conditioner (UPQC).**

I. INTRODUCTION

Conversely, power-electronics-driven loads by and large require perfect sinusoidal supply voltage with a specific end goal to function appropriately, though they are the most mindful ones for unusual harmonic currents level in the distribution system. In this situation, devices that can relieve these downsides have been produced throughout the years. Absolutely, power-electronics devices have achieved extraordinary technological improvements. However the expanding number of power-electronics-driven loads utilized for the most part in the business has achieved extraordinary power quality issues. A portion of the arrangements include A adaptable compensator, known as the unified power quality conditioner (UPQC) [1] – [7] and the static synchronous compensator (STATCOM) [8] – [13].

Power circuit of A UPQC comprises of the combination of a shunt active filter and a series active filter associated in a consecutive configuration. This combination permits the concurrent pay of the load current and the supply voltage, so the repaid current drawn from the grid and the remunerated supply voltage conveyed to the load are kept adjusted and sinusoidal. The fuzzy logic and dual topology of the UPQC, i.e., the iUPQC, was introduced in [14]– [19], where the shunt active filter carries on as A air conditioner voltage source and the series one as A air conditioner current source, both at the fundamental frequency. This is a key point to better outline the control picks up, and additionally to upgrade the LCL filter of the power converters, which permits enhancing altogether the general execution of the compensator [20].

Dynamic reactive power remuneration that means of the STATCOM has been utilized broadly in transmission networks to control the voltage. These days, the STATCOM is to a great extent utilized for voltage regulation [9], while the UPQC and the iUPQC and fuzzy logic control have been chosen as answer for more particular applications [21]. In addition, these last ones are utilized just specifically cases, where their moderately high expenses are legitimized by the power quality improvement it can give, which would be unfeasible by utilizing conventional arrangements. By joining the additional functionality like a STATCOM in the iUPQC gadget, a more extensive situation of utilizations can be come to, especially in the event of distributed generation in smart grids and as the coupling gadget in grid-tied microgrids.

In [16], the execution of the iUPQC and the UPQC was looked at when filling in as UPQCs. The main contrast between these compensators is the kind of source copied 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. Henceforth, progressively, the UPQC controller and fuzzy logic controller needs to decide and synthesize precisely the harmonic voltage and current to be adjusted. Then again, in the iUPQC approach, the series converter carries on as a controlled sinusoidal current source and the shunt converter as a controlled sinusoidal voltage source. It isn't important to decide the harmonic voltage and current to be adjusted, since the harmonic voltages show up normally over the

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series current source and the harmonic currents flow normally into the shunt voltage source.

As the switching frequency expands, the power rate capacity is diminished in real power converters. Accordingly, the iUPQC offers better arrangements if contrasted and the UPQC if there should arise an occurrence of high-power applications, since the iUPQC remunerating references are unadulterated sinusoidal waveforms at the fundamental frequency. Besides, the UPQC has higher switching losses because of its higher switching frequency. An iUPQC controller incorporates all functionalities of those past ones, including the voltage regulation at the load-side bus, and now giving additionally voltage regulation at the grid-side bus, similar to a STATCOM to the grid. Simulation results are given to approve the new controller outline.

II. EQUIPMENT APPLICABILITY

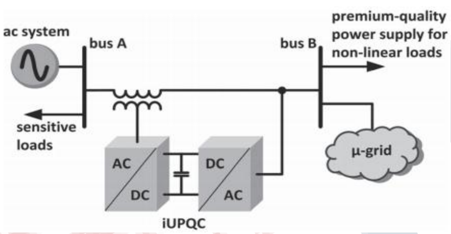

Fig. 1. Example of applicability of iUPQC.

Fig. 1 portrays an electrical system with two busses in spotlight, i.e., bus A and bus B. Bus A will be a critical bus of the power system that provisions delicate loads and fills in as point of coupling of a microgrid, so as to clear up the relevance of the improved iUPQC controller. Bus B is a bus of the micro grid; nonlinear loads are associated with the bus B, which requires premium-quality power supply. The voltages at busses A and B must be managed, keeping in mind the end goal to legitimately supply the touchy loads and the nonlinear loads. The impacts caused by the harmonic currents drawn by the nonlinear loads ought to be alleviated, staying away from harmonic voltage engendering to bus A.

