

CONTROL ALGORITHM BASED ON LIMIT CYCLE OSCILLATOR-FLL FOR UPQC-S WITH OPTIMIZED PI GAINS

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Abstract— A simplified intelligent control technique for a dual three-phase topology of a unified power quality conditioner iUPQC. The i-UPQC is composed of two active filters, a series active filter and a shunt active filter (parallel active filter), used to eliminate harmonics and unbalances. This project explains an enhanced Fuzzy controller for the dual topology of the unified power quality conditioner (iUPQC) expanding its pertinence in power quality compensation, and additionally in microgrid applications. Implementation of intelligence controller by using voltage as feedback for significantly improving the dynamic performance of UPQC, the comparative analysis of several control strategies fed UPQC for power quality improvement features is presented. Fuzzy control has emerged as one of the most active and prolific areas for research in the applications of fuzzy set theory, especially in the realm of industrial process, which do not lend of quantities data regarding the input-output relations. By using PI controller, beyond the conventional UPQC power quality features, including voltage sag/swell compensation, the iUPQC will also provide reactive power support to regulate not only the load-bus voltage but also the voltage at the grid-side bus. In other words, the iUPQC will work as a static synchronous compensator (STATCOM) at the grid side, while providing also the conventional UPQC compensations at the load or microgrid side. By using Fuzzy logic controller also we have the same functioning of iUPQC and additionally the harmonics are reduced. Here three different cases are taken into consideration considering loads. Comparison results are validated with the tabular form. Simulations results are provided to verify that fuzzy logic controller is better than PI controller using MATLAB/ SIMULINK software.

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Keywords— Algorithm, Limit Cycle Oscillator-FLL, UPQC-S, Optimized PI Gains.

I. INTRODUCTION

FACTS devices are capable of mitigating the power quality problems. FACTS devices are designed using power electronics. Undoubtedly power-electronics devices have brought about great industrial improvements. On the other hand, the ever-increasing number of power-electronics-driven loads used usually in the industry has brought about unusual power quality problems. In division, power-electronics-driven loads generally need ideal sinusoidal supply voltage in order to function appropriately, whereas they are the most responsible ones for uncharacteristic harmonic

currents level in the distribution system. In these circumstances, devices that can mitigate these drawbacks have been developed over the years.

Some of the solutions occupy a flexible compensator, known as the unified power quality conditioner (UPQC) [1]–[7] and the static synchronous compensator (STATCOM) [8]–[13]. The power circuit of a UPQC consists of a combination of a shunt active and series active filters are connected in a back-to-back configuration. This combination allows the instantaneous compensation of the load current and the supply voltage, so that the compensated current drawn from the grid and the supply voltage which is compensated delivered to the load are kept balanced and sinusoidal. The 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 filter as an ac-current source, both at the fundamental frequency. This is a key point to better design the control gains, to optimize the LCL filter of the power converters, which allows improving significantly the overall performance of the compensator [20].

The STATCOM has been used widely in transmission networks to regulate the voltage by means of energetic reactive power compensation. Nowadays, the STATCOM is largely used for voltage regulation [9], whereas the UPQC and the iUPQC have been selected as solution for more specific applications [21]. Moreover, these are used only in particular cases, wherever their relatively high costs are acceptable by the power quality improvement it can offer, which would be not viable by using conventional solutions. By adding the extra functionality like a STATCOM in the iUPQC mechanism, a wider state of applications can be reached, particularly in case of DG in smart grids and as the pairing device in grid-tied

microgrids. In [16], the act of the iUPQC and the UPQC was compared when running as UPQCs.

The major difference between these compensators is the kind of source emulated by series and shunt power converters. In the UPQC approach, the shunt one as a non-sinusoidal current source and the series converter is controlled as a non-sinusoidal voltage source. Hence, in actual time, the UPQC controller has to establish and synthesize correctly the harmonic voltage and harmonic current to be compensated. Moreover, in the iUPQC approach, the series converter acts as a controlled sinusoidal current source and the shunt converter acts as a controlled sinusoidal voltage source. This means that it is not essential to find out the harmonic voltage and current to be compensated, because the harmonic voltages appear physically across the series current source and the harmonic currents flow obviously into the shunt voltage source.

In definite power converters, as the switching frequency increases, the power rate capability is decreases. Therefore, the iUPQC offers superior solutions if compared with the UPQC in case of large-power applications, since the iUPQC compensating references are clean sinusoidal waveforms at the elemental frequency. Moreover, the UPQC has high switching losses due to higher switching frequency. This manuscript proposes an improved controller, which expands the iUPQC functionalities. This enhanced version of iUPQC controller contains all functionalities of those previous converters, as well as the voltage regulation at the load-side bus, and also providing voltage regulation at the grid-side bus, like a STATCOM to the grid. Simulation results will provide to legalize the new controller design.

II. POWER QUALITY

Power quality is defined as the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment. There are many different reasons for the enormous increase in the interest in power quality. Some of the main reasons are:

- Electronic and power electronic equipment has especially become much more sensitive. Equipment has become less tolerant of voltage quality disturbances, production processes have become less

tolerant of incorrect of incorrect operation of equipment, and companies have become less tolerant of production stoppages. The main perpetrators are interruptions and voltage dips, with the emphasis in discussions and in the literature being on voltage dips and short interruptions. High frequency transients do occasionally receive attention as causes of equipment malfunction.

