A Control Scheme for Dual Unified Power Quality Conditioner to Improve Power Quality

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Abstract- This paper presents a dual three-phase topology of a unified power quality conditioner— iUPQC. The iUPQC is composed of two active filters, a series active filter and a shunt active filter (parallel active filter), used to eliminate harmonics and unbalances. Different from a conventional UPQC, the iUPQC has the series filter controlled as a sinusoidal current source and the shunt filter controlled as a sinusoidal voltage source. Therefore, the pulse width modulation (PWM) controls of the iUPQC deal with a well-known frequency spectrum, since it is controlled using voltage and current sinusoidal references, different from the conventional UPQC that is controlled using non sinusoidal references with the help of fuzzy and PID controller.

Key words—Active filters, control design, fuzzy logic control, power line conditioning, unified power quality conditioner(UPQC).

I. INTRODUCTION

The Usage of power quality conditioners in the distribution system network has increased during the past years due to the steady increase of nonlinear loads connected to the Electrical grid. The current drained by nonlinear loads has a high harmonic content, distorting the voltage at the utility grid and consequently affecting the operation of critical loads. By using a unified power quality conditioner (UPQC) it is possible to ensure a regulated voltage for the loads, balanced and with low harmonic distortion and at the same time draining undistorted currents from the utility grid, even if the grid voltage and the load current have harmonic contents. The UPQC consists of two active filters, the series active filter (SAF) and the shunt or parallel active filter (PAF).

The PAF is usually controlled as a non sinusoidal current source, which is responsible for compensating the harmonic current of the load, while the SAF is controlled as a non sinusoidal voltage source, which is responsible for compensating the grid voltage. Both of them have a control reference with harmonic contents, and usually, these references might be obtained through complex methods. The line 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. In this way, both grid current and load voltage are sinusoidal, and therefore, their references

are also sinusoidal. The aim of this is to propose dual three-phase four wire unified power quality conditioner (iUPQC) by using fuzzy logic in shunt active filter. It is to be used in the utility grid connection.

Fuzzy logic control methodology has been demonstrated to allow solving uncertain and vague problems. In this paper fuzzy logic controller is used for generation of switching pulses for PWM controllers. The advantages of using fuzzy system are simplicity, ease of application, flexibility, speed and ability to deal with imprecision and uncertainties. Due to absorbing and supplying of active and reactive power in active filter, the capacitance voltage is not maintained constant. In literature many controllers are used for capacitance balancing, such as PI, PID, and fuzzy logic controller. In this paper, fuzzy control algorithm is used to balance the dc voltage of capacitance in order to improve the performance of controller. The proposed method is evaluated and tested under non sinusoidal source voltage conditions using Mat lab/Simulink software. The performance of UPQC depends on the characteristic of the active filters. The fuzzy logic controller is used in almost all sectors of industry and power systems and science and one among them is harmonic current and reactive power compensation.

II. GENERAL UPQC

The general UPQC consisting of the combination of a series-active and shunt-active filter is shown in Fig.1.
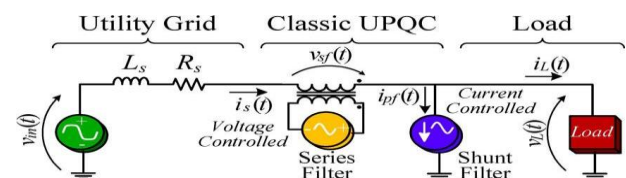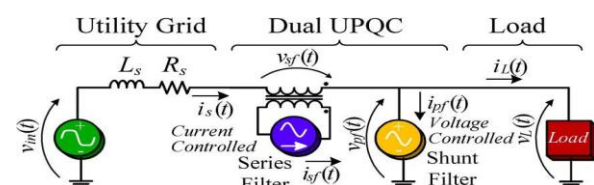

Fig.1. General UPQC

Fig.2. Dual UPQC (iUPQC)

The general UPQC will be installed at substations by electric power utilities in the near future. The main purpose of the series-active filter is harmonic isolation between a sub transmission system and a distribution system. In addition, the series-active filter has the capability of voltage flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). The main purpose of the shunt active filter is to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc-link voltage between both active filters .In this paper, the integration of the series-active and shunt active filters is called the UPQC.

