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Voltage and Current Harmonic Mitigation using Fuzzy logic Controller Based UPQC for Power Quality Improvement

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Abstract

The UPQC is being used as a universal active power conditioning device to mitigate both current and voltage harmonics at a distribution side of power system network. The performance of UPQC mainly depends upon how quickly and accurately compensation signals are derived by using control schemes. In this work to enhance the power quality, UPQC with FLC and PI Controller are used. The proposed FLC is capable of providing good static and dynamic performances compared to the PI Controller. The static and dynamic performances of the current source inverter based UPQC with proposed control schemes are tested at different load current and utility voltages conditions. The Unified Power Quality Conditioner is simulated through synchronous reference frame theory. The proposed system is comprised of series and shunt Inverters which can compensate the sag, swell, and unbalance voltage, harmonics and reactive power. PI Controller and Fuzzy Logic Controller are used to stabilize DC Link voltage and balance the active power between shunt and series inverters for the enhancement of power quality.

Keywords: *UPQC, synchronous refrence frame, PI controller, Fuzzy logic controller.*

1. Introduction

The Unified Power Quality Conditioner is a custom power device that incorporates the series and shunt active filters, connected back-to-back on the dc side and allotment a common DC capacitor, it utilizes two voltage source inverters (VSIs) that are connected to a common DC energy storage capacitor. One of these two VSIs is coupled in series with the feeder and the other one is connected in parallel to the same feeder. The series element of the UPQC is accountable for mitigation of the supply side disturbances such as voltage sags/swells, flicker, voltage unbalance and harmonics. It inserts voltages so as to maintain the load voltages at a desired level balanced and distortions free. The simulation part analyzes the dynamic and steady-state performance of UPQC with two typical case studies.

In case one CSI based UPQC using PI Controller and Fuzzy Logic Controller and in case two UPQC by synchronous reference frame theory with PI Controller and Fuzzy Logic Controller have been simulated and the results of voltage and current waveforms are analyzed and presented in this chapter.

The Unified Power Quality Conditioner is a combination of series and parallel active power filters connected back-to-back to a common dc energy storage capacitor, as mentioned earlier. One form of UPQC configuration, which is used in three-phase three wire systems, is shown in Figure 1.

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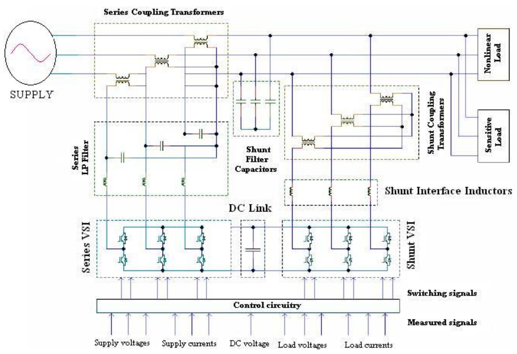

Figure: 1 Detailed Power circuit structure for a Three-Phase UPQC.

For power factor improvement and compensation of load current harmonics and unbalances the shunt active filter is accountable. Also, the DC storage capacitor maintains constant average voltage across it.

The shunt part of the UPQC consists of a VSI connected to the common DC storage capacitor on the dc side and on the ac side it is connected in parallel with the load through the shunt interface inductor and shunt coupling transformer. The shunt interface inductor and shunt filter capacitor are used to filter out the switching frequency harmonics produced by the shunt VSI [8]. To match the network and VSI voltages the shunt coupling transformer is used.

Principle of Operation

In order to recognize its compensation objectives, reactive and harmonic components of the load currents are cancelled and the load current unbalance is eliminated due to shunt active filter injects currents at the point of common coupling, This current injection is offered by the dc storage capacitor and the shunt VSI. The control system generates the appropriate switching signals for the shunt VSI switches based on measured currents and voltages. The specific currents and voltages to be measured depend on the applied control method. The shunt VSI is controlled in current control mode. The suitable VSI switches are turned on and off at definite time instances such that the currents injected by the shunt active filter track some reference currents within a fixed hysteresis band (assuming a hysteresis controller is used) according to the compensation points. The VSI switches alternately join the dc capacitor to the system, either in the positive or negative sense. When the dc capacitor voltage is connected in the positive sense, it is added to the supply voltage and the VSI current is increasing.