- Equipment produces more current disturbances than it used to do. Both low and high power equipment is more and more powered by simple power electronic converters which produce a broad spectrum of distortion. There are indications that the harmonic distortion in the power system is rising, but no conclusive results are obtained due to the lack of large scale surveys.
- The deregulation of the electricity industry has led to an increased need for quality indicators. Customers are demanding, and getting, more information on the voltage quality they can expect.
- Also energy efficient equipment is an important source of power quality disturbance. Adjustable speed drives and energy saving lamps are both important sources of waveform distortion and are also sensitive to certain type of power quality disturbances. When these power quality problems become a barrier for the large scale introduction of environmentally friendly sources and users' equipment, power quality becomes an environmental issue with much wider consequences than the currently merely economic issues.

2.2 Need for Power Quality improvement:

Presently each and every power utility system is demanding for good power quality as compared to the earlier decades of power generation, due to the following technical reasons:

1) Equipment has become less tolerant of voltage quality disturbances, production processes have become less tolerant of incorrect of incorrect operation of Equipment and companies have become less tolerant of production stoppages. Note that in many discussions only the first problem is mentioned, whereas the latter two may be at least equally important. All this leads to much higher costs than before being associated with even a very short duration disturbance. The main perpetrators are interruptions and voltage dips, with the emphasis in discussions and in the literature being on voltage dips and short interruptions. High frequency transients do occasionally receive attention as causes of equipment malfunction but are generally not well exposed in the literature.

2) Equipment produces more current disturbances than it used to do. Both low and high power equipment is more and more powered by simple power electronic converters which produce a broad spectrum of distortion. There are indications that the harmonic distortion in the power

system is rising, but no conclusive results are obtained due to the lack of large scale surveys.

3) The deregulation of the electricity industry has led to an increased need for quality indicators. Customers are demanding, and getting, more information on the voltage quality they can expect. Some issues of the interaction between deregulation and power quality are discussed.

4) Also energy efficient equipment is an important source of power quality disturbance. Adjustable speed drives and energy saving lamps are both important sources of waveform distortion and are also sensitive to certain type of power quality disturbances. When these power quality problems become a barrier for the large scale introduction of environmentally friendly sources and users' equipment, power quality becomes an environmental issue with much wider consequences than the currently merely economic issues.

2.3 Power Quality Standards:

2.3.1 Purpose of Standardization:

Standards that define the quality of the supply have been present for decades already. Almost any country has standards defining the margins in which frequency and voltage are allowed to vary. Other standards limit harmonic current and voltage distortion, voltage fluctuations, and duration of an interruption. There are three reasons for developing power quality standards.

2.3.2 The European voltage characteristics Standard:

European standard describes electricity as a product, including its shortcomings. It gives the main characteristics of the voltage at the customer's supply terminals in public low-voltage and medium-voltage networks under normal operating conditions. Some disturbances are just mentioned, for others a wide range of typical values are given, and for some disturbances actual voltage characteristics are given.

Voltage variations:

Standard EN 50160 gives limits for some variations. For each of these variations the value is given which shall not be exceeded for 95% of the time. The measurement should be performed with a certain averaging window. The length of this window is 10 minutes for most variations; thus very short time scales are not considered in the standard. The following are the limits for the low-voltage supply.

Voltage magnitude: 95% of the 10-minute averages during one week shall be within $\pm 10\%$ of the nominal voltage of 230 V.

Table representing voltage & frequency limits:

voltage magnitude variations	Shall be between 207 and 244 volts
Voltage unbalance	Should be up to 2%
Voltage fluctuations	Should not exceed flicker level
Frequency	Should be in between 49.5 and 50.5 Hertz

2.4 Power quality Terminology:

DSTATCOM means Distribution Static Compensator. STATCOM is a static VAR generator, whose output is varied so as to maintain or control specific parameters of the electric power system.

SAG is a decrease in rms voltage or currents to between 0.1 to 0.9 p.u at the power frequency for duration of time from 0.5 cycles to 1 minute.

Balanced Sag is an equal drop in the rms value of voltage in the three-phases of a three-phase system or at the terminals of three-phase equipment for duration up to a few minutes.

Voltage dip is sudden reduction in the supply voltage by a value of more than 10% of the reference value, followed by a voltage recovery after a short period of time.

Unbalanced Fault is a short circuit or open circuit fault in which not all three phases are equally involved.

Voltage Tolerance it is the immunity of a piece of equipment against voltage magnitude variations (Sags, Swells and Interruptions) and short duration over voltages.

Duration (of Voltage Sag) it is the time during which the voltage deviates significantly from the ideal voltage.

Critical Distance is the distance at which a short-circuit fault will lead to a voltage sag of a given magnitude for a given load position.

Current Disturbance it is a variation of event during which the current in the system or at the equipment terminals deviates from the ideal sine wave.

Voltage Disturbance it is a variation of event during which the voltage in the system or at the equipment terminals deviates from the ideal sine wave.

Power Quality it is the study or description of both voltage and current disturbances. Power quality can be seen as the combination of voltage quality and current quality.

Interruption is the voltage event in which the voltage is zero during a certain time. The time during which the voltage is zero is referred to as the "duration" of the interruption. (OR) A voltage magnitude event with a magnitude is less than 10% of the nominal voltage.

Over Voltage is an abnormal voltage higher than the normal service voltage, such as might be caused from switching and lightning surges. (OR) Abnormal voltage between two points of a system that is greater than the highest value appearing between the same two points under normal service conditions.

Under Voltage is a voltage event in which the rms voltage is outside its normal operating margin for a certain period of time. (OR) A voltage magnitude event with a magnitude less than the nominal rms voltage, and a duration exceeding 1 minute.

Swell it is a momentary increase in the rms voltage or current to between 1.1 and 1.8pu delivered by the mains, outside of the normal tolerance, with a duration of more than one cycle and less than few seconds.

Recovery Time is the time interval needed for the voltage or current to return to its normal operating value, after a voltage or current event.

Fault is an event occurs on the power system and it effects the normal operation of the power system.