III. DUAL UPQC WITH FUZZY LOGIC CONTROLLER

The conventional UPQC structure is composed of a SAF and a PAF, as shown in Fig.1. In this configuration, the SAF works as a voltage source in order to compensate the grid distortion, unbalances, and disturbances like sags, swells, and flicker. Therefore, the voltage compensated by the SAF is composed of a fundamental content and the harmonics. The PAF works as a current source and it is responsible for compensating the unbalances, displacement, and harmonics of the load current, ensuring a sinusoidal grid current. The series filter connection to the utility grid is made through a transformer, while the shunt filter is usually connected directly to the load, mainly in low-voltage grid applications. The conventional UPQC has the following drawbacks: complex harmonic extraction of the grid voltage and the load involving complex calculations, voltage and current references with harmonic contents requiring a high bandwidth control, and the leakage inductance of the series connection transformer affecting the voltage compensation generated by the series filter.

In order to minimize these drawbacks, the iUPQC is investigated in this paper, and its scheme is shown in Fig. 2. The scheme of the iUPQC is very similar to the conventional UPQC, using an association of the SAF and PAF, diverging only from the way the series and shunt filters are controlled. In the iUPQC, the SAF works as a current source, which imposes a sinusoidal input current synchronized with the grid voltage. The PAF works as a voltage source imposing sinusoidal load voltage synchronized with the grid voltage. The SAF acts as high impedance for the current harmonics and indirectly compensates the harmonics, unbalances, and disturbances of the grid voltage since the connection transformer voltages are equal to the difference between the grid voltage and the load voltage. In the same way, the PAF indirectly compensates the unbalances, displacement, and harmonics of the grid current, providing a low-impedance path for the harmonic load

current.

Fig. 3(a) shows iUPQC with PID controller in SAF. This system generates unbalances and harmonic distortions. By using fuzzy controller in SAF shown in Fig.3 (b) , the responses of the both SAF and PAF are good.
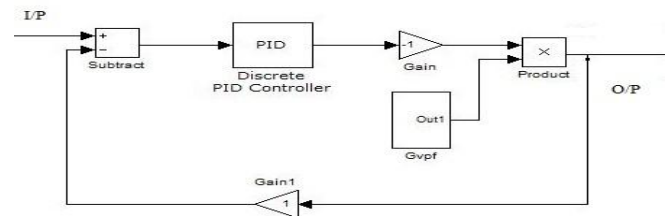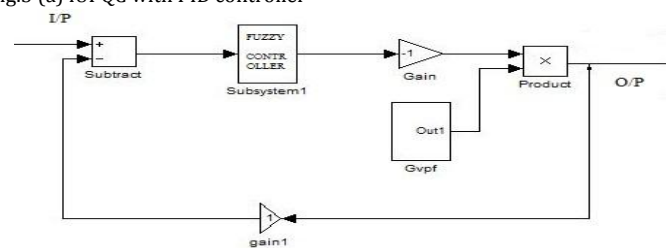

Fig.3 (a) iUPQC with PID controller

Fig.3 (b) iUPQC with Fuzzy Controller

IV. POWER CIRCUIT

The power circuit of the proposed iUPQC is made up of two four-wire three-phase converters connected back to back and their respective output filters, as shown in Fig. 4.Three single-phase transformers are used to connect the SAF to the utility grid, while the PAF is connected directly to the load.
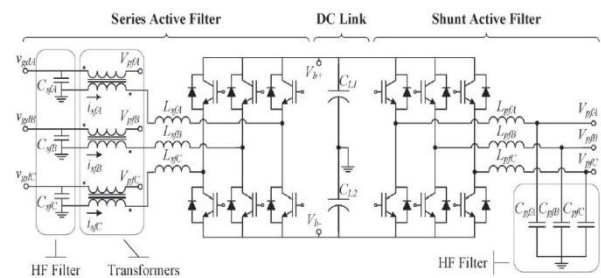