The voltage regulation at bus A isn't sufficient in light of the fact that the harmonic currents drawn by the nonlinear loads are not alleviated by utilization of a STATCOM. Then again, an UPQC or an iUPQC between bus A and bus B can repay the harmonic currents of the nonlinear loads and remunerate the voltage at bus B, as far as voltage harmonics, unbalance, and sag/swell. All things considered, this is as yet insufficient to ensure the voltage regulation at bus A. Subsequently, to accomplish all the coveted objectives, a STATCOM at bus A and an UPQC (or an iUPQC) between busses A and B ought to be utilized. Be that as it may, the expenses of this arrangement would be preposterously high.

Note that the altered iUPQC fills in as an intertie between busses A and B. Additionally, the microgrid associated with the bus B could be an intricate system including distributed generation, energy administration system, including microgrid, and additionally smart grid ideas. An attractive arrangement would be the utilization of a changed iUPQC controller to give likewise reactive power support to bus A, notwithstanding each one of those functionalities of this hardware, as introduced. In rundown, the altered iUPQC can give the accompanying 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 (forced by a tertiary control layer for the microgrid);
c) Reactive power bolster at bus A of the power system;
d) Voltage/frequency bolster at bus B of the microgrid;
e) Harmonic voltage and current isolation between bus A and bus B (synchronous grid-voltage and load-current active filtering capacity);
f) Voltage and current awkwardness compensation.

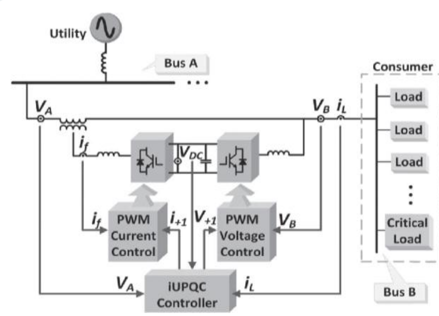

Fig. 2. Modified iUPQC configuration.

Fig. 2 portrays, in detail, the associations and estimations of the iUPQC between bus A and bus B. The functionalities (d) – (f) already recorded were broadly clarified and confirmed through simulations investigation [14] – [18], though the functionality (c) involves the first commitment of the present work.

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Utilizing fuzzy the series converter of a conventional iUPQC utilizes just A active-power control variable p, so as to synthesize a fundamental sinusoidal current drawn from bus A, comparing to the active power requested by bus B.As an outcome, the shunt converter has no further level of opportunity as far as repaying active-or reactive-power variables to grow its functionality. As indicated by the conventional iUPQC controller, the shunt converter forces a controlled sinusoidal voltage at bus B, which compares to the previously mentioned functionality (d).

Important to give A energy source (or huge energy storage) related to the dc link of the iUPQC is take after the case .The iUPQC can fill in as: a) "smart" circuit breaker and as b) power flow controller between the grid and the microgrid just if the repaying active and reactive-power references of the series converter can be set discretionarily. For this situation, it is the last level of flexibility is spoken to by a reactive-power control variable q for the series converter of the iUPQC. Along these lines, the iUPQC will give reactive-power compensation like a STATCOM to the bus A of the grid. As it will be affirmed, this functionality can be included into the fuzzy controller without corrupting every other functionality of the iUPQC.

III. IMPROVED IUPQC CONTROLLER

A. Main Controller

Fig. 3 demonstrates the proposed controller. Fig. 2 delineates the iUPQC equipment and the deliberate units of a three-phase three-wire system that are utilized as a part of the controller.

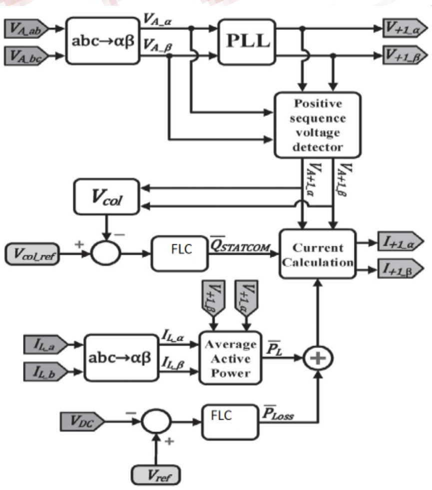

Fig. 3. Novel iUPQC controller.