In the case of the dc capacitor connected in the negative sense, its voltage is in opposition to the supply voltage and the VSI current is decreasing. Hence alternately increasing and decreasing the current within the hysteresis band, the reference current is tracked. This control procedure is called "hysteresis3].Thedc sideband co capacitor assists two main purposes, it maintains the dc voltage with a small ripple in the steady state and it assists as an energy storage element to supply the real power during the transient period. The average voltage across the dc capacitor is maintained constant and in order that the shunt active filter can draw a leading current, this voltage has to be higher then the peak of the supply voltage. This is achieved through an suitable PI control, by regulating the quantity of active current drawn by the shunt active filter from the system.

The series active filter is accountable for voltage compensation during supply side disturbances, such as voltage sag/swell, flicker and unbalance. The series part of the UPQC also consists of a VSI connected on the dc side to the same energy storage capacitor and on the ac side it is connected in series with the line, through the series low pass filter (LPF) and coupling transformers [63]. The series LPF prevents the switching frequency harmonics produced by the series

VSI entering the system. The series coupling transformers offer voltage matching and isolation between the network and the VSI. The series active filter compensation objectives are achieved by injecting voltages in series with the supply voltages such that the load voltages are balanced and undistorted. Their magnitudes are maintained at the desired level. This voltage injection is supplied by the dc storage capacitor and the series VSI. Based on measured supply and/or load voltages the control system generates the suitable

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switching pulses for the series VSI switches. The series VSI is controlled in voltage-control mode using the well-known pulse-width-modulated (PWM) switching technique described in detail.

In order to construct the injected voltage of desired magnitude, waveform, phase shift and frequency, the desired signal is calculated with a triangular waveform signal of higher frequency and suitable switching signals are generated. The dc capacitor is alternately connected to the inverter outputs with positive and negative polarity. The output voltages of the series VSI do not have the shape of the desired signals, but contain switching harmonics, which are filtered out by the series low pass filter. The amplitude, phase shift, frequency and harmonic content of injected voltages are controllable.

Control Strategies

Control of the Shunt Active Filter

The success of an active power filter depends basically on the design characteristics of the current controller, the technique implemented to produce the reference model and the modulation procedure used. The control process of a shunt active power filter must estimate the current reference waveform for each phase of the inverter, preserve the dc voltage constant, and produce the inverter gating signals. Also the compensation effectiveness of an active power filter depends on its aptitude to follow the reference signal calculated to compensate the distorted load current with a minimum error and time delay.

The shunt component of UPQC can be controlled in two ways:

Tracking the Shunt Converter Reference Current

The load current is sensed and the shunt compensator reference current is calculated from it. The reference current is determined by calculating the active fundamental component of the load current and subtracting it from the load current. This control technique involves both the shunt active filter and load current measurements.

Tracking the Supply Current

In this case the shunt active filter guarantees that the supply reference current is tracked. Thus, the supply reference current is analyzed rather than the current injected by the shunt active filter.

The supply current is often required to be sinusoidal and in phase with the supply voltage. Since the waveform and phase of the supply current is known, only its amplitude needs to be determined. Also, when used with a hysteresis current controller, this control technique involves only the supply current measurement.

Average DC Voltage Regulation

This method is used for supply reference current determination and it is based on the fact that the magnitude of the supply current depends on power balance between the supply and the load. The dc capacitor serves as energy storage element. If the shunt active filter losses are neglected, in steady-state, the power supplied by the system has to be equal to the real power demand of the load and no real power flows into the dc capacitor.

The average dc capacitor voltage is thus maintained at reference voltage level. If a power unbalance caused by a load change occurs, the dc capacitor must supply the power difference between the supply and load that will result in reducing the dc capacitor voltage. To reestablish the average dc capacitor voltage to the reference level some active power has to be supplied to the dc capacitor, so the magnitude of the supply current has to be increased.