Voltage Fluctuation is a special type of voltage variation in which the voltage shows changes in the magnitude and/or phase angle on a time scale of seconds or less. Severe voltage fluctuations lead to light flicker.

Voltage Source Converters (VSC):

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual.

2.5 About power Quality Disturbances:

2.5.1 Voltage sags:

Major Causes: Faults, Starting of large loads, and brown-out recovery.

Major Consequences: Short circuits accelerated aging, loss of data or stability, Process interrupts, etc.

2.5.2 Capacitor Switching Transients:

Major Causes: A power factor correction method

Major Consequences: Insulation breakdown or spark over, semi conductor device damage, shorts, accelerated aging, loss of data or stability.

2.5.3 Harmonics:

Major Causes: Power electronic equipment, arcing, transformer saturation.

Major Consequences: Equipment Over heating, high voltage/current, Protective device operations.

2.5.4 Lightning Transients:

Major Causes: Lightning strikes

Major Consequences: Insulation breakdown or spark over, semi conductor device damage, shorts, accelerated aging, loss of data or stability.

2.5.5 High Impedance faults:

Major Causes: Fallen conductors, trees (fail to establish a permanent return path)

Major Consequences: Fire, threats to personal safety.

UPQC (UNIFIED POWER QUALITY CONDITIONER)

A Unified Power Quality Conditioner (UPQC) is a device that is similar in construction to a Unified Power Flow Conditioner (UPFC). The UPQC, just as in a UPFC, employs two voltage source inverters (VSIs) that are connected to a D.C. energy storage capacitor. One of these two VSIs is connected in series with the A.C. line while the other is connected in shunt with the A.C. system.

A UPQC that combines the operations of a Distribution Static Compensator (DSTATCOM) and Dynamic Voltage Regulator (DVR) together.

One of the serious problems in electrical systems is the increasing number of electronic components of devices that are used by industry as well as residences. These devices, which need high-quality energy to work properly, at the same time, are the most responsible ones for injections of harmonics in the distribution system. Therefore, devices that soften this drawback have been developed. One of them is the **unified power quality conditioner (UPQC)**. It consists of a shunt active filter together with a series-active filter.

This combination allows a simultaneous compensation of the load currents and the supply voltages, so that compensated current drawn from the network and the compensated supply voltage delivered to the load are

sinusoidal, balanced and minimized. The series- and shunt-active filters are connected in a back-to-back configuration, in which the shunt converter is responsible for regulating the common DC-link voltage.

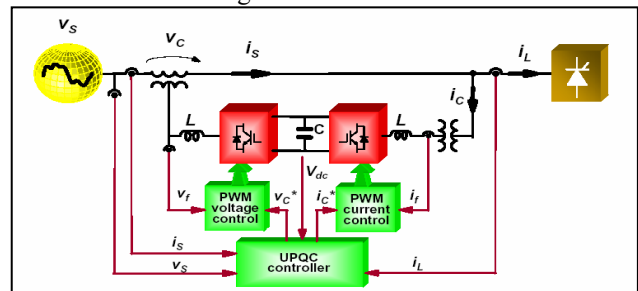


Fig General Configuration of the Unified Power Quality Conditioner — UPQC

A UPQC is employed in a power transmission system to perform shunt and series compensation at the same time. A power distribution system may contain unbalance, distortion and even D.C. components. Therefore a UPQC operates better than a UPFC, with all these aspects in order to provide shunt or series compensation.

The UPQC is a relatively new device and not much work has yet been reported on it. Sometimes it has been viewed as a combination of series and shunt active filters.

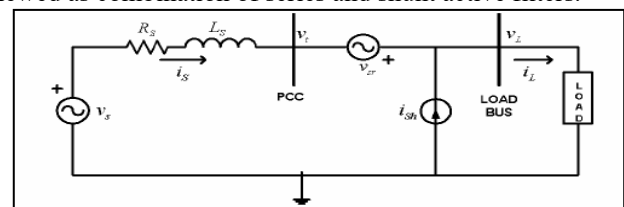
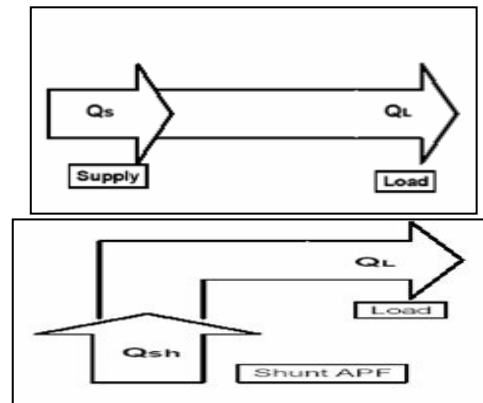


Fig Equivalent Circuit for a UPQC

CASE I:



a) No UPQC

b) With Shunt APF

3.1 Reactive Power Flow

The reactive power flow during the normal working condition when UPQC is not connected in the circuit is shown in the Fig.(a). In this condition the reactive power required by the load is completely supplied by the source only. When the UPQC is connected in the network and the shunt APF is put into the operation, the reactive power required by the load is now provided by the shunt APF alone; such that no reactive power burden is put on the mains.

So as long as the shunt APF is ON, it is handling all the reactive power even during voltage sag, voltage swell and current harmonic compensation condition. The series APF is not taking any active part in supplying the load reactive power. The reactive power flow during the entire operation of UPQC is shown in the Fig. (b). In this case no active power transfer takes place via UPQC, termed as **Zero Active Power Consumption Mode**.