Fig.4. Power circuit of the iUPQC

V. OUTPUT PASSIVE FILTER DESIGN

Fig.5 shows the equivalent circuit used for the SAF output impedance analysis, and Fig.6 shows the equivalent circuit used for the PAF output impedance analysis. In order to simplify the analysis of the PAF, the voltage source v_{sc} and the inductance L_{sf} , which are series connected, were considered as a current source. Observing the equivalent circuits, we can claim that the PAF output impedance affects the frequency response of the SAF, while the SAF output impedance does not affect the frequency response of the PAF.

Therefore, the output passive filter design of the iUPQC should be started with the PAF design followed by the SAF design.

The high-frequency filter transfer function of the PAF is derived by analyzing the circuit of Fig. 6 and is shown in

$$\frac{v_L(s)}{v_{pc}(s)} = \frac{1}{L_{pf}C_{pf}} \cdot \frac{1}{s^2 + s \cdot \frac{1}{C_{pf}R_L} + \frac{1}{L_{pf}C_{pf}}} \qquad (1)$$

The inductor L_{pf} was defined by the power design, so the capacitor C_{pf} will be defined according to the desired cut-off frequency of the filter. In this design, a 2.9-kHz cut-off frequency was used, resulting in a value of 10 μF for the C_{pf} filter capacitor. Fig. 7 shows the PAF frequency response for the nominal load and no load.

The high-frequency filter transfer function of the SAF is derived by analyzing the circuit of Fig. 6 and is shown in

$$\frac{i_s(s)}{v_{sc}(s)} = \frac{n}{\{sL_{sf} + n^2[sL_{lg} + R_{lg} + \alpha + \beta].\gamma\}} \qquad (2)$$

Where

$$\alpha = \frac{sL_{pf}R_L}{s^2 L_{pf}C_{pf}R_L + sL_{sf} + R_L} \qquad (3)$$

$$\beta = \frac{sL_{rd} + R_{rd}}{s^2 L_s C_{sf} + sC_{sf}R_s + 1} \qquad (4)$$

$$\gamma = s^2 L_s C_{sf} + sC_{sf}R_{lg} + 1 \qquad (5)$$

As the inductor L_{sf} was defined by the power design, the capacitor C_{sf} will be defined according to the desired cut-off frequency of the filter
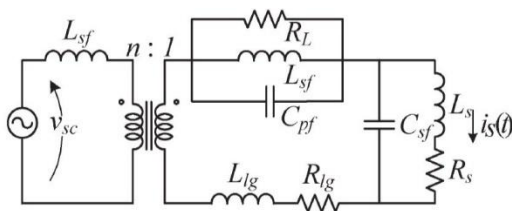

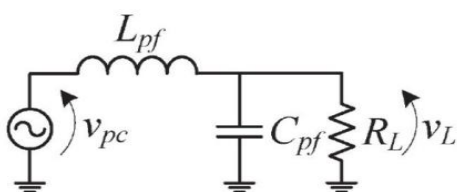Fig .5. Equivalent circuit as viewed by SAF

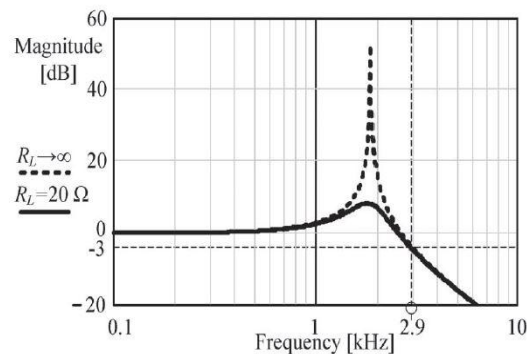Fig.6. Equivalent circuit as viewed by PAF

