International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 11, Issue 11 (November 2015), PP.45-60

Hybrid Fuzzy-PI Controller Based UPQC for Power Quality Enhancement

Subrahmanyam Vaddi, R. Mahanty
Department of Electrical Engineering, Indian Institute of Technology, (Banaras Hindu University), Varanasi, India
Professor, Department of Electrical Engineering, Indian Institute of Technology, (Banaras Hindu University), Varanasi, India

Abstract: Power quality problems like voltage sag/swell, flickers, interruptions, voltage distortions and unbalance can have drastic effects on home appliances, industries, processing plants and other applications.Although a number of conventional techniques like active filters, passive filters, hybrid filters, etc. have been developed to increase the power quality standards, these are inadequate for the increasing number of applications and have some drawbacks. Unified Power Quality Conditioner (UPQC) is a modern solution for the supply voltage and load current imperfections. A UPQC is an integration of both series and shunt active power filters, connected back-to-back and sharing a common DC link capacitor, which suppliesthe real power difference between load and source during transient periods. Control of this DC link capacitor voltage plays an important role in achieving desired UPQC performance. A novel hybrid fuzzy-PI controller based UPQC control scheme has been designed and the performance of UPQC for steady state and dynamic conditions have been discussed through simulation results and are compared with those using PI and fuzzy control schemes. It is shown that the performance of UPQC using hybrid fuzzy-PI controller is superior to both PI and fuzzy controllers.

Keywords:-*unified power quality conditioner, PI control, Fuzzy control, hybrid fuzzy-PI control, SRF based control, hysteresis current control, DC voltage control*

I. INTRODUCTION

With increasing use of power electronic converters, consumers are concerned not only about continuity of supply but also about the quality of power delivered. Power electronic converter based power processing offers higher efficiency, compact size and better controllability. However, due to switching actions, these systems behave as non-linear loads. Therefore, whenever these systems are connected to utility, they draw non-sinusoidal and/or lagging current from the source. As a result, these systems behave as loads with poor displacement and distortion factors. Hence they draw considerably high reactive volt-amperes from the utility and inject harmonics to the power supply networks. Various problems such as voltage sags/swells, voltage interruptions, voltage imbalances, harmonics, voltage flickers, undervoltages and overvoltages result in poor power quality. This lack of standard quality power can cause loss of production, damage of equipment andappliances [1].

Extensive work has been done in order to resolve these power quality problems [2]-[7].Several new techniques were developed among which shunt Active Power Filter (APF) is one of the most promising methods to tackle the current related problems, whereas series APF is most suitable for voltage related problems [8]-[9]. Since modern distribution systems demand a better quality of supply voltage and drawn current, installation of these APFs has a great scope in actual practical implementation. However, installing two separate devices to compensate voltage and current related power quality problems independently may not be a cost effective solution.Thus UPQC, an integration of both series and shunt active filters, connected back-to-back on the dc side and sharing a common DC capacitor,is used [10]-[16].

The shunt APF, connected in parallel with the utility, works as a current source and usually compensates for current quality problems of the load, such as poor power factor, load harmonic currents, load imbalance and DC offset. It injects currents in the AC system such that the source currents become balanced sinusoids and in phase with the source voltages. The shunt device is also used for providing a path for real power flow to aid the operation of series connected voltage source inverter (VSI). In addition, the shunt APF maintains constant average voltage across the DC storage capacitor.

The series APF, on the other hand, is connected in series with the utility and is responsible for mitigation of the supply side disturbances like voltage sags/swells, flicker, voltage unbalance and harmonics. It inserts voltages in the utility so as to maintain the load voltages at desired levels; balanced and distortion free. This way, operation of UPQC isolates the utility from current related problems of load and further, isolates the load from voltage quality problems of utility.Figure 1 shows the structure of UPQC [17].

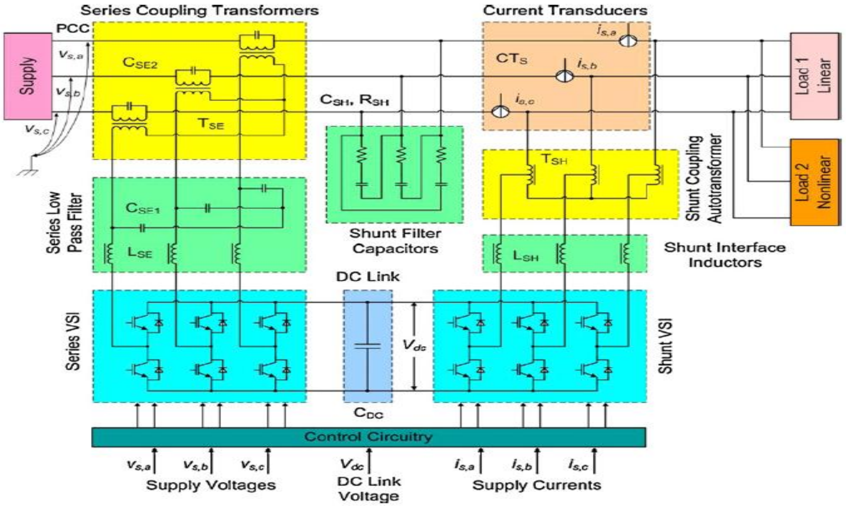

Figure 1: Structure of three-phase three-wire UPQC

In order to achieve its compensation goals, the shunt APF injects harmonic currents at point of common coupling (PCC) such that the reactive and harmonic components of the load currents are cancelled and the load current is balanced. The current injection is provided by the DC storage capacitor and shunt VSI. Based on measured currents and voltages, the control scheme generates appropriate switching signals for the shunt VSI switches. The shunt VSI is controlled in current control mode.

The DC side capacitor serves as an energy storage element to supply a real power difference between the load and source during the transient period [18]. The average voltage across the dc capacitor is maintained constant, and for the shunt APF to draw a leading current, this voltage has to be higher than the peak of the supply voltage. Various control techniques are used to maintain DC link voltage constant by regulating the amount of active current drawn by the shunt APF from the supply system.

The series part of UPQC also consists of a VSI connected on the DC side to the same energy storage capacitor, and on the AC side, to the feeder, through the series low pass filter (LPF) and coupling transformers. The series LPF prevents the switching frequency harmonics produced by the series VSI from entering the system. The series coupling transformer provides voltage matching and isolation between the network and the VSI.

II. CONTROL STRATEGIES

The performance of an APF depends on the design characteristics of the currentcontroller. The control scheme of a shunt active power filter must calculate the current reference waveform for each phase of the inverter, maintain the DC link voltage constant and generate the inverter gating signals. Also, the compensation effectiveness of an active power filter depends on its abilityto follow the reference signal calculated to compensate the distorted load current with aminimum error and time delay.The current reference circuit generates the reference currents required to compensate the load current harmonics, load reactive power and also to maintain the dc link voltage constant. Synchronous Reference Frame (SRF) based control is used to achieve this objective.

Synchronous Reference Frame (SRF) based control:

In this control, the three phase load currents I_a, I_b and I_c are transformed into α-β frame using the following transformation relations [19]:

$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \qquad \text{Equation 1}$$

Where p and q are active and reactive powers respectively. From equation 1, we get:

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = 1/\ (v\alpha 2 + v_\beta^2)\begin{pmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{pmatrix}\begin{pmatrix} p \\ q \end{pmatrix}$$ Equation 2

These load currents presented in the α-β frame are transformed into synchronous reference frame as shown below:

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{pmatrix}\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix}$$ Equation 3

The reference frame is synchronised with the supply voltages and rotates with the same frequency. A Phase Locked Loop(PLL) is needed for implementing this method. $I_d$and $I_q$are composed of DC and AC components as

$$I_d = \overline{Id} + \widetilde{Id}$$ Equation 4

$$I_q = \overline{Iq} + \widetilde{Iq}$$ Equation 5

The DC components $\overline{Id}$and $\overline{Iq}$correspond to the fundamental load currents and the AC components $\widetilde{Id}$and $\widetilde{Iq}$correspond to the load currents harmonics. Component $\widetilde{Iq}$corresponds to the reactive power drawn by the load. The isolation of the AC component can be achieved by filtering out the DC offset. The compensation reference signals are obtained from the following expressions:

$$I_{d,ref} = -\ \widetilde{Id}$$ Equation 6

$$I_{q,ref} = -\ \overline{Iq} - \widetilde{Iq}$$ Equation 7

This means that there will be no harmonics and reactive components in the system currents after the compensation. However, in real time, capacitor voltage may vary due to switching loss or other disturbances such as imbalance and sudden load variations. Thus an extra term to account for capacitor voltage balancing needs to be added in, which is shown below in theFigure 2 [20].