When the average dc capacitor voltage increases, the magnitude of the supply current has to be decreased. So, by controlling the average voltage across the dc capacitor the amplitude of the supply current is spontaneously controlled. Applying this concept, the control circuit can by simplify and the number of current sensors reduced. Therefore, this control technique has been chosen to be used in the UPQC simulation model (presented in section 6.4). This method is discussed in detail in [48, 49]. The dc voltage

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regulation is achieved by using a PI Controller and Fuzzy Logic Controller. Fuzzy Logic Controller gives fast response than PI Controller. The capacitor voltage is compared with some reference value and a PI Controller processes the voltage error then this error and change of error are inputs of Fuzzy Logic Controller.

Control of the DC Bus

For a voltage source inverter the dc voltage needs to be preserved at a certain level to make sure the dc-ac power transfer. For a current source inverter the dc current needs to be preserved at a certain level to make sure the dc-ac power transfer. Because of the switching and other power losses inside UPQC, the voltage level of the dc capacitor will be reduced if it is not compensated. Thus, the DC Link voltage control unit is intended to keep the average dc bus voltage constant and equal to a given reference value. The DC Link voltage control is achieved by adjusting the small amount of real power absorbed by the shunt inverter. This small amount of real power is regulated by changing the amplitude of the fundamental component of the reference current. The ac source offers some active current to recharge the dc capacitor.

Thus, in addition to reactive and harmonic components, the reference current of the shunt active filter has to have some amount of active current as compensating current. This active compensating current flowing through the shunt active filter regulates the dc capacitor voltage. The DC Link inductor functions as dc power supply sources and hence does not demand any external power source.

However, in order to maintain constant dc current in the energy storage element, a small fundamental current is drawn to compensate active filter losses.

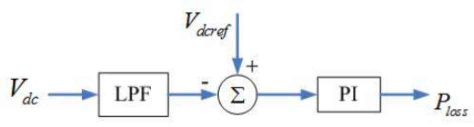

Figure 2: Block diagram of DC Link Voltage PI Controller

Usually a PI Controller is used for determining the magnitude of this compensating current from the error between the average voltage across the dc capacitor and the reference voltage. A practical approach (Ziegler-Nichols tuning rules) for tuning the PI Controller is proposed. The PI Controller has a simple structure and fast response.

As an alternative to PI Controller, a simple linear control technique is proposed with application to a single-phase shunt active filter. This is a proportional gain type control and the proportional coefficient is calculated instantaneously as a function of the dc capacitor average voltage error.

Here, the expression used for calculation of the proportional coefficient is obtained through integration of a fist-order differential equation. However, the formula derivation for the proportional coefficient is not that simple for a three-phase UPQC; if possible at all (a high-order differential equation has to be integrated analytically).

Also, a residual steady-state error occurs with a proportional only controller.

The general structure of a complete fuzzy control system is given in Figure 3. The plant Du' control is inferred'from the variables, error (i) and change). in error (Δ

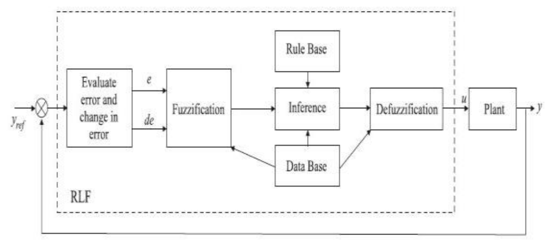

Figure3: Basic structure of fuzzy control system

The actual crisp input are approximates to the closer values of the respective universes of is course. Hence, the fuzzyfied inputs are described by singleton fuzzy sets. The elaboration of this controller is based on the phase plan. Here NB is negative big, NM is negative medium, ZR is zero, PM is positive medium and PB is positive big, are labels of fuzzy sets

Table: 1 Rules Base for current control

Du		Δi				
		NB	NM	ZR	PM	PB
i	NB	NB	NB	NM	NM	ZR
	NM	NB	NM	NM	ZR	PM
	ZR	NM	NM	ZR	PM	PM
	PM	NM	ZR	PM	PM	GP
	PB	ZR	PM	PM	GP	GP

Table 6.1 shows one of possible control rule base. The rows represent the rate of the error change e and the columns represent the error i. Each pair (i, Δi) determines the output level NB to PB corresponding to u.