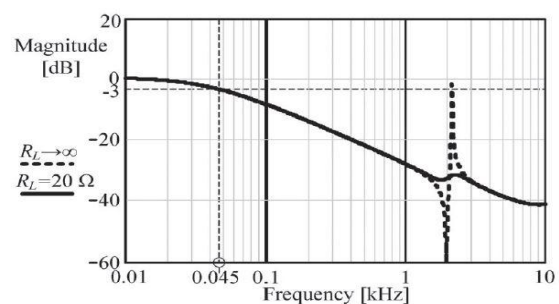Fig. 7. HF filter frequency response of the PAF

Fig.8. HF filter frequency response of the SAF

In this design, a 45-Hz cut-off frequency was used, resulting in a value of 1 μF for the C_{sf} . Fig. 8 shows the SAF frequency response for nominal load and no load It can be noted that the filter response has a low cut off frequency that can reduce the bandwidth of the SAF, decreasing its effectiveness under operation with harmonic contents on the grid voltage. This characteristic of low-frequency attenuation is undesirable and intrinsic to the structure due to the leakage impedance of the coupling transformers.

An important contribution of this paper and different from what it was stated in some previous articles, which deal with the same iUPQC control strategy, is that, in spite of the SAF operates with sinusoidal reference, the control of this filter needs to deal with high frequency since the current imposed by the SAF is obtained through the voltage imposition on this filter output inductor. The voltage imposed on these inductors is complementary to the utility grid voltage harmonics so that it guarantees a sinusoidal current through the filter. Different from the conventional UPQC whose narrow-band frequency control may distort the load voltage, in the iUPQC, the narrow-band frequency control may distort the current drained from the utility grid. The usage of high-power coupling transformers, with low leakage inductance, and the design of higher voltage dc link, allowing the imposition of higher current rate of change on the filter output inductor, is solutions to change the characteristics of the filter attenuation in low

frequencies.
VII. PROPOSED CONTROL SCHEME

In the proposed control scheme, the power calculation and harmonic extraction are not needed since the harmonics, unbalances, disturbances, and displacement should be compensated. The SAF has a current loop in order to ensure a sinusoidal grid current synchronized with the grid voltage. The PAF has a voltage loop in order to ensure a balanced regulated load voltage with low harmonic distortion. These control loops are independent from each other since they act independently in each active filter.

A. SAF Control

The SAF control scheme consists of three identical grid current loops and two voltage loops. The current loops are responsible for tracking the reference to each grid input phase in order to control the grid currents independently. One voltage loop is responsible for regulating the total dc link voltage, and the other is responsible for avoiding the unbalances between the dc link capacitors. The resistor R_b is absent in the real circuit ($R_b \to \infty$); it just represents instantaneous active power consumption of the dc link. The term instantaneous is related to the time of the switching period, since active power consumption of the dc link is null for the utility grid voltage frequency.
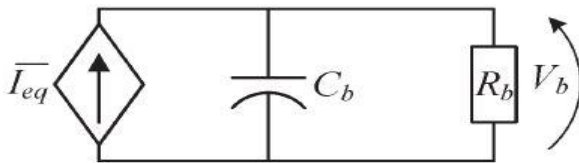

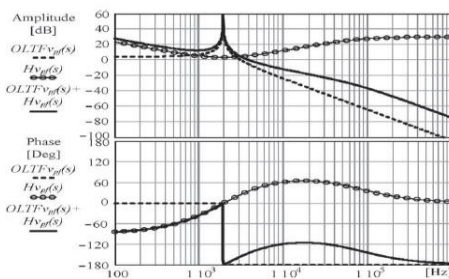Fig. 9. Equivalent circuit of the SAF voltage loop