Fig. 3 demonstrates the proposed controller. Fig. 2 portrays the iUPQC equipment and the deliberate units of a three-phase three-wire The controller inputs are the voltages at busses A and B, the current requested by bus B (iL), and the voltage Vdc of the regular dc link. The outputs are the shunt-voltage reference and the series-current reference to the pulse width tweak (PWM) controllers. The voltage and current PWM controllers can be as straightforward as those utilized, or be improved further to better manage voltage and current awkwardness and harmonics [11].

To start with, the improved Clark change is connected to the deliberate variables. As case of this change, the grid voltage in the αβ-reference casing can be computed as system that is utilized as a part of the controller.

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

Consequently, the signals sent to the PWM controller are the phase-bolted circle (PLL) outputs with amplitude equivalent to 1 p.u. The shunt converter forces the voltage at bus B. Along these lines, it is important to synthesize sinusoidal voltages with ostensible amplitude and frequency. There are numerous conceivable PLL calculations, which could be utilized as a part of this case, as checked in [29]– [33].In the first approach of iUPQC, this current is ascertained through the normal active power required by the loads PL in addition to the power PLoss. The series converter synthesizes the current drawn from the grid (bus A). The load active power can be assessed by

$$P_L = V_{+1\_\alpha}.i_{L\_\alpha} + V_{+1\_\beta}.i_{L\_\beta} (2)$$

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 utilized to acquire the normal active power (PL).The losses in the power converters and the circulating power to give energy adjust inside the iUPQC are ascertained in a roundabout way from the estimation of the dc-link voltage. At the end of the day, the power signal Ploss is dictated by a fuzzy logic controller (fuzzy block in Fig. 3), by contrasting the deliberate dc voltage VDC and its reference value. Fig. 3 demonstrates extra control circle to give voltage regulation like a STATCOM at the grid bus is spoken to by the control signal QSTATCOM. This control signal is acquired through a fuzzy logic controller, in which the information variable

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is the error between the reference esteem and the genuine total voltage of the grid bus, given by

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

The total of the power signals PL and PLoss makes the active-power control variable for the series converter of the iUPQC (p) depicted. Similarly, QSTATCOM is the reactive-power control variable q. Consequently, the present references i+1α and i+1β of the series converter are dictated by

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

B. Power Flow in Steady State

The accompanying strategy, based on the normal power flow, is helpful for evaluating the power appraisals of the iUPQC converters.

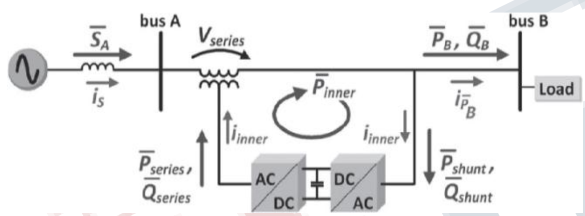

Fig. 4. iUPQC power flow in steady-state.

As indicated by Fig. 4, the compensation of a voltage sag/swell unsettling influence at bus B causes a positive sequence voltage at the coupling transformer (Vseries 0), since VA VB. For consolidated series– shunt power conditioners, for example, the UPQC and the iUPQC, just the voltage sag/swell unsettling influence and the power factor (PF) compensation of the load create a circulating normal power through the power conditioners [34]. Besides, Vseries and iPB in the coupling transformer prompts a circulating active power Pinner in the iUPQC. Furthermore, the compensation of the load PF builds the current provided by the shunt converter. The accompanying investigation is legitimate for an iUPQC acting like a conventional UPQC or including the additional compensation like a STATCOM.