CASE II:

Ps'= Power Supplied by the source to the load during voltage sag condition

Psr'= Power Injected by Series APF in such way that sum Psr'+Ps' will be the required load power during normal working condition i.e. PL

Psh'= Power absorbed by shunt APF during voltage sag condition

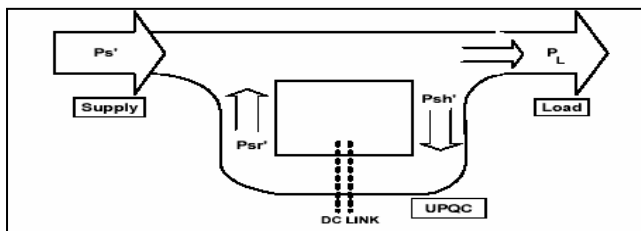
$$P_{sr}' = P_{sh}'$$


Fig Active Power Flow during Voltage Sag Condition

If $k < 0$, i.e. $V_f < V_L$, then PS_r will be positive, means series APF supplies the active power to the load. This condition is possible during the utility voltage sag condition. i_s will be more than the normal rated current. Thus we can say that the required active power is taken from the utility itself by taking more current so as to maintain the power balance in the network and to keep the dc link voltage at desired level. This active power flows from the source to shunt APF, from shunt APF to series APF via dc link and finally from series APF to the load. Thus the load would get the desired power even during voltage sag condition.

Therefore in such cases the active power absorbed by shunt APF from the source is equal to the active power supplied by the series APF to the load. Since series APF supplies active power, termed as **Active Power Delivering Mode**. The overall active power flow is shown in the Fig.

CASE III:

Ps"= Power Supplied by the source to the load during voltage swell condition

Ps^r = Power Injected by Series APF in such way that sum Ps^r-Ps^r will be the required load power during normal working condition

P_{sh}= Power delivered by shunt APF during voltage sag condition

Psr''=Psh''

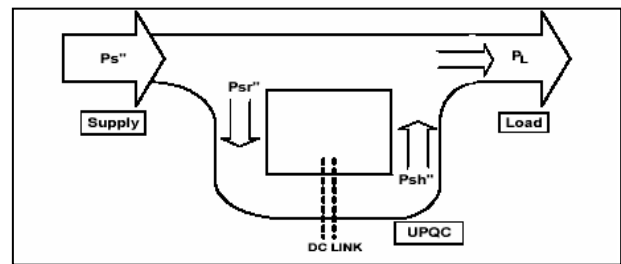


Fig Active Power Flow during Voltage Swell

If $k > 0$, i.e. $V_t > V_L$, then PSr will be negative, this means series APF is absorbing the extra real power from the source. This is possible during the voltage swell condition. Again i_s will be less than the normal rated current. Since V_s is increased, the dc link voltage can increase. To maintain the dc link voltage at constant level the shunt APF controller reduces the current drawn from the supply. In other words we can say that the UPQC feeds back the extra power to the supply system. Since series APF absorbs active power, termed as **Active Power Absorption Mode**. The overall active power flow is shown in the Fig. .

CASE IV:

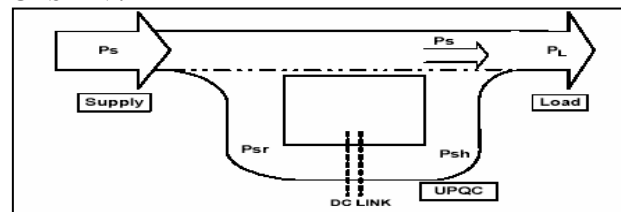


Fig Active Power Flow during Normal Working Condition

If $k = 0$, i.e. $V_1 = V_L$, then there will not be any real power exchange though UPQC. This is the normal operating condition. The overall active power flow is shown in the Fig.

CASE V:

If the terminal voltage is distorted one containing several harmonics, in such cases the series APF injects voltage equal to the sum of the harmonics voltage at PCC but in opposite direction. Thus the sum of voltage injected by series APF and distorted voltage at PCC will get cancelled out. During this voltage harmonic compensation mode of operation the series APF does not consume any real power from sources since it injects only harmonics voltage. Here **UPOC works in zero active power consumption mode.**

CASE VI:

If the load is a non linear one producing harmonics, in such cases the shunt APF injects current equals to the sum of harmonics current but in opposite direction, thus cancelling out any current harmonics generated by non linear load. During this current harmonics compensation mode of operation them shunt APF does not consume any real power from the source since it injected only harmonics currents. Here **UPOC** works in **zero active power consumption mode**.

The phasor representations of the above discussed conditions are shown in the Fig.1(a)–(d) and Fig.2(a)–(d) for inductive and capacitive type of load respectively. Phasor 1 (a) represents the normal working condition, considering load voltage V_L as a reference phasor. L is lagging power factor

angle of the load. During this condition i_s will be exactly equal to the i_L since no compensation is provided. When shunt APF is put into the operation, it supplies the required load vars by injecting a 900 leading current such that the source current will be in phase with the terminal voltage. The phasor representing this capacitive effect is shown in Fig. 1(b). The phasor representations during voltage sag and voltage swell condition on the system are shown in the Fig.1(c) and Fig.1(d) respectively. The deviation of shunt compensating current phasor from quadrature relationship with load voltage suggests that there is some active power flow through the shunt APF during these conditions