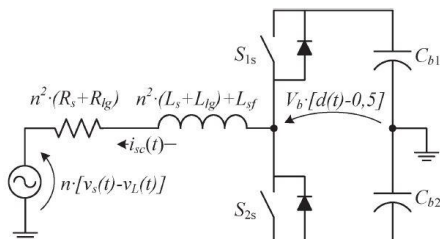Fig.10. Voltage Loop frequency response of the PAF
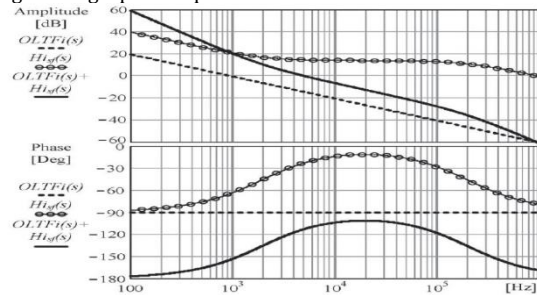

Fig.11. Single phase equivalent circuit of SAF

Fig. 12. Current loop frequency response of the SAF

The average charge current of the dc link is given by

$$\overline{I_{eq}} = \frac{3}{2} \cdot \frac{n.V_{gdpk}.I_{sfpk}}{V_b} \qquad (6)$$

The Km_{fs} gain is obtained by considering the gain of the multiplier integrated circuit and the peak of the synchronized sinusoidal signal generated by the DSP. The frequency response of the total voltage loop is shown in Fig. 10, including the open-loop transfer function (OLTF$_v$), controller transfer function (H$_{vsf}$), and compensated loop transfer function (OLTF$_v$ + H$_{vsf}$).

The unbalanced-voltage control loop also has a low-frequency loop and acts on the dc level of the grid current reference in order to keep the voltage equilibrium in dc link capacitors. When a voltage unbalance occurs, this loop adds a dc level to the references of the grid currents, aiming to equalize both C_{L1} and C_{L2} voltages $d(t)$ represents the duty cycle. Through the mesh analysis and by applying Laplace, the unbalanced-voltage loop transfer function is obtained and given by

$$Gd_{sf}(s) = \frac{v_{b+}(s) - v_{b-}(s)}{I_{sc}(s)} = \frac{3}{2.s.C_b} \qquad (7)$$

The open -loop transfer function (OLTF$_d$) is given by

$$OLTFd(s) = Gd_{sf}(s). \frac{Kd_{sf}}{Ki_{sf}} \qquad (8)$$

Where

Kd_{sf} Differential voltage sensor gain

The frequency response of the differential voltage loop is shown in Fig. 12, including the open-loop transfer function (OLTF$_d$), controller transfer function (H$_{dsf}$), and compensated loop transfer function (OLTF$_d$ + H$_{dsf}$).The current loops have a fast response to track the sinusoidal references, allowing the decoupling analysis in relation to the voltage loop. The current loop transfer function is obtained through the analysis of the single-phase equivalent circuit shown in Fig. 11.

The dynamic model is obtained through the circuit

analysis using average values related to the switching period. Under these conditions, the voltages $v_s(t)$ and $v_L(t)$ are constants.

The open loop transfer function ($OLTFi(s)$)

$$OLTFi(s) = Gi_{sf}(s).Kpwm_{sf}.Ki_{sf} \qquad (9)$$

Where

$Kpwm_{sf}$ is the series filter pulse width modulation (PWM) modulator gain.

The $Kpwm_{sf}$ gain is equal to the inverse peak value of the triangular carrier. The frequency response of the current loop is shown in Fig. 12, including the open-loop transfer function ($OLTFi$), controller transfer function (His_f), and compensated loop transfer function ($OLTF_i + His_f$).

B. PAF Control

The PAF control scheme is formed by three identical load voltage feedback loops, except for the $120°$ phase displacements from the references of each other.

The dynamic model is obtained through the circuit analysis using average values related to the switching period. Through small signal analysis and by using Laplace, the voltage loop transfer function is given by

$$Gv_{pf}(s) = \frac{V_b}{L_{pf}C_{pf}} \cdot \frac{1}{s^2 + s \cdot \frac{1}{C_{pf}RL} + \frac{1}{L_{pf}C_{pf}}} \qquad (10)$$

Where $Gv_{pf}(s) = V_L(s)/D(s)$

The open-loop transfer function ($OLTFvpf$) is given by

$$OLTFv(s) = Gv_{pf}(s).Kpwm_{pf}.Kv_{pf} \qquad (11)$$

Where

$Kpwm_{pf}$ is the shunt filter PWM modulator gain.