The continuity of input membership functions, reasoning method, and defuzzification method for the continuity of the mapping ufuzzy(i, Δi) is necessary. The triangular membership function, the max-min reasoning method, and the center of gravity defuzzification method are used.

In [98], instead of the PI Controller, Fuzzy Logic Controller is proposed for processing the dc capacitor average voltage error. The Fuzzy Logic Controller has advantages over the PI Controller. It does not require an accurate mathematical model can work with imprecise inputs, it can handle non-linear functions and it is more robust. As per the simulation results presented in following sections show that the Fuzzy Logic Controller have a better dynamic behavior than the PI Controller.

Control of the Series Active Filter

The series component of UPQC is controlled to insert the proper voltage between the point of common coupling and load, such that the load voltages become balanced, distortion free and have the desired magnitude. Theoretically the injected voltages can be of any arbitrary magnitude and angle. However, the power flow and device rating are significant issues that have to be considered when determining the magnitude and the angle of the injected voltage.

While the shunt compensator VA rating is reduced as the active power consumption of the series compensator is minimized and it also compensates for a part of the load reactive power demand. Also the shunt compensator must provide the active power injected by the series compensator. Thus, in this case the VA rating of the shunt compensator increases, an analysis for optimization of the converter rating is presented and an approximate sub optimal control strategy for UPQC minimum losses operation is proposed.

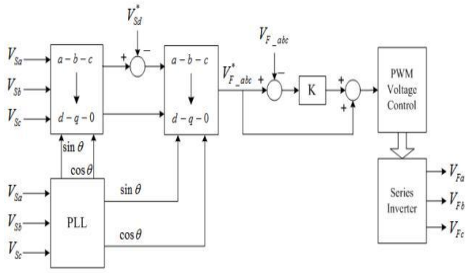

Figure 4:Series Active Filter Control Block.

The load voltage V_l is equal to the sum of the voltage at the point of common coupling V_t and the voltage injected by the series filter V_f:

$$\overline{V_l} = \overline{V_t} + \left|V_f\right|(a + jb) \quad (1)$$

where $a + jb$ is a vector of unity magnitude and 90^0 ahead the supply current.

If the load voltage is assumed to be

$$\overline{V_l} = \left|V_l\right| \angle 0^0$$

the following quadratic equation is obtained from

$$\left|V_f\right|^2 - 2a\left|V_l\right|\left|V_f\right| + \left|V_l\right|^2 - \left|V_t\right|^2 = 0 \quad (2)$$

Solving this quadratic equation the magnitude of the injected voltage reference is obtained. As it was mentioned above, the phase of the injected voltage reference is 90^0 from the supply current. The quadratic equation (1) gives two solutions, from which the solution corresponding to a smaller voltage injection has to be chosen. The fundamental of the instantaneous injected voltage is obtained by multiplying V_f determined from (1) with the sinusoidal template phase locked to

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the supply current. To compensate for supply voltage unbalance and distortion some additional component has to be added to the reference calculated above, which can be determined by subtracting the positive sequence fundamental component from the voltage at the PCC [7].

An alternative strategy for the determination of the UPQC-Q injected voltage reference, based on instantaneous symmetrical components, is proposed in [5]. The instantaneous power in a three-phase system is defined as (2).

$$P = v_a i_a + v_b i_b + v_c i_c \quad (3)$$

The instantaneous symmetrical components for i_a , i_b and i_c are defined as (4).

$$i_{a012} = \begin{bmatrix} i_{a0} \\ i_{a1} \\ i_{a2} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ a1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

Where $a \; e^{j1200}$ and the subscripts 0, 1 and 2 correspond to zero, positive and negative sequence respectively. For balanced currents the component $i_{a\;0}$ is equal to zero and the component $^{i}a1$ is complex conjugate of $ia\;2$. The same transformation is applied for voltages.