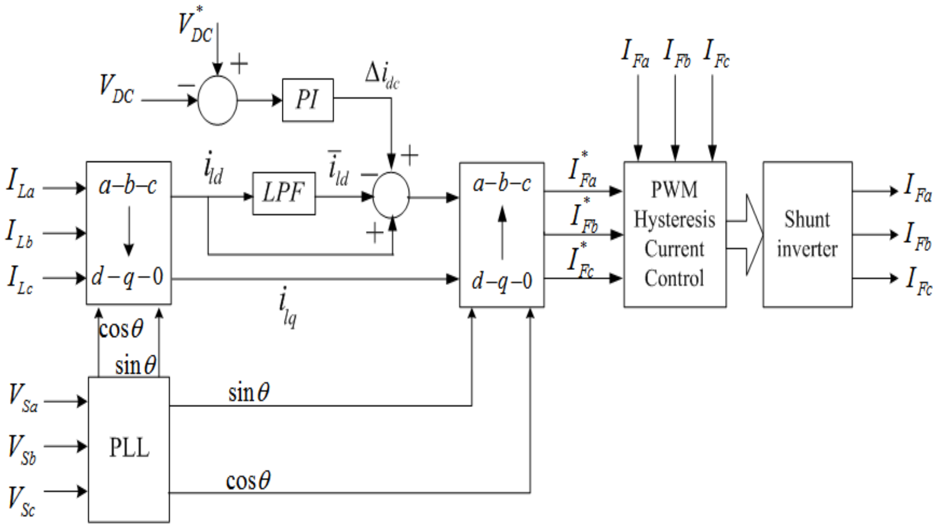

Figure 2: SRF control block diagram for shunt active filter [20]

It is observed that the unbalanced load currents generate a different harmonic spectrum in the DC reference frame, and low order harmonic components appear in the reference signal. In order to separate these unwanted low frequency current components, the cut-off frequency of the low pass filter must be reduced.One of the important characteristics of this algorithm is that, the reference signals are directly derived from the load current without the need of source voltages. This shows that the SRF control is not affected by the voltage unbalance or distortion, which is the case with other conventional techniques like instantaneous p-q theory. Thus SRF control has greater compensation robustness and superior performance than p-q control.

Hysteresis current control is used in the simulation for the shunt part of UPQC. In hysteresis control, as shown in Figure 3error signal, e(t), is used to control theswitches in an inverter. This error is the difference between the desired current, I_F^*(t)andthe current being injected by the inverter, I_F(t). When the error reaches an upper limit, thecurrent is forced to decrease and when the error reaches a lower limit the current is forced toincrease. The minimum and maximum values of the error signal are e_{min} and e_{max}respectively. The range of the error signal, $e_{max} - e_{min}$, directly controls the amount of ripplein the output current from the inverter and is called "hysteresis band". The hysteresislimits, e_{min} and e_{max} , relate directly to an offset from the reference signal and are referred to asthe Lower Hysteresis Limit and the Upper Hysteresis Limit. The current is forced to staywithin these limits even when the reference current is changing.

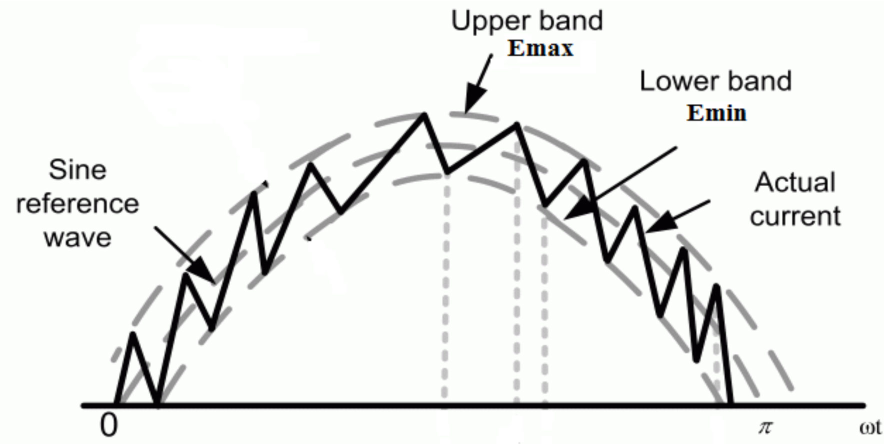

Figure 3: Hysteresis band control

Voltage Control of DC Bus:

For a voltage source inverter, the DC voltage needs to be maintained at a certain levelto ensure the DC-AC power transfer. Because of the switching and other power losses insideUPQC, the voltage level of the DC capacitor will be reduced even in the steady state, if it isnot compensated. Thus, the DC link voltage control unit is meant to keep the average DC busvoltage constant and equal to a given reference value. The DC link voltage control isachieved by adjusting the small amount of real power absorbed by the shunt inverter. Thisreal power is adjusted by changing the amplitude of the fundamental component of thereference current. The AC source provides some active current to recharge the DC capacitor.Thus, in addition to reactive and harmonic components, the reference current of the shuntactive filter has to contain some amount of active current as compensating current. This active compensating current flowing through the shunt active filter regulates the DC capacitorvoltage. Control of shunt active filter along with the modification for regulating the voltage ofDC link capacitor is shown inFigure 2.

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. But due to its fixed proportional gain (K_p) and integral gain (K_i), the performance of the PI controllers are affected by parameter variations, load disturbances etc.

However, instead of the PI controller, a fuzzy logic controller is proposed for processing the DC capacitor average voltage error[21]. The fuzzy controller claims to have the following advantages over the PI controller:

- it does not require an accurate mathematical model,
- it can work with imprecise inputs and handle non-linearity,
- it is more robust,
- it has fast dynamic response.

But under steady state conditions, PI controller has superior performance comparedto the fuzzy controller. Hence, a hybrid fuzzy-PI controller has been proposed to utilize best attributes of the PI controller and fuzzy controller therefore providing a controller that can produce better response than both PI and fuzzy controllers[22]. Fuzzy controller offers a better speed response for large reference input changes (largevoltage error) whereas the PI controller supports steady state accuracy. The superiority ofboth fuzzy and PI controller are integrated together by using a switching function.

Control of Series APF:

The series component of UPQC is controlled to inject the appropriate voltage betweenthe point of common coupling (PCC) and load, such that the load voltage becomes balanced,distortion free and has the desired magnitude. Theoretically the injected voltage can be ofarbitrary magnitude and angle. However, the power flow and device rating are importantissues that need to be kept in mind while determining the magnitude and angle ofinjected voltage. In-phase compensation (UPQC-P)control strategy has been used in the UPQC simulation model.

UPQC-P:

In this scheme, in general the injected voltage is in phase with the supply voltagewhen the supply is balanced. Therefore, mostly the series inverter would consume activepower. By virtue of in phase injection, UPQC-P will mitigate voltage sag conditions byminimum injected voltage.The phasor diagram in Figure 4explains the operation of UPQC-P for thefundamental frequency[20]. When the system voltage and current are in phase due to the action ofthe shunt compensator, the series converter handles purely active power. As seen from Figure **4**, the shunt inverter current increases when there is supply voltage sag, as the seriesinverter consumes active power through the shunt inverter. When the supply sag is created,the series inverter of the UPQC-P should compensate for the fall in voltage to maintain theload voltage to its specified value. The injected voltage being in-phase with the supplyvoltage, the supply current and injected voltages are also in-phase with each other. Hence, theseries inverter handles only active power. The series inverter delivers this additional activepower by drawing the same from the DC link of the UPQC-P. Therefore, it acts as an activeload to the shunt inverter. As seen from the phasor diagram, I_{C2} has an additional active and same reactive component as I_{C1}.

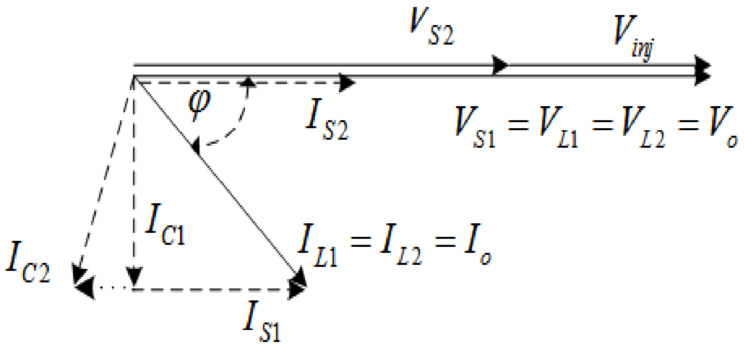

Figure 4: Phasor diagram for UPQC-P

Figure 5shows the block diagram of UPQC-P control scheme. The desired value offload voltage in d-axis and q-axis is compared with the load voltage and the result isconsidered as the reference signal. This control further contains a feed-forward voltage loop which is followed by PWM voltage control.