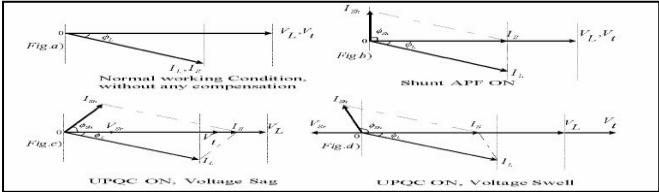


Fig. 1 a) – d) Phasor Representation: Inductive Load

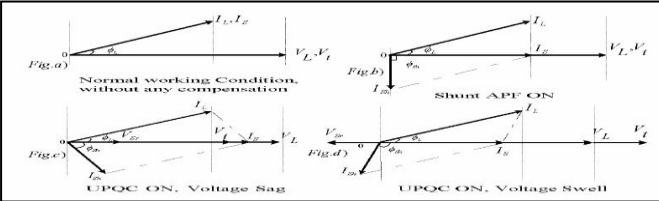


Fig. 2 a) – d) Phasor Representation: Capacitive Load

Phasor in Fig. 2 (a) represents the normal working condition, considering leading power factor angle of the load. During this condition i_s will be exactly equal to the i_L . When shunt APF is put into the operation, it cancels out the vars generated by load by injecting a 900 lagging current such that the source current will be in phase with the terminal voltage. The phasor representing this inductive effect is shown in Fig. 2 (b). The phasor representations during voltage sag and voltage swell condition on the system are shown in the Fig. 2 (c) and Fig. 2 (d) respectively.

Fig. 3 shows variation of angle ϕ_{sh} during different modes of operations of UPQC, represented by zones. Figure consists of seven zones of operations. The x axis represents the reference load voltage whereas the shunt APF compensating current can vary from 00 to 3600. Zone I, II and III represents the case of pure resistive, inductive and capacitive load respectively. If the load is pure resistive, shunt APF does not inject any compensating current since there is no reactive power demand from the load, this condition is represented by zone I. Considering the case of inductive load, the load var requirement is supplied by shunt APF by injecting 900 leading current. The magnitude of the compensating current would depend on the vars to be compensated. This condition is represented by zone II. Now, if the load is capacitive one, theoretically, the load would draw leading current from the source, i.e. load generates vars. This load generated vars are compensated by shunt APF by injecting 900 lagging current. The magnitude of compensating current depends on the vars to be cancelled out, represented by zone III. During the operation of UPQC in zone II and III larger the

var compensation more would be the compensating current magnitude.

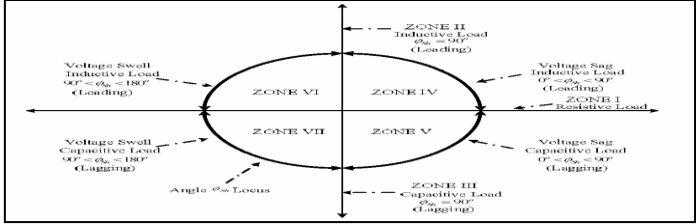


Fig. 3. Variation of angle during different modes of operations of UPQC

Zone IV and zone V represents the operating region of UPQC during the voltage sag on the system for inductive and capacitive type of the loads respectively. During the voltage sag as discussed previously, shunt APF draws the required active power from the source by taking extra current from the source. In order to have real power exchange between source, UPQC and load, the angle ϕ_{sh} should not be 900. For inductive type of the load, this angle could be anything between 00 to 900 leading and for capacitive type of the load, between 00 to 900 lagging. This angle variation mainly depends on the % of sag need to be compensated and load var requirement. Zone VI and zone VII represents the operating region of UPQC during the voltage swell on the system for inductive and capacitive type of the loads respectively. During the voltage swell as discussed previously, shunt APF feeds back the extra active power from the source by taking reduced current from the source. In order to achieve this angle ϕ_{sh} would be between 900 to 1800 leading and between 900 to 1800 lagging for inductive and capacitive type of load respectively.

3.2 UPQC IN DOUBLE FEEDER DISTRIBUTION SYSTEM

A new connection proposal for UPQC, as shown in Figure 6, to improve the power quality of two feeders in a distribution system which is termed Interline UPQC (IUPQC). The purpose of the IUPQC is to hold the feeder voltages constant against voltage sag/swell and temporary interruption in either of the two feeders. It has been demonstrated that the IUPQC can absorb power from one feeder to hold the other feeder voltage constant in case of a voltage sag in the other source voltage. This UPQC can also be implemented in a Custom Power Park or Microgrid system. This can further be improved as a multi-converter based UPQC where multiple VSI are connected back to back on the dc side.

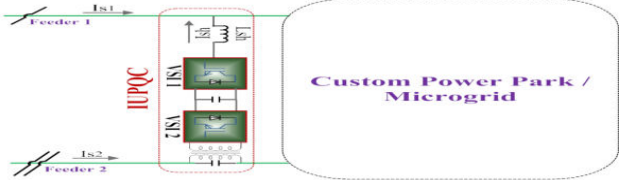


Fig 6 – (a) Typical IUPQC connected in a distribution system

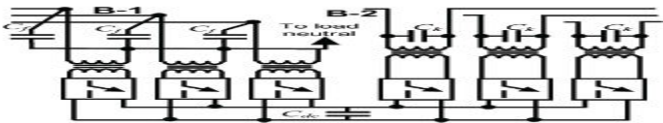


Fig 6 – (b) Internal Structure of IUPQC

Advantages:-

- We have analyzed the operation of a **UPQC** that combines the operations of a Distribution Static Compensator (**DSTATCOM**) and Dynamic Voltage Restorer (**DVR**) together.
- The series component of the **UPQC** inserts voltage so as to maintain the voltage at the Point of Common Coupling (PCC) balanced and free of distortion.
- Simultaneously, the shunt component of the **UPQC** injects current in the a.c. system such that the currents entering the bus to which the **UPQC** is connected are balanced sinusoids.
- Both these objectives must be met irrespective of unbalance or distortion in either source or load sides.

PROPOSED SYSTEM CONFIGURATION

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 microgrid. Bus B is a bus of the microgrid, where nonlinear loads are connected, which requires premium-quality power supply. The voltages at buses A and B must be regulated, in order to properly supply the sensitive loads and the nonlinear loads. The effects caused by the harmonic currents drawn by the nonlinear loads should be mitigated, avoiding harmonic voltage propagation to bus A.