VIII. POWER FLOW

The active power flow of the iUPQC is shown in Fig. 13. In Fig. 13(a), the grid voltage v_s has a lower amplitude than the load voltage v_L. In this case, the SAF delivers active power to the load, while the parallel active filter consumes active power. In Fig. 13(b), the grid voltage v_s has a higher amplitude than the load voltage v_L. In this case, the SAF consumes active power, while the PAF filter delivers active power to the load. In an ideal situation

when v_s is equal to v_L, there is no active power flow through the SAF. The power drained from the electrical grid is equal to the sum of the load power and the iUPQC power losses. In this paper, the output voltage v_L is kept in phase with the fundamental component of the input voltage v_{in}; thus, the SAF operates with reactive power only when there are harmonics on the input voltage v_{in} because the fundamental component of the coupling transformer voltage is always in Phase with the current drained from the utility grid i_s.
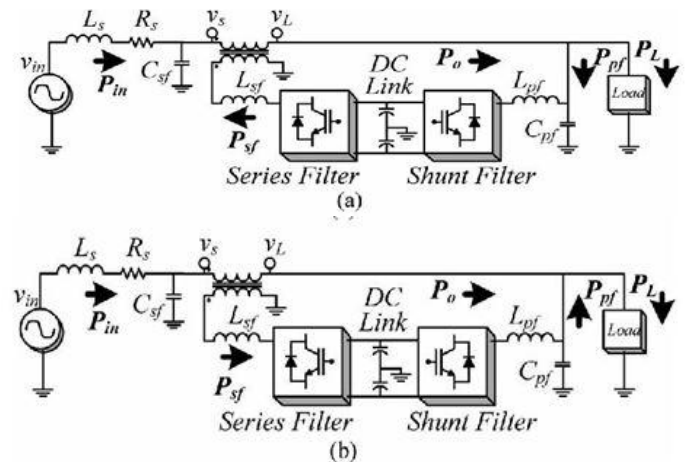
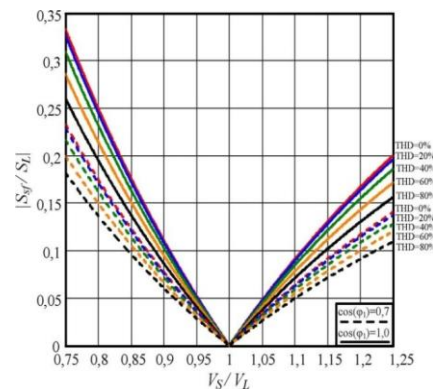Fig.13. power flow of iUPQC (a) Vs<V_L (b)Vs>V_L
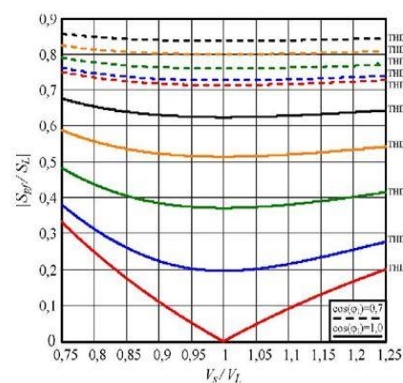
Fig. 14. Normalised apparent power of the SAF

Fig. 15. Normalised apparent power of the PAF

In steady state, assuming a sinusoidal and balanced

utility grid voltage and disregarding the dual UPQC losses, the apparent power of SAF S_{sf} and PAF S_{pf} normalized in relation to the apparent power of the load respectively, are represented in Figs. 15 and 16.

IX. RESULTS

Fig. 16(a) shows the currents and voltages in the load for phase A. Fig. 16(b) shows the currents through the PAF. The PAF indirectly supplies the load harmonic currents because the SAF only drains the fundamental current component from the source.