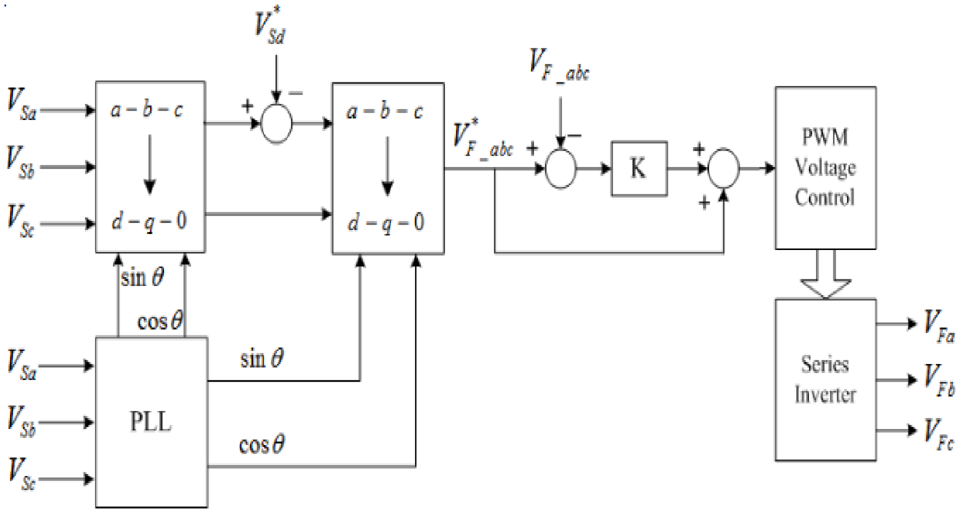

Figure 5: Control block diagram of UPQC-P for series inverter of UPQC [20]

Modeling of UPQC with PI Controller

Conventionally, PI controller has been used for regulating the voltage of DC link capacitor. The output of PI controller is applied to current control system of shunt inverter, to maintain the DC capacitor voltage by drawing the required amount of active power from the grid. DC link voltage control using a PI controller is shown inFigure 6.

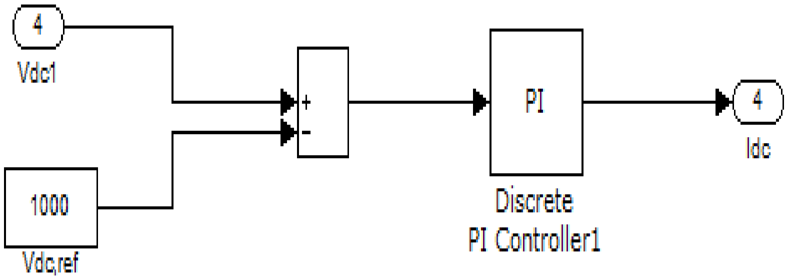

Figure 6: DC link voltage control using PI controller.

In case of PI controller, proportional gain (K_p) and integral gain (K_i) values plays animportant role in voltage regulation. Values of K_p and K_i are chosen by repeated simulationby keeping in mind the following points:

Too much increase in proportional gain leads to instability in control system and toomuch reduction decreases the responding speed of control system.

Integral gain of controller corrects the steady state error of the voltage control system.Also, too much increase in its value may also leads to instability.

Thus, values of K_p and K_i used in simulation are 0.8 and 25 respectively.

In order to achieve the desired performance of UPQC in dynamic conditions of power system such as voltage sags/swells, load change, unbalance etc., response of DC link voltage control should be as fast as possible while retaining capacitor voltage with a minimum delay time and lower overshoot.Conventionally PI controller is used for regulation of DC link voltage constant whose response is system parameters dependant. On the other hand, fuzzy controller has the advantage of giving robust performance in case where effects of parameter variation are present. Also there is no need of mathematical model of the system for applying fuzzy control. Hence fuzzy logic controller is used for the control of DC capacitor voltage and its modelling is described below.

Modelling of UPQC with Fuzzy Controller

Fuzzy logic (FL) basically deals with reasoning that is approximate rather than fixed and exact. In contrast with traditional logic theory, where binary sets have two-valued logic: true or false, fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true (1) and completely false (0). Furthermore, when linguistic variables are used, these degrees may be managed by specific functions.

Fuzzy logic system provides a convenient way of nonlinear mapping from the input to output space. By elaborating on the notion of fuzzy sets and fuzzy relations, fuzzy logic systems (FLS) can be defined. These are rule-based systems in which an input is first fuzzified (i.e., converted from a crisp number to a fuzzy set) and subsequently processed by an inference engine that retrieves knowledge in the form of fuzzy rules contained in a rule-base. The fuzzy sets computed by the fuzzy inference as the output of each rule are then composed and defuzzified (i.e., converted from a fuzzy set to a crisp number). Implementation of fuzzy logic controller block using Simulink is shown below:

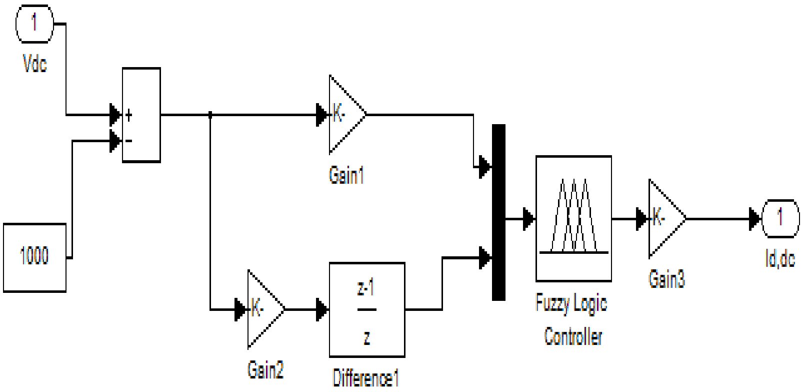

Figure 7: DC link Voltage regulation using Fuzzy logic control in MATLAB.

ECE	PL	PM	PS	ZE	NS	NM	NL
NL	ZE	NS	NM	NL	NL	NL	NL
NM	PS	ZE	NS	NM	NL	NL	NL
NS	PM	PS	ZE	NS	NM	NL	NL
Z	PL	PM	PS	ZE	NS	NM	NL
PS	PL	PL	PM	PS	ZE	NS	NM
PM	PL	PL	PL	PM	PS	ZE	NS
PL	PL	PL	PL	PL	PM	PS	ZE

Table 1: Rule table for Fuzzy DC link Controller.

The general considerations in the design of the controller are:
if both E and CE are zero, then maintain the present control setting $I_{d,\,DC} = 0$
if E is not zero but is approaching to the reference value at a satisfactory rate, then maintain the present control setting
if E is increasing, then change the control signal $I_{d,\,DC}$ depending on the magnitude and sign of E and CE to force E towards zero.
Membership functions for the error signal ($V_{DC} - V_{DC,\,ref} =$ E), change in error (de/dt) and output $I_{d,DC}$ is shown inFigure 8, 9 and 10.Symmetrical triangular membership functions are taken, as unsymmetrical membership functions give same steady state response but poor dynamic response as compared to symmetrical membership function.