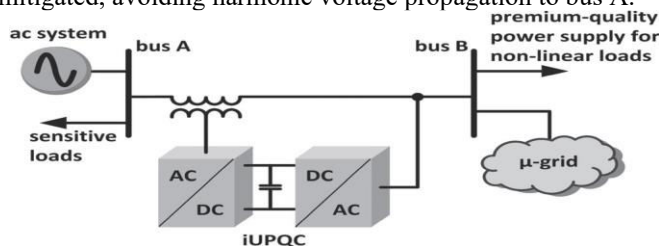


Fig. 1 Example of applicability of iUPQC

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, a UPQC or an iUPQC between bus A and bus B can compensate the harmonic currents of the nonlinear loads and compensate the voltage at bus B, in terms of voltage harmonics, unbalance, and sag/swell. Nevertheless, this is still not enough to guarantee the voltage regulation at bus A. Hence, to achieve all the desired goals, a STATCOM at bus A and a UPQC (or an iUPQC) between buses A and B should be employed. However, the costs of this solution would be unreasonably high.

An attractive solution would be the use of a modified iUPQC controller to provide also reactive power support to bus A, in addition to all those functionalities of this equipment, as presented in [16] and [18]. Note that the modified iUPQC serves as an intertie between buses A and B. Moreover, the microgrid connected to the bus B could be a complex system comprising distributed generation, energy management system, and other control systems involving microgrid, as well as

smart grid concepts [22]. 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.

The functionalities (d)–(f) previously listed were extensively explained and verified through simulations and experimental analysis [14]–[18], 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.

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.

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 necessary to provide an energy source (or large energy storage) associated to the dc link of the iUPQC.

The last degree of freedom is represented by a reactive-power control variable 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 controller without degrading all other functionalities of the iUPQC.

4.1 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. 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 in [18], or be improved further to better deal with voltage and current imbalance and harmonics [23]–[28]. 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, as verified in [29]–[33].

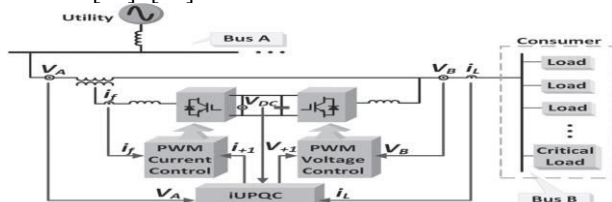


Fig. 2 Modified iUPQC configuration

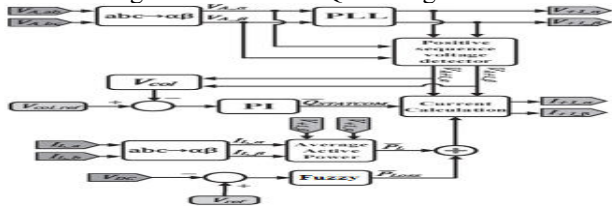


Fig. 3 Novel iUPQC controller with fuzzy system

In the original iUPQC approach as presented in [14], 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 P_{Loss} . The load active power can be estimated by

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

where iL_a , iL_b are the load currents, and $V+1_a$, $V+1_b$ 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 iUPOC are calculated

indirectly from the measurement of the dc-link voltage. In other words, the power signal P_{Loss} is determined by a fuzzy logic (FLC) controller (fuzzy block in Fig. 3), by comparing the measured dc voltage V_{DC} with its reference value. The additional control loop to provide voltage regulation like a STATCOM at the grid bus is represented by the control signal $Q_{STATCOM}$ in Fig. 3. This control signal is obtained through a PI controller, in which the input variable is the error between the reference value and the actual aggregate voltage of the grid bus, given by

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

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

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

B. Power Flow in Steady State

The following procedure, based on the average power flow, is useful for estimating the power ratings of the iUPQC converters. For combined series–shunt power conditioners, such as the UPQC and the iUPQC, only the voltage sag/swell disturbance and the power factor (PF) compensation of the load produce a circulating average power through the power conditioners [34], [35]. According to Fig. 4, the compensation of a voltage sag/swell disturbance at bus B causes a positive sequence voltage at the coupling transformer ($V_{\text{series}} = 0$), since $V_A = V_B$.

Moreover, V_{series} and i_{PB} in the coupling transformer leads to a circulating active power 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.

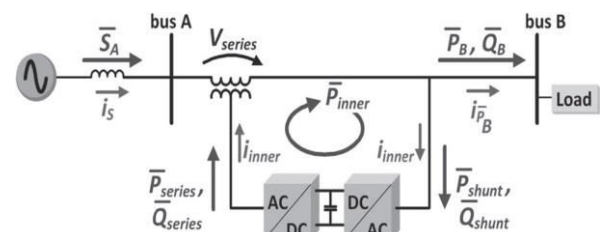


Fig. 4 iUPQC power flow in steady-state

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

Equations (5) and (8) are derived from the constraint of keeping unitary the PF at bus A. In this case, the current passing through the series converter is responsible only for supplying the load active power, that is, it is in phase (or counter phase) with the voltages V_A and V_B . Thus, (7) can be stated. Consequently, the coherence of the power flow is ensured through (8).