Taking into consideration (4) and above comments, equation (3) can be rewritten as (5).

$$p = v_{a0} i_{a0} + v_{a2} i_{a1} + v_{a1} i_{a2} = v_{a1}^{*} i_{a1} + v_{a1} i_{a1}^{*} = 2\operatorname{Re}(v_{a1} i_{a1}^{*}) \quad (5)$$

Since the desired load voltages are balanced sinusoids and the currents flowing through the series compensator are also balanced (shunt compensator action), the instantaneous UPQC output power *Pout* is constant and this must be equal to the average power entering the UPQC (losses are neglected) *Pin,av* . Thus from (5) we get (6).

$$P_{out} = 2\operatorname{Re}\left(v_{l,a1} i_{s,a1}^{*}\right) = 2\left|v_{l,a1}\right|\left|i_{s,a1}\right| \cos\left(\theta_{vl,al} - \theta_{is,al}\right) = p_{in,av} \quad (6)$$

$$\theta_{vl,al} = \cos\left(\frac{p_{in,av}}{2\left|v_{l,a1}\right|\left|i_{s,a1}\right|}\right)^{-1} + \theta_{is,a1} \quad (7)$$

$$\begin{bmatrix} v_{la0} \\ v_{la1} \\ v_{la2} \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 0 \\ V_m e^{j\theta_{vl,a1}} \\ V_m e^{-j\theta_{vl,a1}} \end{bmatrix} \quad (8)$$

The instantaneous load voltages are calculated by applying a transformation inverse to (6).

Simulation parameters of UPQC

For the verification of the performance of UPQC the system is simulated. Simulation parameters mentioned in the following table 2. To observe the performance of shunt filter for voltage correction, the shunt filter is switched on first and then the series filter is switched on.

Table 2: specifications of Fuzzy based upqc

supply	3-phase,50HZ,230 volts rms with 10% of 5th and 5% of 7th harmonics
load	(150+j12.56)
Dc link inductance	150 mH
Dc linkresistance	0.01Ω
Lc filter	25µF, 1Ω,0.4mH
Sampling time	1µs
Line inductance	50µH
Line resistance	0.01Ω
Smoothening inductor	1mH

The large data of source current, reference load voltage, power loss component and reference compensation current from conventional method are collected at a sample rate of 0.05 sec. These data are used for Fuzzy Logic Controller. The performance of UPQC using designed based on PI Controller and Fuzzy Logic Controller for a non linear load derived using an uncontrolled diode bridge with Total Harmonic Distortion is presented in the table 3.

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Table 3 Comparison of Total Harmonic Distortion

S. No.	Parameter	Upqc with pi controller	Upqc with fuzzy logic controller
1	THD for load current	29.29%	28.14%
2	THD for source current	5.34%	0.76%
3	THD for load voltage	5.16%	1.16%
4	THD for source voltage	0.34%	0.33%

UPQC by Synchronous Reference Frame Theory with PI Controller and Fuzzy Logic Controller

Nonlinear apparatus, such as power electronics converters, introduce harmonic currents in the AC system and amplify overall reactive power demanded by the equivalent load. Also, the number of sensitive loads that require ideal sinusoidal supply voltages for their appropriate operation has increased. In order to keep power qualityunder limits proposed by standards, it is necessary to include some sort of compensation.

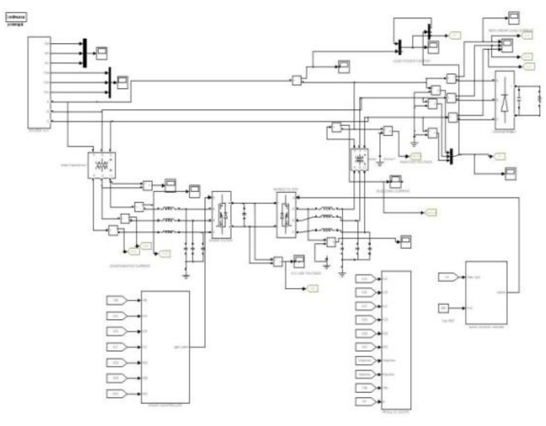

Figure 5 UPQC with Synchronous Reference Frame Theory

The aim of this work is to present a unified power quality conditioner by Synchronous Reference frame Theory and its simulation model is given in Figure 5.