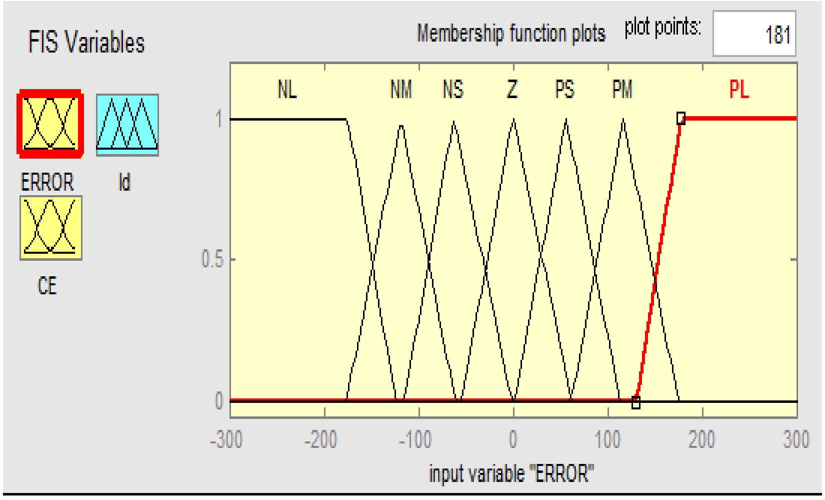

Figure 8: Membership functions for the error signal ($V_{DC} - V_{DC,\,ref}$)

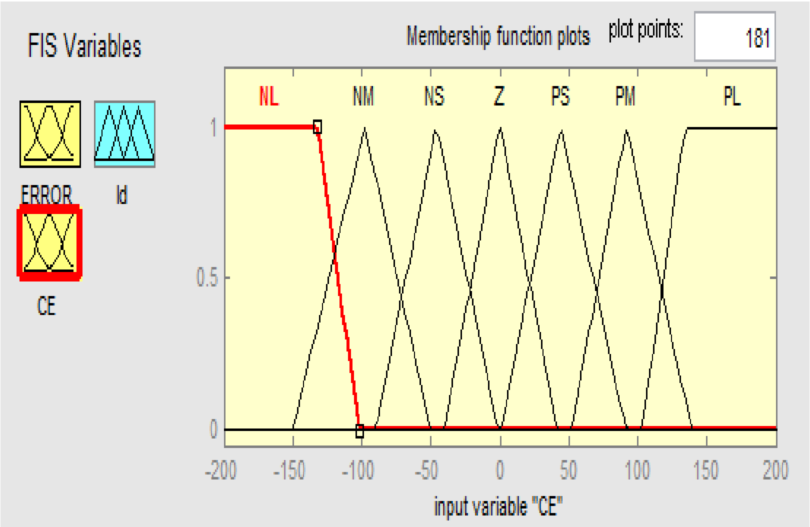

Figure 9: Membership functions for the change in error signal

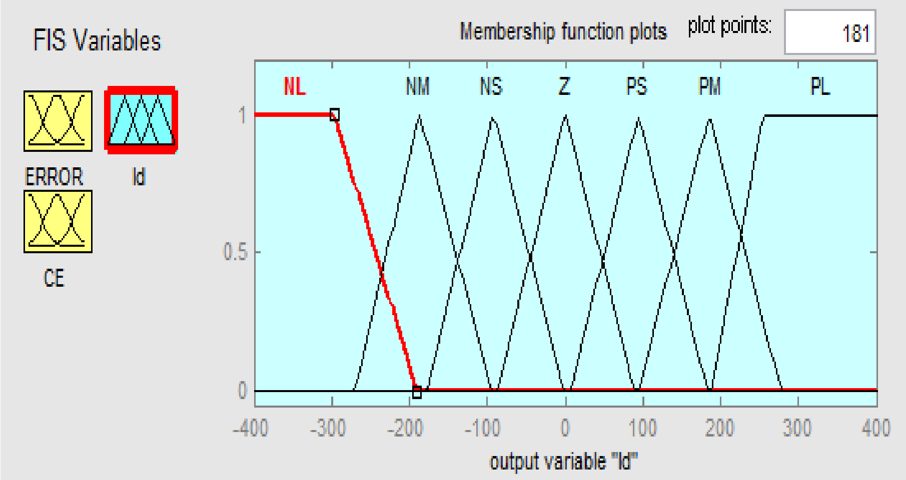

Figure 10: Membership functions for the output signal ($I_{d,\,DC}$).

Modelling of UPQC with Hybrid Fuzzy-PI Controller

Various types of switching functions can be implemented to combine these two controller outputs to make a hybrid controller and based on the switching functions, the performance of the UPQC will vary. The main focus of the controller design is not only to improve the performance of the controller, but also to reduce the computational burden and thereby to reduce the algorithm execution time.

The switching function has its own rules for assigning the weights for both the fuzzy and PI controller outputs. The switching function is based on a rule, that during the transient conditions, the output of the fuzzy logic controller has the prominent effect on the output of the hybrid controller and during the steady state conditions, the PI controller has the more prominent effect. The advantages of this switching function are absence of chattering, less computational burden resulting in reduced ripples, and simple yet robust switching algorithm.

The selection between fuzzy and PI controllers is based on set of simple rulesshown in Table 2. Under the dynamic conditions, the weightage given to the fuzzy controller output is more than that of the PI controller output, and under the steady state conditions, the weightage given to the PI controller output is more than that of the fuzzy controller output. The combined weightage is decided by another fuzzy controller. The rule table and membership functions of the fuzzy controller which generates switching function are given in Table 2 andFigure 11, respectively. Singleton output membership functions are used to generate weights for both the controllers.

ERROR	FUZZY	PI
NL	PS	NM
NM	Z	NS
NS	NS	Z
Z	NM	PS
PS	NS	Z
PM	Z	NS
PL	PS	NM

Table 2: Rule table for switching function of hybrid controller.

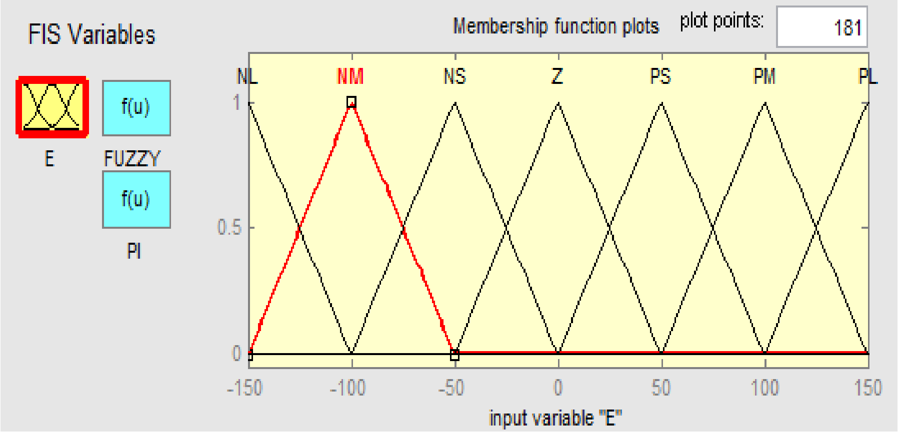

Figure 11: Membership functions for generating switching function of hybrid controller.

The control block diagram of DC link voltage regulation using hybrid fuzzy-PI controller in MATLABsoftware is shown in Figure 12.

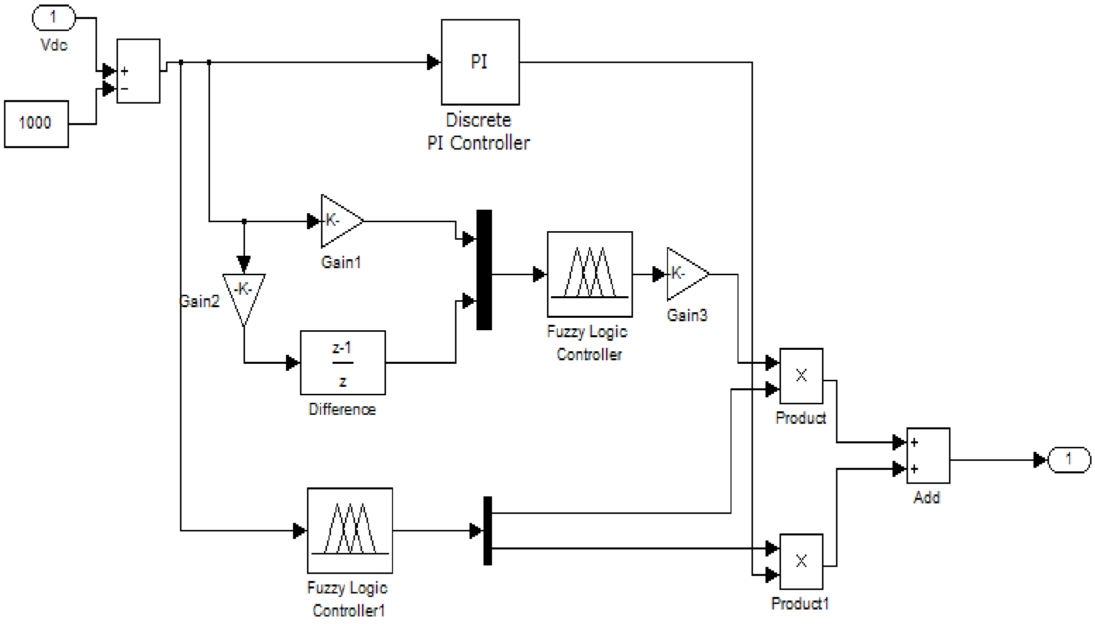

Figure 12: DC link Voltage regulation using Hybrid Fuzzy-PI controller in MATLAB.