If a voltage sag or swell occurs, $\bar{P}_{series}$ and $\bar{P}_{shunt}$ will not be zero, and thus, an inner-loop current (i_{inner}) will appear. The series and shunt converters and the aforementioned circulating active power (P_{inner}) flow inside the equipment. It is convenient to define the following sag/swell factor. Considering V_N as the nominal voltage

$$k_{sag/swell} = \frac{|V_A|}{|V_N|} = \frac{V_A}{V_N} \quad (9)$$

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

$$\sqrt{3} \cdot k_{sag/swell} \cdot V_N \cdot i_S = \sqrt{3} \cdot V_N \cdot i_{PB} \quad (10)$$

$$i_S = \frac{i_{PB}}{k_{sag/swell}} = i_{PB} + i_{inner} \quad (11)$$

The circulating power is given by

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

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

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

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

Thus, (14) demonstrates that P_{inner} depends on the active power of the load and the sag/swell voltage disturbance. In order to verify the effect on the power rate of the series and shunt converters, a full load system $\bar{S}_B = \bar{P}_B + j\bar{Q}_B = 1 \text{ p.u.}$ with PF ranging from 0 to 1 was considered. It was also considered the sag/swell voltage disturbance at bus A ranging $k_{sag/swell}$ from 0.5 to 1.5. In this way, the power rating of the series and shunt converters are obtained through (6)–(8) and (14).

Fig. 5 depicts the apparent power of the series and shunt power converters. In these figures, the $k_{sag/swell}$ -axis and the PF-axis are used to evaluate the power flow in the series and shunt power converters according to the sag/swell

voltage disturbance and the load power consumption, respectively.

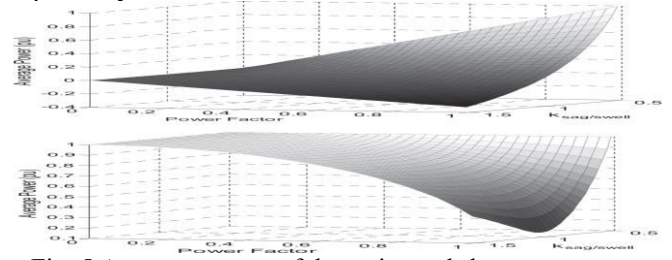


Fig. 5 Apparent power of the series and shunt converters, respectively

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. Moreover, in case of compensating sag/swell voltage disturbance with high reactive power load consumption, only the shunt converter has high power demand, since P_{inner} decreases. It is important to highlight that, for each PF value, the amplitude of the apparent power is the same for capacitive or inductive loads. In other words, Fig. 5 is the same for $\bar{Q}_B$ capacitive or inductive.

If the iUPQC performs all original UPQC functionalities together with the STATCOM functionality, the voltage at bus A is also regulated with the same phase and magnitude, that is, $V_A = V_B = V_N$, 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

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

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

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

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

where $\bar{Q}_{STATCOM}$ 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. Consequently, if the series converter is properly designed along with the coupling transformer to synthesize the controlled currents $I_{+1\alpha}$ and $I_{+1\beta}$, 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.

3.3. Fuzzy Logic Control

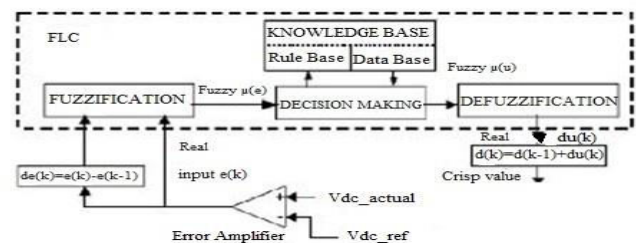


Fig 5 Block diagram of the Fuzzy Logic Controller (FLC) for proposed converter

L. A. Zadeh displayed the first paper on fuzzy set hypothesis in 1965. From that point forward, another dialect was produced to depict the fuzzy properties of reality, which are extremely troublesome and at some point even difficult to be portrayed utilizing traditional techniques. Fuzzy set hypothesis has been broadly utilized as a part of the control territory with some application to power framework [16]. A basic fuzzy logic control is developed by a gathering of tenets in view of the human information of framework conduct. Matlab/Simulink recreation model is constructed to examine the dynamic conduct of converter. Moreover, plan of fuzzy logic controller can give attractive both little flag and substantial sign element execution at same time, which is impractical with direct control method. In this way, fuzzy logic controller has been potential capacity to enhance the heartiness of compensator.

The fundamental plan of a fuzzy logic controller is appeared in Fig 5 and comprises of four central parts, for example, a fuzzy fiction interface, which changes over info information into suitable etymological qualities; a learning base, which comprises of an information base with the important semantic definitions and the control guideline set; a choice making logic which, reenacting a human choice procedure, deduce the fuzzy control activity from the learning of the control rules and phonetic variable definitions; a de fuzzification interface which yields non fuzzy control activity from a construed fuzzy control Standard Base: the components of this principle base table are resolved taking into account the hypothesis that in the transient state, extensive blunders need coarse control, which requires coarse in-put/yield variables; in the enduring state, little mistakes require fine control, which requires fine data/yield variables. Taking into account this the components of the standard table are gotten as appeared in Table 1, with "Vdc" and "Vdc-ref" as inputs.