In a similar way, Fig. 16(c) shows the voltages synthesized by the SAF. The SAF indirectly processes the harmonic grid voltages because the PAF imposes a synchronized sinusoidal voltage on the load.

In order to verify the dynamic response of the iUPQC, Fig. 17(a) shows the source and load voltages during a voltage interruption in phase A. Fig. 17(b) shows the source currents during a fault in phase A. It is possible to see that the source currents in the other phases have the amplitudes increased in order to keep the nominal power of the load.

Fig. 17(c) shows the load voltages and the load currents during a load step from 50% to 100%. The load voltages and the load currents are shown in Fig. 17(d) during a load step from 100% to 50%.

The experimental results confirm the efficacy of the proposed scheme to control the iUPQC.
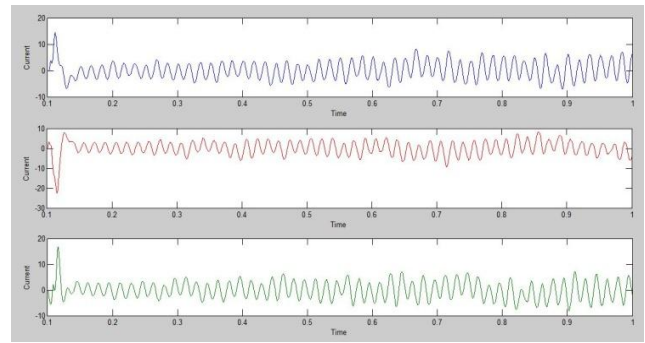

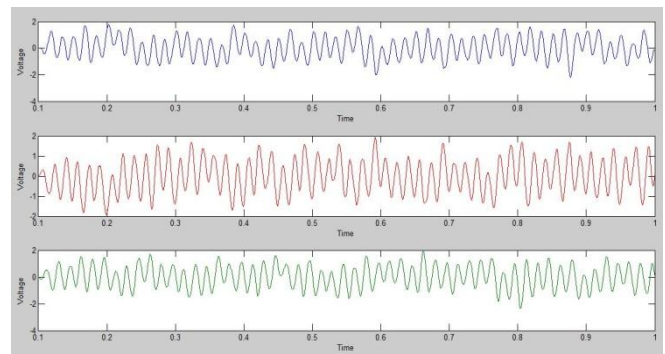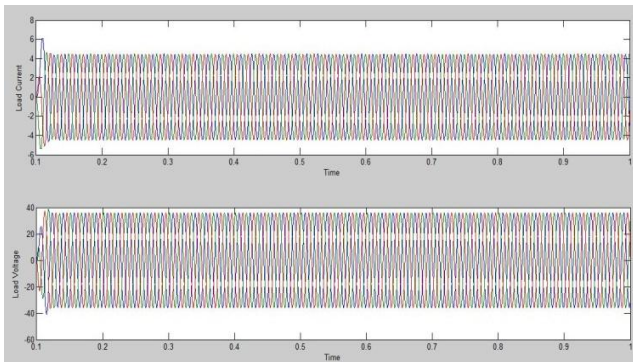Fig.16 (a). Load Currents (2A/div and 100ms/div)and Load Voltages(20V/div and 100ms/div)

Fig.16 (b). PAF currents (10A/div and 100ms/div)

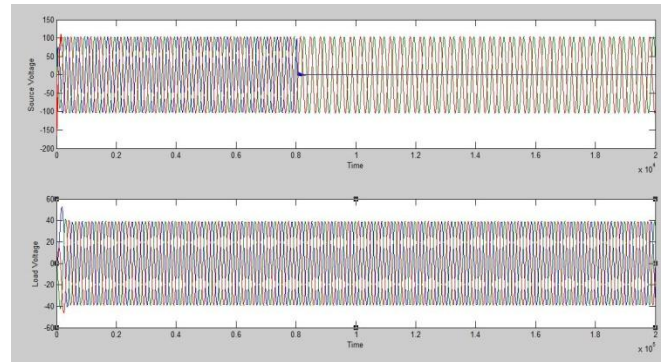Fig.16(c). SAF voltages (2V/div and 100ms/div)