For straightforwardness, the losses in the iUPQC will be fail to these takes after. To start with, the circulating power will be ascertained when the iUPQC is working quite recently like a conventional UPQC. Thereafter, the conditions will incorporate the STATCOM functionality to the grid bus A. In the two cases, it will be expected that the iUPQC controller can drive the shunt converter of the iUPQC to create fundamental voltage dependably in phase with the grid voltage at bus A. For the main case, the accompanying normal powers in steady state can be resolved:

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

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

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

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

Where, SA and QA are the clear and reactive power infused in the bus A; PB and QB are the active and reactive power infused in the bus B; Pshunt and Qshunt are the active and reactive power depleted by the shunt converter; Pseries and Qseries are the active and reactive power provided by the series converter, separately.

The requirement of keeping unitary the PF at bus Aderivedto conditions (5) and (8). For this situation, the present going through the series converter is dependable just to supply the load active power, that is, it is in phase (or counter phase) with the voltages VA and VB. In this way, (7) can be stated. Therefore, the lucidness of the power flow is guaranteed through (8).

In the event that a voltage sag or swell happens, Pseries and Pshunt won't be zero, and therefore, an inward circle current (Iinner) will show up. The series and shunt converters and the previously mentioned circulating active power (Pinner) flow inside the hardware. It is advantageous to characterize the accompanying sag/swell factor. Considering VN as the ostensible voltage

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

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

$$\sqrt{3}.\, k_{sag/swell}.\, V_N.\, i_S = \sqrt{3}.\, V_N.\, i_{P_B}$$

$$i_S = \frac{i_{P_B}}{k_{sag/swell}} = i_{\bar{P}_B} + i_{inner} (10)$$

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

The circulating power is given by

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

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

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

$$\bar{P}_{inner} = \bar{P}_{sreies} = \bar{P}_{shunt} = \frac{1 - K_{sag/swell}}{k_{sag/swell}} \bar{P}_B. \qquad (14)$$

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With a specific end goal to check the impact 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 running from 0 to 1 was considered. Subsequently, (14) shows that Pinner relies upon the active power of the load and the sag/swell voltage unsettling influence. It was likewise viewed as the sag/swell voltage unsettling influence at bus A going ksag/swell from 0.5 to 1.5. Along these lines, the power rating of the series and shunt converters are acquired through (6) – (8) and (14).

The obvious power of the series and shunt power converters delineates to the Fig. 5. In these figures, the ksag/swell-hub and the PF-hub are utilized to assess the power flow in the series and shunt power converters as per the sag/swell voltage unsettling influence and the load power utilization, individually. The power flow in the series converter shows that a high power is required if there should arise A occurrence of sag voltage aggravation with high active power load utilization.

In the event that the iUPQC plays out all unique UPQC functionalities together with the STATCOM functionality, the voltage at bus A is additionally managed with a similar phase and extent, that is, ˙V A = ˙VB = ˙VN, and after that, the positive sequence of the voltage at the coupling transformer is zero (V Series = 0). Along these lines, in steady state, the power flow is controlled by

$$\bar{S}_A = \bar{P}_B + \bar{Q}_{STATCOM} \quad (15)$$
$$\bar{Q}_{STATCOM} + \bar{Q}_{SERIES} = \bar{Q}_{SHUNT} + \bar{Q}_B \quad (16)$$
$$\bar{Q}_{series} = 0\ var \quad (17)$$
$$\bar{P}_{series} = \bar{P}_{inner} = 0\ W \quad (18)$$

In a perfect world, the STATCOM functionality mitigates the inward circle active power flow (Pinner), and the power flow in the series converter is zero. Where, QSTATCOM is the reactive power that gives voltage regulation at bus A. Thusly, by utilizing fuzzy control if the series converter is appropriately composed alongside the coupling transformer to synthesize the controlled currents I+1_α and I+1_β, as appeared in Fig. 3, at that point a lower power converter can be utilized. Oppositely, the shunt converter still needs to give the full reactive power of the load and furthermore to deplete the reactive power infused by the series converter to control the voltage at bus A. In a perfect world, the STATCOM functionality mitigates the internal circle 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.

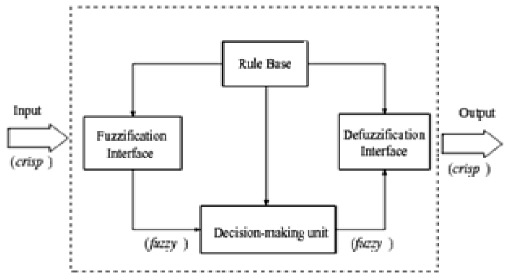

Fig.5. Fuzzy logic controller

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.