Table 1: Fuzzy rules

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

SIMULATION RESULTS

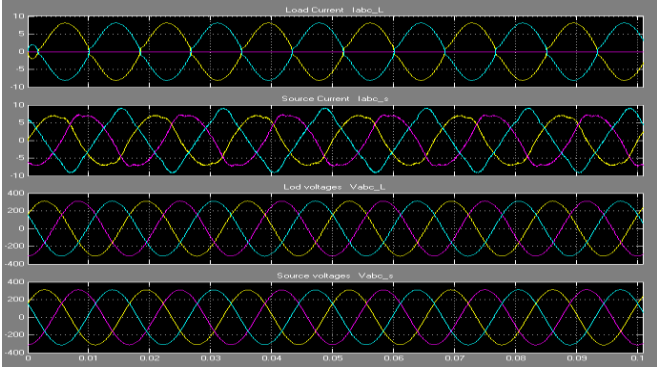
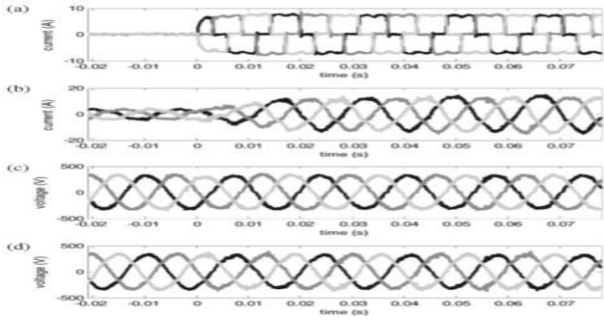


Fig. 6. iUPQC transitory response during the connection of a three-phase diode rectifier: (a) load currents, (b) grid currents, (c) load voltages and (d) grid voltages.

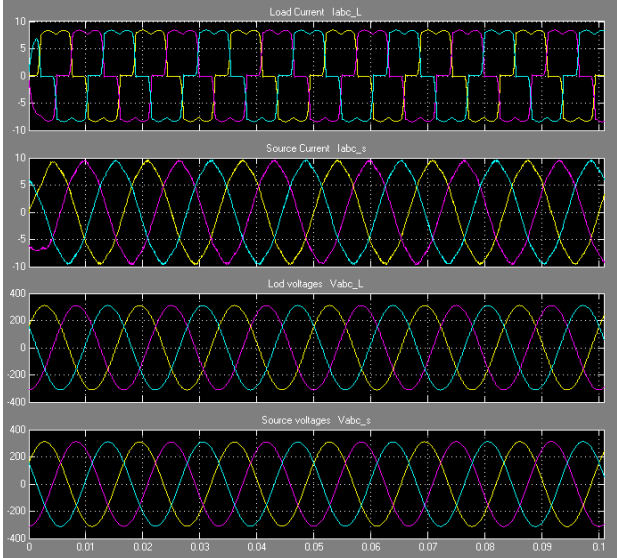
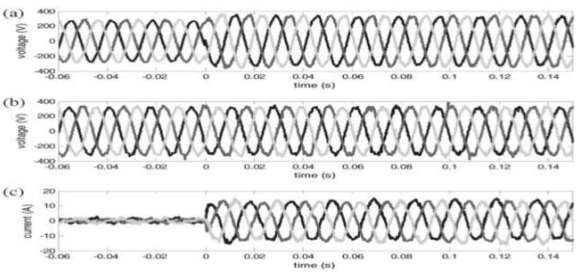
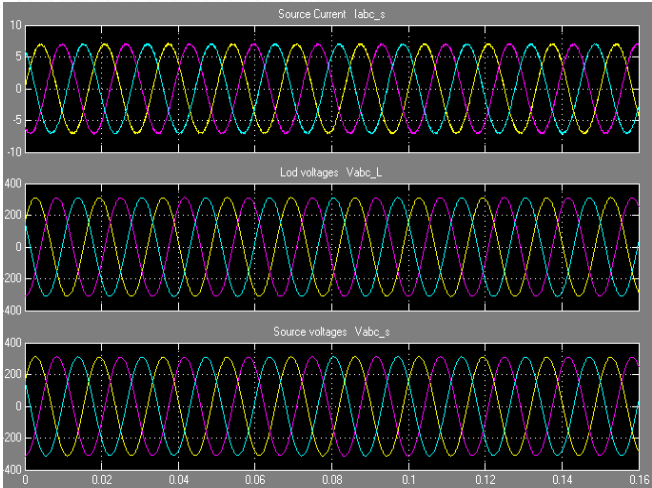


Fig. 7. iUPQC response at no load condition: (a) grid voltages V_A , (b) load voltages V_B , and (c) grid currents.



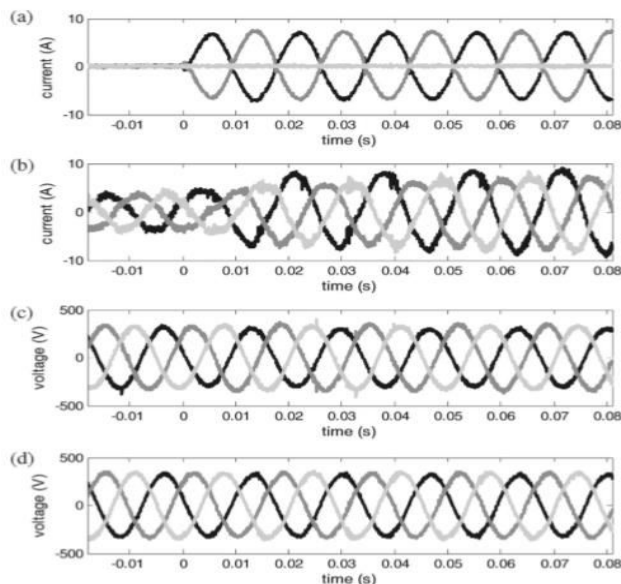


Fig. 9. iUPQC transitory response during the connection of a two-phase diode rectifier: (a) load currents, (b) source currents, (c) load voltages, and (d) source voltages.

CONCLUSION

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. 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.

This new feature enhances the applicability of the iUPQC and provides new solutions in future scenarios involving smart grids and micro grids. 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.

The grid-voltage regulation was achieved with no load, as well as when supplying a three-phase and two-phase nonlinear load. Simulation results and comparison table of % THD have verified a suitable performance of voltage regulation at both sides of the iUPQC, and Fuzzy logic controller is better than PI in compensating harmonic current and voltage imbalances.

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