III. SIMULATION RESULTS

A three-phase four-wire UPQC is connected to a 440V, 50Hz three-phase four-wire 400KVA distribution system with nominal distributed line parameters. It is connected to a linear RL load and a non-linear load comprised of three-phase diode bridge rectifier feeding an RL load.This configuration is modelled in MATLAB/Simulink and the performance of this UPQC is evaluated in terms of mitigation of voltage and current harmonics, and voltage sags and swell. Power flow analysis during the UPQC operation is also evaluated.

Parameter/Component	Symbol	Value
Supply Voltage	V_s	440V (RMS) L-L
DC link capacitor	C_{DC}	10000 μF
DC link voltage	V_{DC}	1000 V
Shunt filter inductance	L_{sh}	0.5 mH
Series filter inductance	L_{se}	0.61 mH
Series filter capacitance	C_{se}	1 μF
Switching frequency of series inverter	f_{se}	10 KHz
Hysteresis band for shunt inverter	h	+- 0.1 A
Linear RL load	$(RL)_{linear}$	180 KW and 1 KVAR
Non-linear load (RL load connected to three-phase diode bridge rectifier)	$(RL)_{non\text{-}linear}$	R =1 Ω, L = 100 mH

Table 3: Parameters of system used for simulation study.

Case Study 1:

A non-linear (RL load connected to a diode bridge rectifier) load as mentioned in Table 3 is considered. UPQC is connected at 0.1sec of operation via a circuit breaker. PI controller is used for DC link voltage regulation. UPQC steady state performance is investigated and the simulation results are shown in the Figure 13.

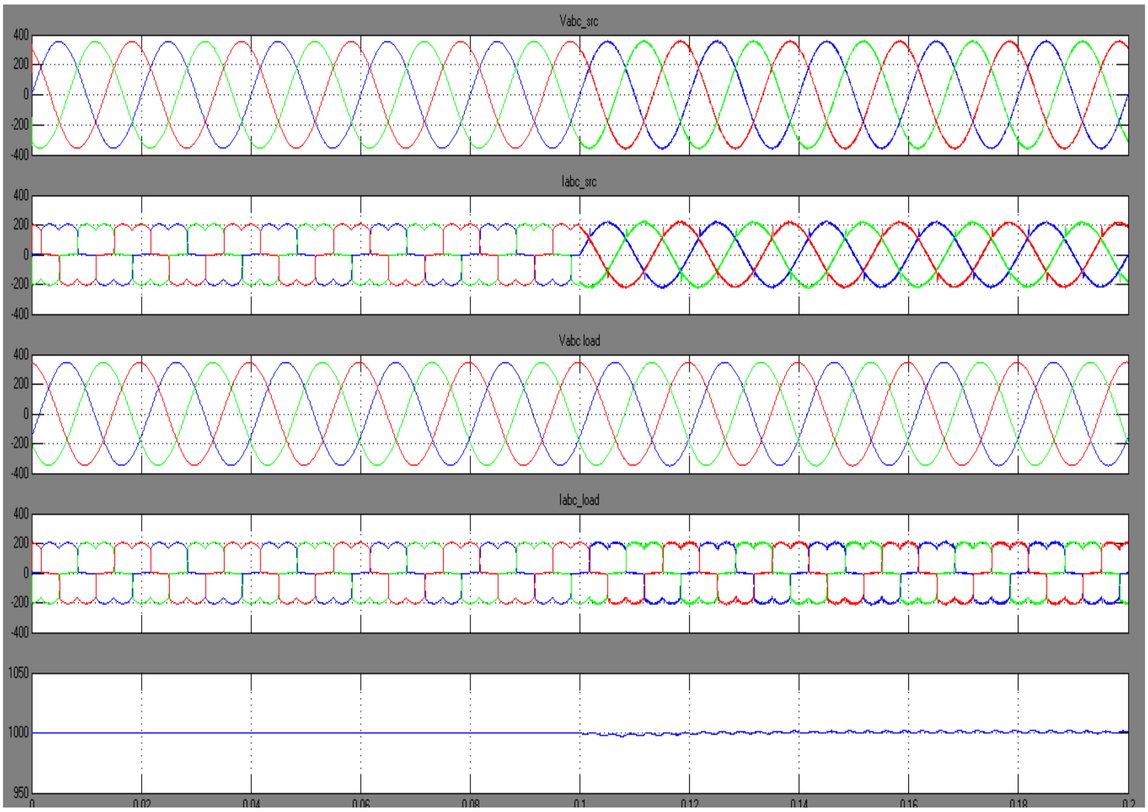

Figure 13: Simulation waveforms with PI control. a) source voltage b) source current c) load voltage d) load current and e) dc link capacitor voltage

It can be clearly seen from the above waveforms of voltages and currents that at 0.1 sec of operation UPQC has cancelled the effect of distorted load currents such that the current drawn from the source is now purely sinusoidal. Also UPQC is able to regulate the DC link voltage to its reference value.

Case Study 2:

Both non-linear (RL load connected to a diode bridge rectifier) and a linear load with distortedload currents having a THD of 16.37% is considered for analysing steady state and dynamic performance of UPQC.UPQC is connected to the distribution system at 0.1sec of operation. Balanced voltage sag of 0.8pu is considered at 0.2sec of operation and removed at 0.4 sec. Following waveforms shows the simulation with Hybrid Fuzzy-PI controller and capacitor voltages of waveforms for PI and fuzzy controllers:

a) Hybrid fuzzy-PI controller:

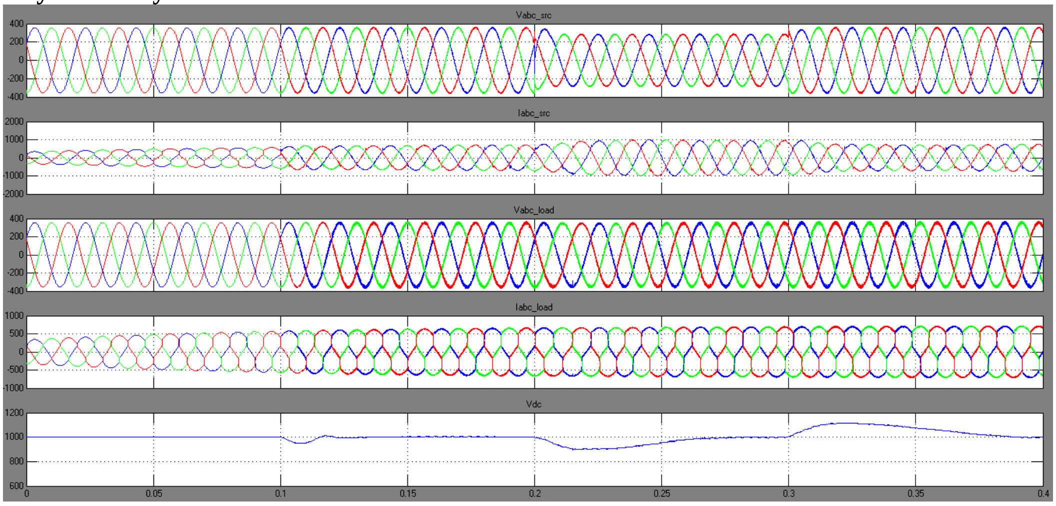

Figure 14: Simulation waveforms with hybrid fuzzy-PI control. a) source voltage b) Source current c) load voltage d) load current and e) dc link capacitor voltage

b) PI controller:

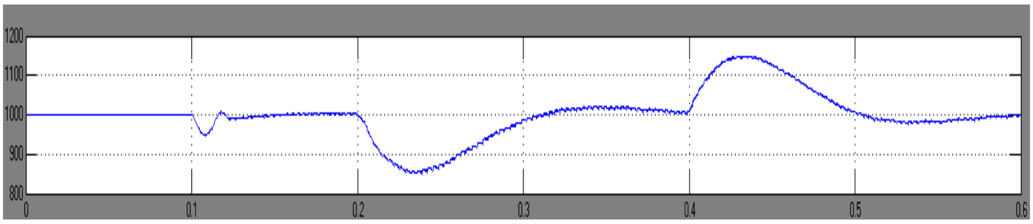

Figure 15: DC link capacitor voltage with PI control

c) Fuzzy Controller:

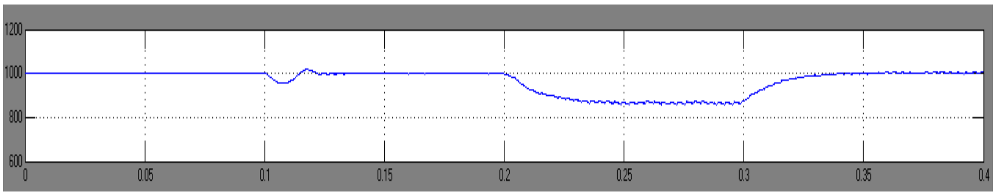

Figure 16: DC link capacitor voltage with fuzzy control

Comparison between PI, Fuzzy and Hybrid Fuzzy-PI Controller Responses for voltage sag analysis: THD of source current during the voltage sag with hybrid controller Figure 14(b) is 3.30 %, with fuzzy controller it is 3.60% and with PI controller it is 3.95%. While after the sag the THD of source current with hybrid controller is 2.68%, with fuzzy controller it is 3.03% and with PI controller it is 3.43%.Thus, THD of source current is lower in both the cases when using a hybrid controller.