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 A 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

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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

$$E(k) = \frac{P_{ph(k)} - P_{ph(k-1)}}{V_{ph(k)} - V_{ph(k-1)}} \tag{31}$$

$$CE(k) = E(k) – E(k-1) \tag{32}$$

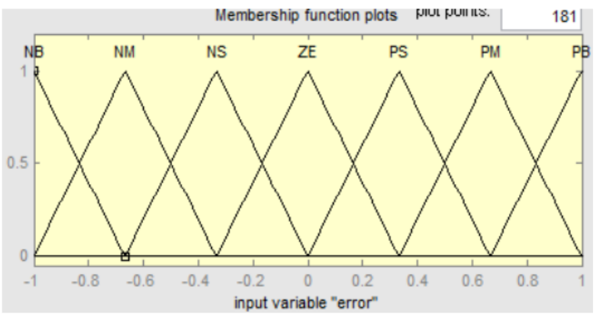

Fig.6. Membership functions

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

$$u=-[\alpha E + (1-\alpha)*C] \tag{33}$$

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. (9) Is given in Table 1.

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.

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. 7.

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

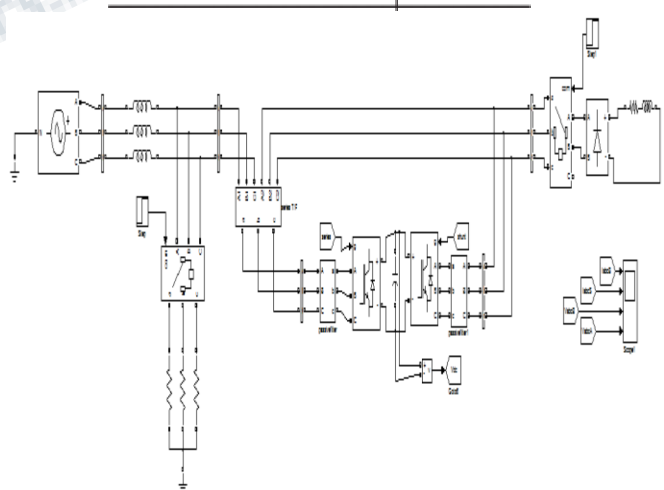

Fig. 7. Block diagram of simulation.

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In this simulation case, LS = 10 mH, and RSag = 7.5 Ω To check the grid-voltage regulation (see Fig. 8), the control of the QSTATCOM variable is empowered to make (4) at moment t = 0 s. As appeared in Fig. 8 preceding the QSTATCOM variable is empowered, just the dc link and the voltage at bus B are directed, and there is voltage sag at bus A. After t = 0s, the iUPQC begins to draw reactive current from bus A, expanding the voltage until the point that its reference esteem. As appeared in Fig. 8, the load voltage at bus B is maintained directed amid constantly and the grid-voltage regulation of bus A has a quick reaction.

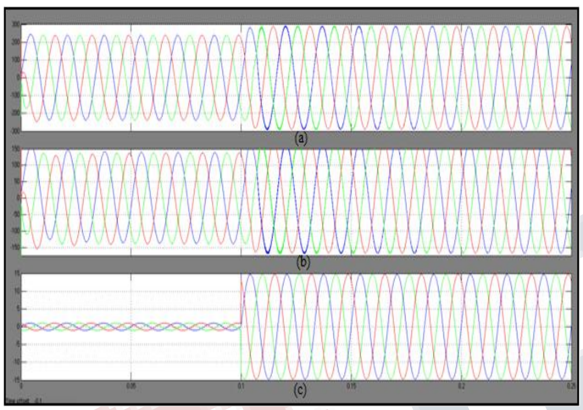

Fig. 8. iUPQC with fuzzy response at no load condition: (a) grid voltages VA, (b) load voltages VB, and (c) grid currents.