The proposed system is comprised of series and shunt Inverters which can compensate the sag, swell, unbalance voltage, harmonics and reactive power. PI Controller and Fuzzy Logic Controllers are used to stabilize DC Link voltage and balance the active power between shunt and series inverters for the enhancement of power quality.

The Fuzzy Logic Controller presents the best performance to achieve tracking of the desired trajectory. The Fuzzy Logic Controller rejects the load disturbance quickly with no overshoot and with a minor steady state error. The current is limited in its maximum allowable value by a saturation function.

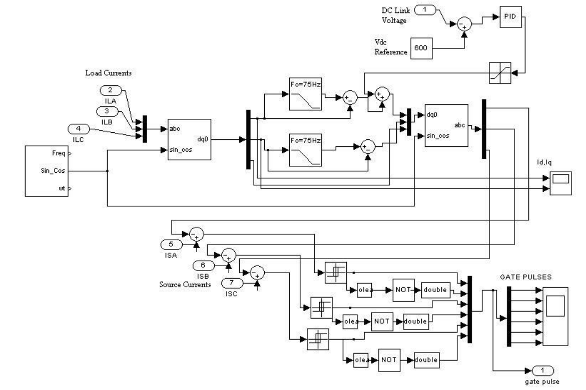

Fig 6 Shunt Controller Subsystem

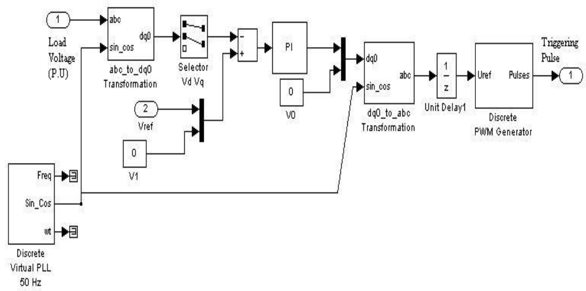

Figure 7 Series Controller Subsystem

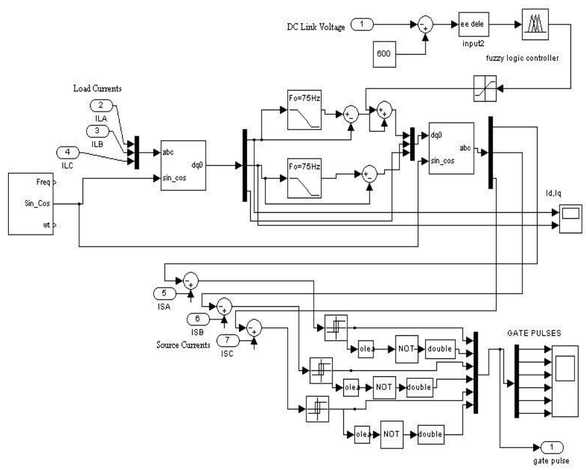

Figure 8 Shunt Active Filter with Fuzzy Logic Controller Subsystem

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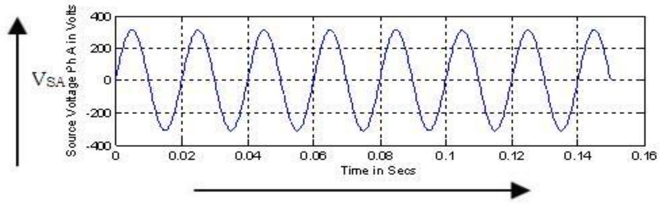

Figure 9 Source Current in Phase A (UPQC with FL Controller)

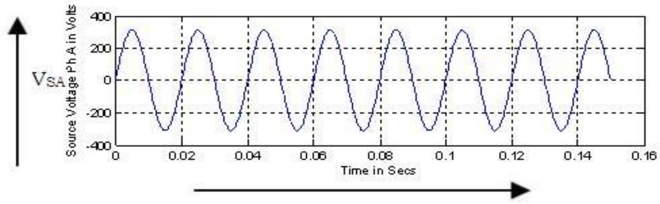

Figure 10 Source Voltage in Phase A (UPQC with FL Controller)