The transient condition for the present case (balanced sag of 0.3pu) after the sag gets cleared is of duration 0.17sec with PI controller, while of 0.04sec with fuzzy controller and 0.06 sec with hybrid controller.

The steady state error with fuzzy controller is 18V while that is 3V with both PI and hybrid controllers.

Hence from above analysis, though fuzzy controller shows faster response, the performance of hybrid controller is much better than fuzzy controller as it has steady state accuracy and better THD values.

Power flow analysis for voltage sag condition:

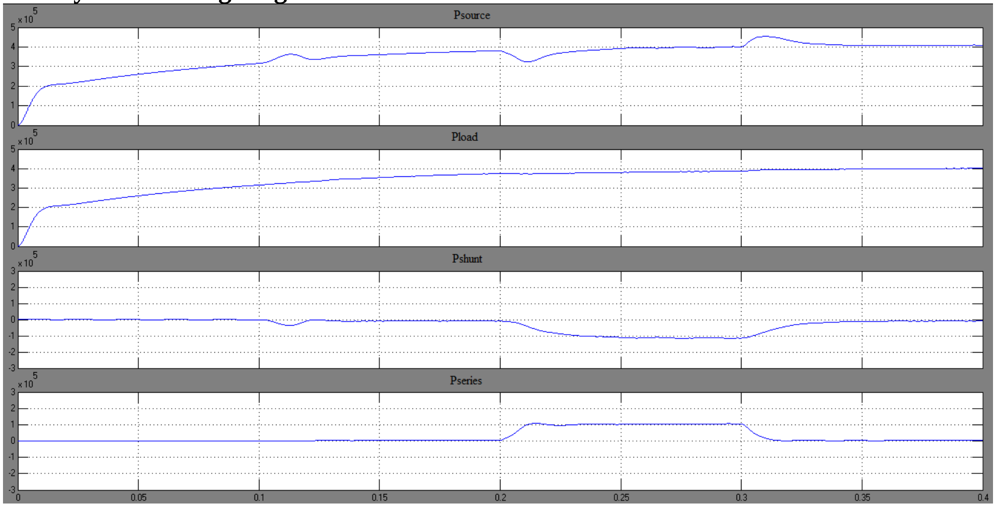

Figure 17: Average active power of a) source, b) load, c) shunt APF and d) series APF

Figure 17 shows the average active powers supplied by source and UPQC. It can be observed from the waveforms that:

During normal operation, average active power supplied/ absorbed by series and shunt compensator of UPQC is zero. It means that whole of the average active power demand of load is met by the source i.e. $P_{load\_avg} = P_{source\_avg}$.

During dynamic operation, i.e. when voltage sag occurs, active power is supplied by series compensator to compensate voltage sag. Since injected voltage by series APF is in phase with the supply voltage, some active power is being transferred to line which is absorbed from the capacitor. Now in order to regulate the DC link voltage, some of the active power is being absorbed by shunt APF which results in waveforms of $P_{series} > 0$ (supplied) and $P_{shunt} < 0$ (absorbed).

Case Study 3:

Both non-linear (RL load connected to a diode bridge rectifier) and a linear load with distortedload currents having a THD of 16.37% are considered for analysing steady state and dynamic performance of UPQC.UPQC is connected to the distribution system at 0.1sec of operation. Balanced voltage swell of 0.5pu is considered at 0.2sec of operation and removed at 0.35 sec. Following waveforms show the simulation with hybrid fuzzy-PI controller and capacitor voltages of waveforms for PI and fuzzy controllers:

a) Hybrid fuzzy-PI controller:

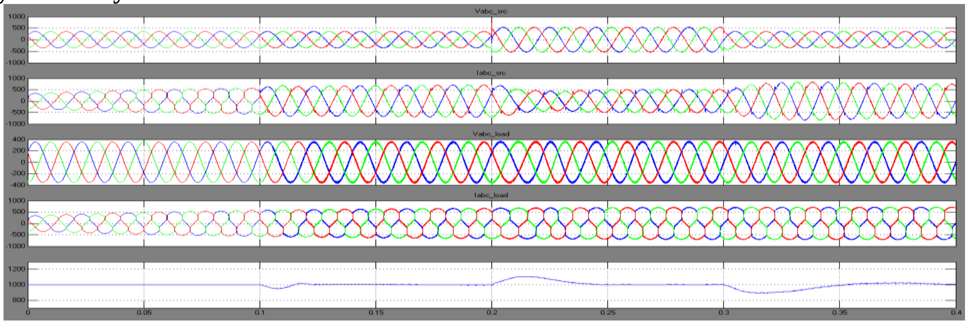

Figure 18: Simulation waveforms with hybrid fuzzy-PI control. a) source voltage b) source current c) load voltage d) load current and e) dc link capacitor voltage

b) PI controller:

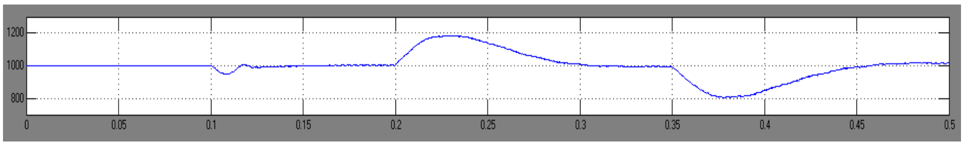

Figure 19: DC link capacitor voltage with PI control

c) Fuzzy controller:

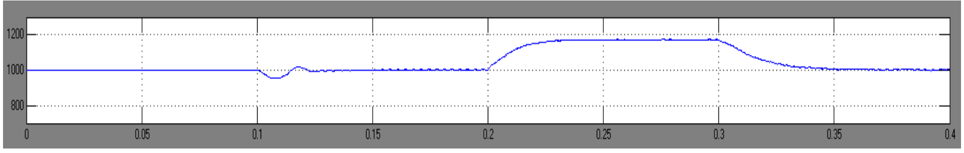

Figure 20: DC link capacitor voltage with fuzzy control

Comparisons between PI, Fuzzy and Hybrid Fuzzy-PI Controller Responses for voltage swell analysis: THD of source current during the voltage swell with hybrid controller Figure 148 (b) is 3.50 %, with fuzzy controller it is 3.91% and with PI controller it is 4.03 %. While after the swell the THD of source current with hybrid controller is 2.8%, with fuzzy controller it is 3.18% and with PI controller it is 3.49%.Thus, THD of source current is less in both the cases with hybrid controller.

The transient condition for the present case (balanced swell of 0.5pu) after the swell gets cleared is of duration 0.12sec with PI controller, while of 0.04sec with Fuzzy controller and 0.05 sec with hybrid controller.

The steady state error with fuzzy controller is 15V while that is 2V with both PI and hybrid controllers.

Hence from above analysis, though fuzzy controller shows faster response, the performance of hybrid controller is much better than fuzzy controller as it has steady state accuracy and better THD values.