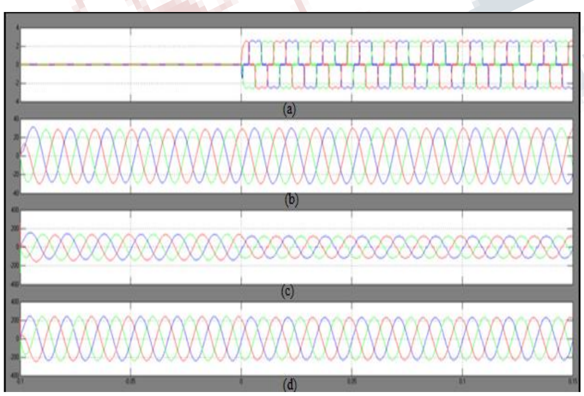

Fig. 9. iUPQC with fuzzy response during the connection of a three phase diode rectifier: (a) load currents, (b) grid currents, (c) load voltages and (d) grid voltages.

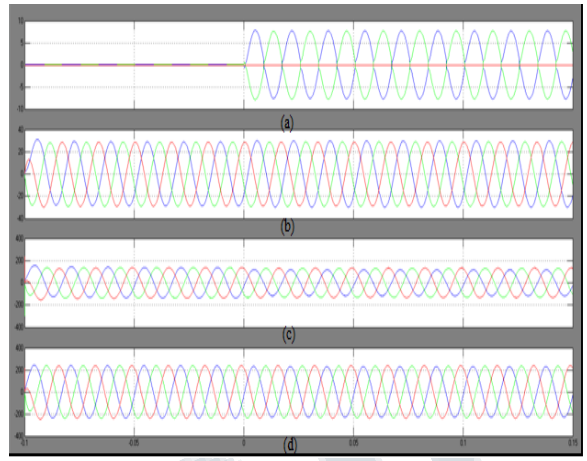

Fig. 10. iUPQC with fuzzy response during the connection of a two phase diode rectifier: (a) load currents, (b) source currents, (c) load voltages, and (d) source voltages.

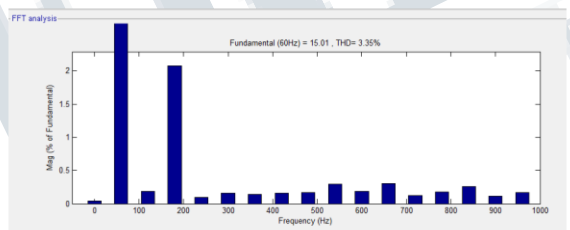

Fig. 11. THD value of grid current with fuzzy controller at no load.

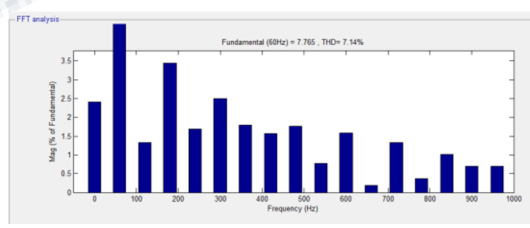

Fig. 12. THD value of grid current without fuzzy controller at no load.

VI. CONCLUSION

In this paper, improved iUPQC controller, the currents synthesized by the series converter are dictated by the normal active power of the load and the active power to give the dc-link voltage regulation, together with a normal reactive power to direct the grid-bus voltage. This new component upgrades the appropriateness of the iUPQC and gives new arrangements in future situations including smart grids and microgrids, including distributed

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generation and energy storage systems to better manage the intrinsic fluctuation of renewable resources, for example, solar and wind power. Regardless of the expansion of one more power-quality compensation include, the grid-voltage regulation decreases the inward circle circulating power inside the iUPQC, which would permit bring down power rating for the series converter. In addition, the improved iUPQC controller may legitimize the expenses and advances the iUPQC relevance in power quality issues of critical systems, where it is important an iUPQC or a STATCOM, as well as both, at the same time. These results have shown an appropriate execution of voltage regulation at the two sides of the iUPQC, even while repaying harmonic current and voltage lopsided characteristics. The simulation results confirmed the improved iUPQC objectives. The grid-voltage regulation was accomplished with no load, and in addition when supplying a three-phase nonlinear load.

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