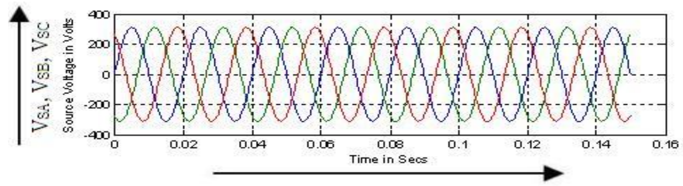

Figure 11 Three Phase Source Voltage (UPQC with FL Controller)

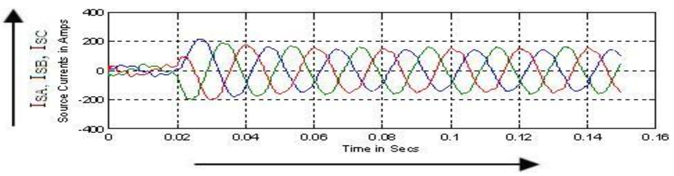

Figure 12 Three Phase Source Current (UPQC with FL Controller)

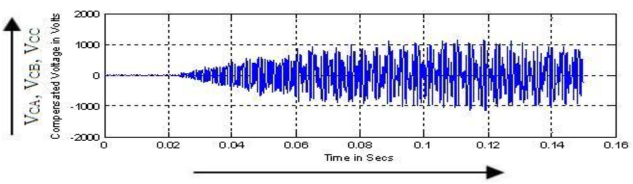

Figure 13 Compensated Voltages (UPQC with FL Controller)

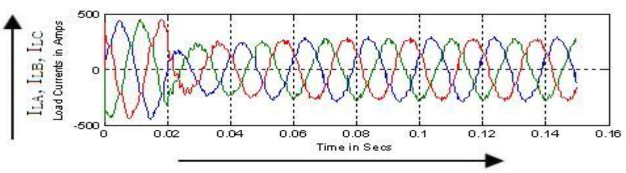

Figure 14 Three Phase Load Current (UPQC with FL Controller)

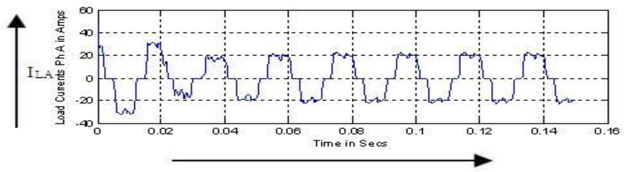

Figure 15 Load Current in Phase A (UPQC with FL Controller)

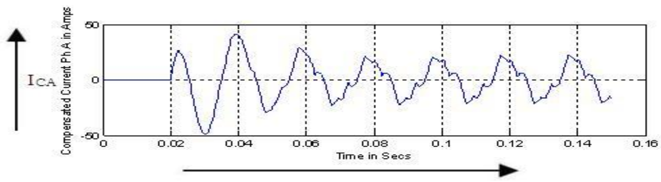

Figure 16 Compensated Current in Phase A (UPQC with FL Controller)

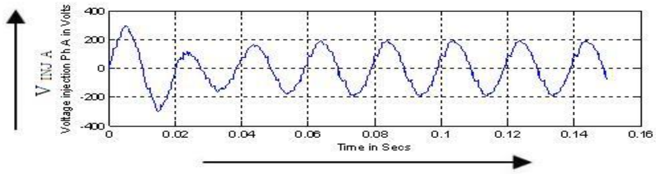

Figure 17 Voltage Injection in Phase A (UPQC with FL Controller)

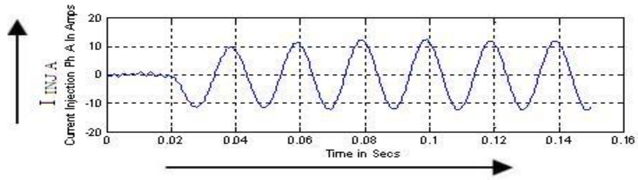

Figure 18 Current Injection in Phase A (UPQC with FL Controller)