Power flow analysis for voltage swells condition:

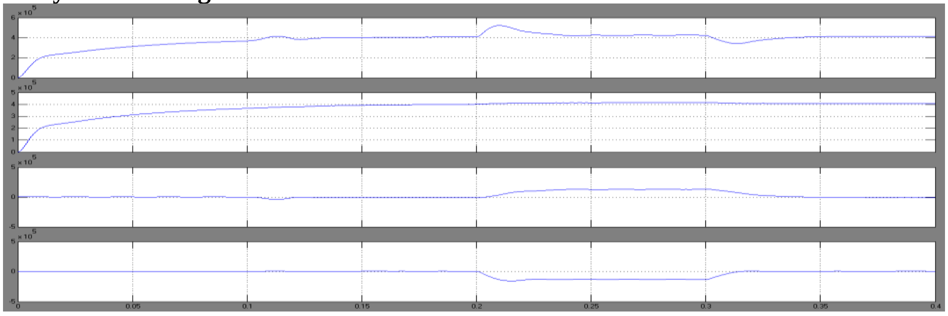

Figure 21: Average active power of a) source, b) load, c) shunt APF and d) series APF

Figure 14shows the average active powers supplied by source and UPQC. It can be seen from the above waveforms that

During normal operation, average active power supplied/ absorbed by series and shunt compensator of UPQC is zero. It means that the entire average active power demand of load is met by the source i.e. $P_{load\_avg} = P_{source\_avg}$.

During dynamic operation, i.e. when voltage swell occurs, series APF absorbs the active power from the line, thus $P_{series}<0$. This increases the capacitor voltage, the source current decreases and that active power is being fed back to line via shunt APF, thus $P_{shunt}>0$.

When the steady state is achieved during voltage swell, average active power absorbed/supplied by UPQC ($P_{upqc} = P_{shunt} + P_{series}$) becomes zero.

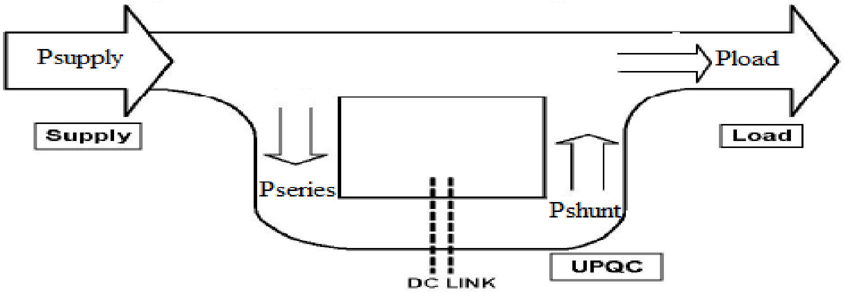

Figure 22: Active power flow during voltage swell condition.

Case Study 4:

In this case study, dynamic and steady state operation of UPQC is investigated for an unbalanced supply voltage sag, where phase a is healthy, phase b has a sag of 0.8 pu with phase jump of -10 degrees, phase c has a sag of 0.8 pu with a phase jump of 10 degrees. Both linear and non-linear loads (RL load connected to a diode bridge rectifier) are considered, and UPQC system is connected at 0.1 sec. Following waveforms show the simulation with hybrid Fuzzy-PI controller and capacitor voltages of waveforms for PI and fuzzy controllers:

a) Hybrid fuzzy-PI controller:

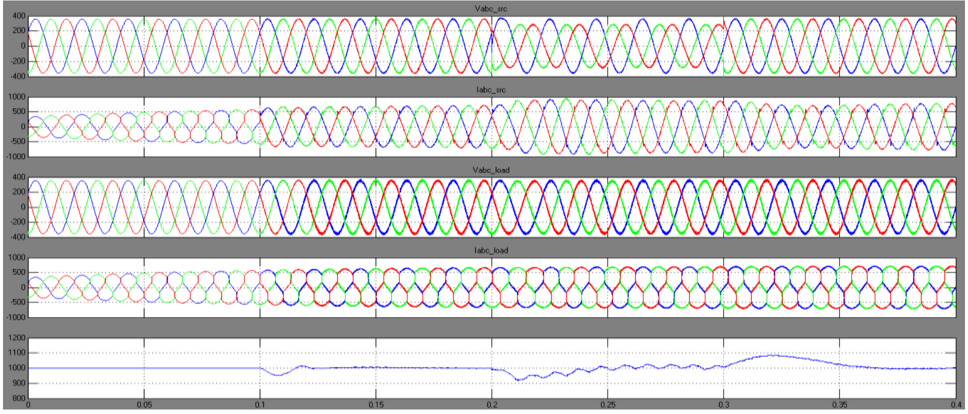

Figure 23: Simulation waveforms with hybrid fuzzy-PI control. a) source voltage b) source current c) load voltage d) load current and e) dc link capacitor voltage

b) PI controller:

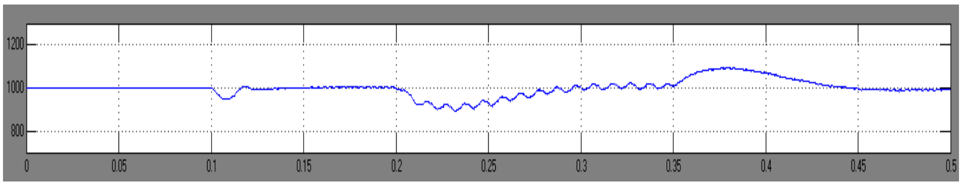

Figure 24: DC link capacitor voltage with PI control

c) Fuzzy controller:

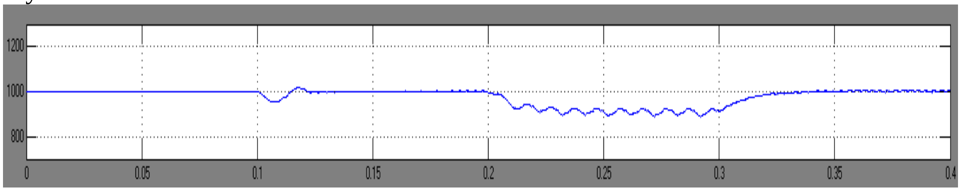

Figure 25: DC link capacitor voltage with fuzzy control

Comparison between PI, Fuzzy and Hybrid Fuzzy-PI Controller Responses for unbalanced voltage sag analysis:

THD of source current during the voltage swell with hybrid controller Figure 14(b) is 3.79 %, with fuzzy controller it is 4.03% and with PI controller it is 4.10 %. While after the swell the THD of source current with hybrid controller is 3.50%, with fuzzy controller it is 4.03% and with PI controller it is 4.17%.Thus, THD of source current is less in both the cases with hybrid controller.

Hence from above analysis, it is clear that the performance of hybrid controller is much better than fuzzy controller and PI controllers as it has steady state accuracy and better THD values.

Case Study 5:

In this case study, dynamic and steady state operation of UPQC is investigated for a sudden change in load. Initially, a load mentioned in section 4.6 is connected to the system. At 0.2 seconds a non-linear load (three phase bridge rectifier connected to R = 1Ω and L = 10mH) is connected and is removed at 0.3 seconds. UPQC is connected to the system at 0.1 sec. Following waveforms show the simulation with Hybrid Fuzzy-PI controller and capacitor voltages of waveforms for PI and fuzzy controllers:

a) Hybrid fuzzy-PI controller:

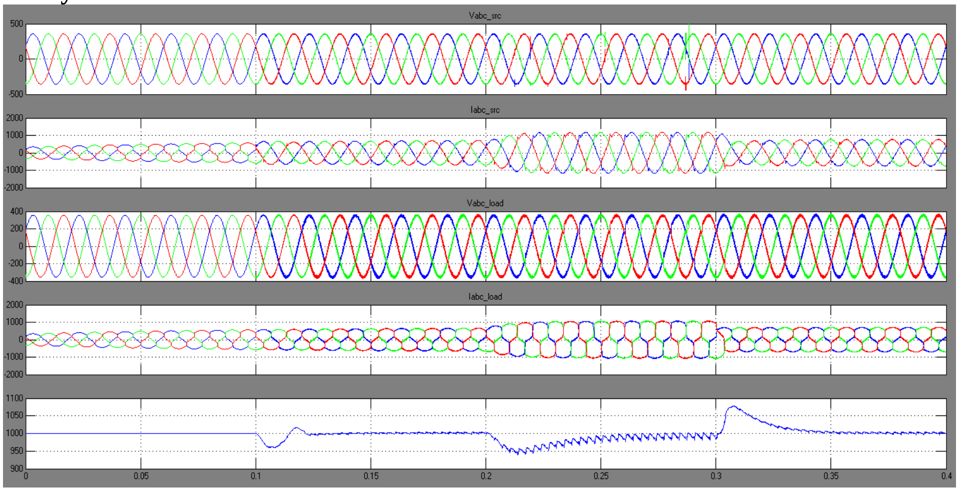

Figure 26: Simulation waveforms with hybrid fuzzy-PI control. a) source voltage b) source current c) load voltage d) load current and e) dc link capacitor voltage

b) PI controller:

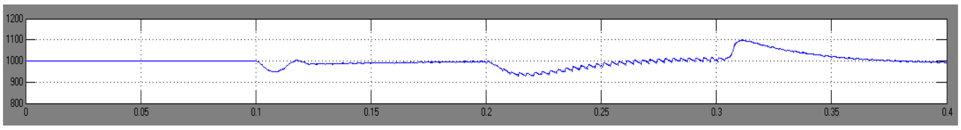

Figure 27: DC link capacitor voltage with PI control

c) Fuzzy controller:

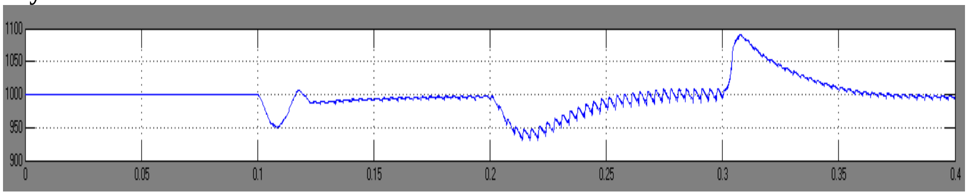

Figure 28: DC link capacitor voltage with fuzzy control

It can be observed from the above waveforms that UPQC is able to bring the system to its stable state operation even after a sudden addition and removal of load. A transition in DC link voltage is observed due to the sudden load change. It was observed that with PI controller, the THD of source current is 4.08% and THD of load voltage is 4.09%. With fuzzy controller, the THD of source current is 3.90% and THD of load voltage is 4.01%. With hybrid controller, the THD of source current is 3.85% ant THD of load voltage is 3.59%.Hence in this case study, it can be seen that the performance of UPQC using hybrid fuzzy-PI controller is much better when compared to fuzzy and PI controllers.

The performance of UPQC with PI, fuzzy and hybrid fuzzy-PI controllers are compared in Table 4.

Results comparison:

Case study	Parameter name	PI	Fuzzy	Hybrid Fuzzy-PI
Voltage sag	THD of source current (%)	3.95	3.60	3.31
	Settling time (secs)	0.17	0.04	0.04
	Steady state error (V)	3	18	3
Voltage swell	THD of source current (%)	4.03	3.91	3.57
	Settling time (secs)	0.12	0.04	0.04
	Steady state error (V)	2	15	2
Unbalanced supply voltage sag with phase jumps	THD of source current (%)	4.10	4.03	3.79
	Settling time (secs)	0.08	0.04	0.04
	Steady state error (V)	2	15	3
Sudden change in load	THD of source current (%)	4.08	3.90	3.85
	Settling time (secs)	0.06	0.05	0.05
	Steady state error (V)	3	18	3

Table 4: THD of source current, settling time and steady state errors of PI, fuzzy and Hybrid Fuzzy-PI controllers for various cases.

IV. CONCLUSIONS

The objective of this paperis to develop a UPQC simulation model as solutions to various power quality problems in distribution systems like voltage sags, swells, distortion, and sudden load change. A novel hybrid Fuzzy-PI controller was designed which combines the advantages of both PI and fuzzy logic controllers to give better steady state and dynamic responses. UPQC was simulated in MATLAB/Simulink using PI, fuzzy and hybrid fuzzy-PI controllers and the performance of UPQC using all the three controllers was compared. Simulation results show that the UPQC was successful for current harmonics such that the supply currents are in phase with line voltages even in dynamic conditions and its THD is within the acceptable limits. Also the compensation performance of UPQC remains unaffected even with unbalance and highly distorted supply voltage with SRF control. FFT analysis of supply current waveforms shows that with hybrid controller THD of supply currents is 0.5% less as compared to fuzzy controller and 1% less as compared to PI controller during dynamic operation. Also, that during dynamic conditions settling time and voltage peak of DC link capacitor using hybrid controller was nearly same as compared to fuzzy controller, which was much lower than that with PI controller. But with fuzzy controller, steady state error of about 15V was observed in dynamic conditions which was negligible with both PI and hybrid controllers. Thus, from the above discussion, it can be concluded that hybrid fuzzy-PI controller performs better than both PI and fuzzy controllers under both steady state and dynamic conditions.

REFERENCES

[1]. Arindam Ghosh and Gerard Ledwich, “Power quality enhancement using custom power devices”. Boston: Kluwer Academic Publishers, 2002.

[2]. C. Sankaran, "Power quality," (CRC Press, New York, 2001)

[3]. Hirofumi Akagi, “Active harmonic filters”, Proceeding of the IEEE, vol. 93, no. 12, pp. 2128-2141, December 2005.

[4]. J. Stones and A. Collinson, "Power quality," Power Eng. Journal, vol.15, pp.58-64, April 2001.

[5]. M. H. J. Bollen, "What is power quality?," Electric Power Systems Research, vol.66, pp.5-14, July 2003.

[6]. A.El Mofty,K. Youssef, "Industrial power quality problems," in Proc. on IEE Int. Conf & Exhib. on Electricity Distribution, 2001, vol.2, June 2001.

[7]. E.W.Gunther and H. Mebta, "A survey of distribution system power quality-preliminary results," IEEE Trans. Power Delivery, vol.10, pp.322-329, Jan.1995.

[8]. W.M. Grady, M.J. Samotyj and A.H. Noyola, "Survey of active power line conditioning methodologies," IEEE Trans. Power Delivery, 1990, 5,pp. 1536-1542.

[9]. H Akagi, "New trends in active Filters for power conditioning," IEEE Trans. Ind Applcat., 1996, 32, pp. 1312-1322.

[10]. S. Moran, “A line voltage regulator/conditioner for harmonic-sensitive load isolation,” in Proc. Ind. Appl. Soc. Annu. Meet. Conf., Oct. 1–5, 1989, pp. 947–951.

[11]. H. Fujita and H. Akagi, “The unified power quality conditioner: The integration of series and shunt-active filters,” IEEE Trans. Power Electron., vol. 13, no. 2, pp. 315–322, Mar. 1998.

[12]. Khadkikar and A. Chandra, “UPQC-S: A novel concept of simultaneous voltage sag/swell and load reactive power compensations utilizing series inverter of UPQC,” IEEE Trans. Power Electron., vol. 26, no. 9, pp. 2414–2425, Sep. 2011.

Elnady and M. M. A. Salama, “New functionalities of an adaptive unified power quality conditioner,” in Proc. Power Eng. Soc. Summer Meet., 2001, pp. 295–300.

[13]. H. Ryoo, G. Rim, T. Kim, and D. Kisek, “Digital-controlled single-phase unified power quality conditioner for non-linear and voltage sensitive load,” in Proc. 30th Annu. Conf. IEEE Ind. Electron. Soc., Nov. 2–6, 2004, pp. 24–29.

Ghosh, A. K. Jindal, and A. Joshi, “Inverter control using output feedback for power compensating devices,” in Proc. Convergent Technol. Conf., Oct. 15–17, 2003, pp. 48–52.

[14]. V. Khadkikar, A. Chandra, A. Barry, and T. Nguyen, “Analysis of power flow in UPQC during voltage sag and swell conditions for selection of device ratings,” in Proc. Can. Conf. Electr. Comput. Eng., May 2006, pp. 867–872.

[15]. Malabika Basu, Michael F. Conlon, “dc link voltage control of UPQC for better dynamic performance” ,Electric Power Systems Research 81 (2011) 1815– 1824.

[16]. Khadkikar, A. Chandra, A. Barry, and T. Nguyen, “Conceptual study of unified power quality conditioner (UPQC),” in Proc. IEEE Int. Symp. Ind. Electron., Jul. 9–13, 2006, pp. 1088–1093.

[17]. Muhammad H. Rashid, Power Electronics Handbook: devices, circuits, and applications. Elsevier, 2007.

[18]. S. Sajedi, F. Khalifeh, “Modeling and Application of UPQC to Power Quality Improvement Considering Loading of Series and Shunt Converters”, Australian Journal of Basic and Applied Sciences, 5(5): 300-309, 2011

[19]. B. N. Singh, A. Chandra, K. Al-Haddad, and B. Singh, “Fuzzy control algorithm for universal active filter,” in Proc. Power Quality Conf., Oct. 14–18, 1998, pp. 73–80

[20]. M. Zerikat and S. Chekroun, “Design and implementation of a hybrid fuzzy controller for a high perforance induction motor” World Academy of Science, Engineering and Technology, vol. 20, pp.263 2007.