Fig.17 (a) Source voltages (50V/div and 100ms/div) and Load voltages (10V/div and 100ms/div) during a voltage dip in Phase A
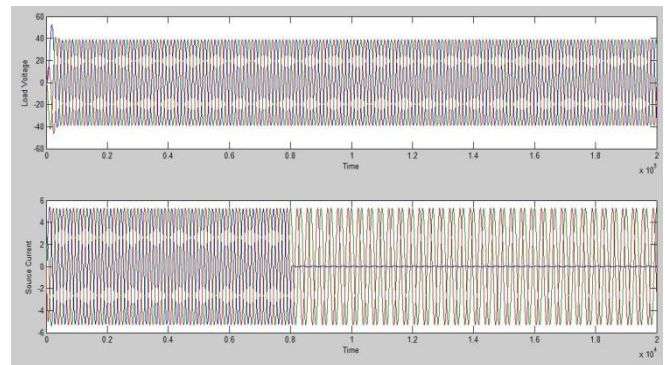

Fig.17 (b). Load Voltages (10V/div and 100ms/div)and Source Currents(2A/div and 100ms/div)
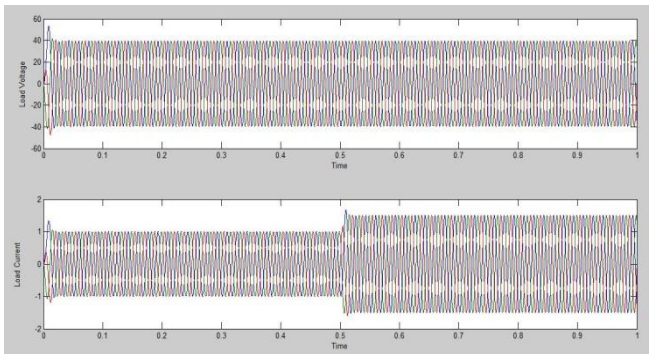
Fig.17(c) Load Voltages (20V/div and 100ms) and Load Currents (2A/div and 100ms) during a load step from 50% to 100%
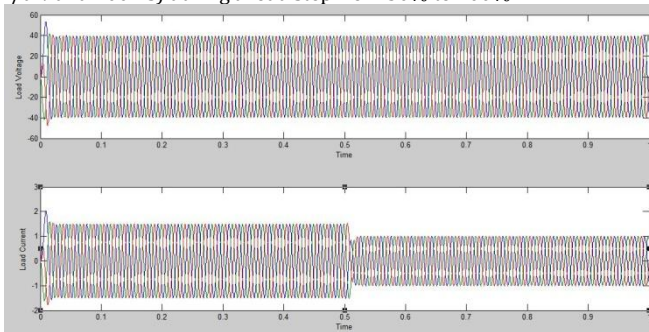

Fig.17 (d). Load Voltages (20V/div and 100ms) and Load Currents (1A/div and 100ms) during a load step from 100% to 50%

X. CONCLUSION

The results obtained with the iUPQC confirm that the proposed ABC reference frame control works very well and that it was able to compensate the nonlinear load currents and also ensure the sinusoidal voltage for the load in all three phases. The main advantages of this proposed control in relation to the other proposed schemes were the utilization of sinusoidal references for both series and shunt active filter controls without the need for complex calculations or coordinate transformations.

The iUPQC references do not have harmonic contents, and the only requirement is the synchronism with the grid voltage. Another positive aspect of the iUPQC in low-voltage applications (distribution system network) is the non interference of the leakage impedance voltage of the SAF connection transformer in the load voltage compensation because the load voltage is directly controlled by the PAF. On the other hand, the leakage impedance interferes in the current loop bandwidth, decreasing its frequency response under distorted grid voltages.

The results validate the proposed iUPQC control scheme using fuzzy controller.

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BIOGRAPHIES

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