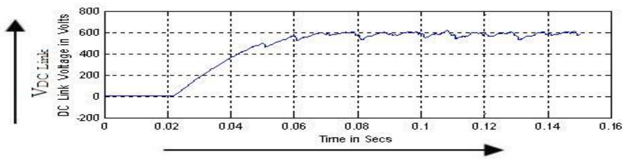

Figure 19 DC Link Voltage (UPQC with FL Controller)

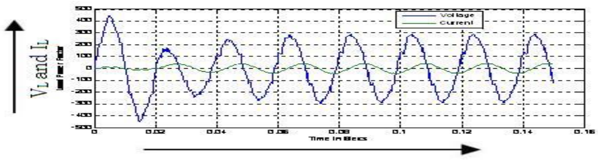

Figure 20 Load Voltage and Current (Power Factor) (UPQC with FL Controller)

In order to validate the control strategies are

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discussed above, digital simulation studies are made the system uncomplicated. The control presents the best performances, to achieve tracking of the desired trajectory. The Fuzzy Logic Controller rejects the load disturbance rapidly with no overshoot and with a negligible steady state error. The current is limited in its maximal admissible value by a saturation function. The reason for superior performance of fuzzy controlled system and the controller is able to realize different control law for each input state (Error and Change in Error).

In this work, power circuit is modeled as a 3-phase 3-wire system with a non linear load comprised of RC load which is connected to source through three phase diode bridge. Simulation parameters used in simulation are shown in table 2. The non linear load is a parallel RC and diode rectifier bridge. It imposes a non sinusoidal current to source. Non linear load current is shown in Figure 15 while providing Fuzzy Logic Controller for UPQC Respectively.

The developed UPQC system has been tested for harmonic elimination and reactive power compensation. Simulation results shown in Figure 9 source current wave forms are plotted. In Figure 18 Plotted injected current wave forms. In Figure 16 plotted compensated current wave forms. Shunt inverter is activated in 0.02 sec of operation. Immediately the source current is corrected. The source current wave forms are shown in Figure 10. Figure 17 shown the voltage injected by the series inverter. The shunt part has been able to correct the source current appropriately. To eliminate swell and sag of the voltage, voltage distortions imposed to **ure** load from the source are properly compensated by series inverter. In this simulation, series inverter operates at 0.02 sec and voltage source faces voltage sag with 100V. A voltage swell with 50 V occurs in 0.08 sec. Simulation results show that the load voltage is constant during the operation of UPQC series inverter.

By using Fuzzy Logic Controllers individually for shunt controller DC Link voltage is shown in Figure 17 . From that the distortions in DC Link voltage can be minimized by Fuzzy Logic Controller. In this simulation, series and shunt inverters start to operate at 0.02 sec. As it is seen, capacitor voltage is decreasing until this moment. By operating shunt inverter, the capacitor voltage increases and reaches to the reference value (600 V). At 0.04 sec of operation voltage sag amplitude for 100 V occurs in source voltage.

Conclusion

The series component of the UPQC is responsible for mitigation of the supply side disturbances viz. voltage sags/swells, flicker, voltage unbalance and harmonics. It inserts voltages so as to maintain the load voltages at a desired level, balanced and distortion free.

Detailed power circuit structure, Principle of operation, Power circuit design considerations, Control strategies for shunt active filter like Tracking the shunt converter reference current, Tracking the supply current in this average dc voltage regulation, Instantaneous p-q theory, Synchronous Reference Frame Theory, for Control of the dc bus, through PI Controller, Fuzzy Logic Control and Control of the series active filter and finally in simulation study part analyze the dynamic and steady-state performance of UPQC with two typical case studies.

In test Case I CSI based UPQC using PI Controller and Fuzzy Logic Controller, the simulation results have shown that the UPQC perform better with FLC proposed scheme eliminates both voltage as well as current harmonics effectively. It is also observed that the response time for derivation of compensation signals reduces significantly with improved accuracy.

And in test Case II UPQC by Synchronous Reference frame Theory with PI Controller and Fuzzy Logic Controller have been simulated. Simulation results show the proposed system's ability in voltage distortion, reactive power and current harmonics compensation.Fuzzy logic controller balances the power between series and shunt inverters by stabilizing DC Link voltage and the resultsof voltage and current waveforms

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are presented in this chapter.

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