Journal of Cybernetics and Informatics

published by

Slovak Society for
Cybernetics and Informatics

Volume 12, 2011

http://www.sski.sk/casopis/index.php (home page)

ISSN: 1336-4774

Journal of Cybernetics and Informatics 12 (2011)
http://www.sski.sk/casopis/index.php

FUZZY LOGIC-BASED UNIFIED POWER QUALITY CONTROLLER FOR ENHANCEMENT OF POWER SYSTEM STABILITY

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Abstract

The paper deals with a Unified Power Quality Conditioner (UPQC), which aims at the integration of series and shunt active power filters for enhancement of power system stability. The proposed UPQC consists of two independent active filters, each with its own dc link, a device known as "OPEN UPQC". The OUPQC is connected to a low voltage grid supplying industrial loads, mainly AC drives. Two controllers are proposed for operating the UPFC, namely a PI controller and fuzzy logic controller FLC. The fault ride through (FRT) ability of the FLC-based UPQC is investigated and compared with the FRT of a PI-based UPQC. This scheme also helps in maintenance cost saving and individual dealing with each customer. The comparison for each type of faults considered included time taken for fault recovery, harmonic level in waveforms, active and reactive power consumption, and system power factor. Also, switching the positions of the shunt and series devices is investigated to conclude the optimum connection status.

1 INTRODUCTION

Quality of the output power delivered from the utilities has become a major concern of the modern industries for the last decade. The ultimate objective of industries is to optimize the production while minimizing the production cost. To achieve this objective, a stable supply of un-interruptible power, balanced voltage of low harmonic content has to be guaranteed during the production process. The power quality associated problems such as voltage sag, surge, flicker, voltage imbalance, interruptions and harmonics cause problems to the industries ranging from malfunctioning of equipment to complete plant shut downs. Those power quality problems affect the microprocessor-based loads, process equipment, adjustable speed drives, automation devices, and power electronic components, which are highly sensitive to voltage level fluctuation, (Granaghan, 1993).

The blame due to degraded power quality is not solely due to the utility itself. Degraded power quality may be generated within the industry itself. For example, most of the non-linear loads within the industries cause transients, which can affect the reliability of the power supply. Some abnormal electrical conditions caused both in the utility end and the customer end that can disrupt a process are voltage sags, voltage swells, phase outages, harmonics, transients due to lighting loads, capacitor switching, non linear loads, etc. As the power quality problems originate from utility and customer sides, the solutions could be utility-based solutions and/ or customer based solutions. The best examples for those two types of solutions are FACTS devices (Flexible AC Transmission Systems) and Custom power devices. FACTS devices are those controlled by the utility, whereas the Custom power devices, installed at the customer premises, are operated, maintained and controlled by the customer. Uninterruptible Power Supplies (UPS), and Active Power Filters (APF) are examples for custom power devices. Unified power quality controller (UPQC) is an example of FACTS devices, (Dixon 2005). The UPFC is characterized by the unique capability to control simultaneously real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it is connected and to damp low frequency power system oscillations. Because of its attractive features, modeling and controlling an UPQC have come into intensive investigation in the recent years (Wei, 2005- Orizondo, 2006).

Almost all previous studies were carried out on the UPQC device constituted of a series and a shunt unit with a common dc link through which power can be exchanged (Wei, 2005- Guo, 2009). A recent study (Saribulut, 2008) suggested the OPEN UPQC (OUPQC) to guarantee different power quality levels to the final customers according to each customer demand. For a complete investigation of the performance of OUPQC, different device controllers have to be studied. In this paper, the performances of PI controlled OUPQC and FL-controlled OUPQC are investigated and compared. The proposed system is shown in Fig.1. First the OUPQC, the transmission line, and the AC drive are modeled. The two controllers are designed to suit the proposed load and power system. The fault ride through (FRT) capability of the power system supplying the AC drive and employing the Fuzzy Logic based OUPQC is compared with the FRT capability of the same system with the PI-based OUPQC. The comparison includes the time taken to restore the voltage value after symmetrical and unsymmetrical line to ground faults, voltage swells, frequency oscillations, the shape of the restored voltage waveforms, the THD, the active and reactive power consumed during and after fault, and the power factor. Simulation results showed that FL controlled OUPQC have faster fault ride through, lower harmonics, and higher power quality than PI controlled OUPQC.

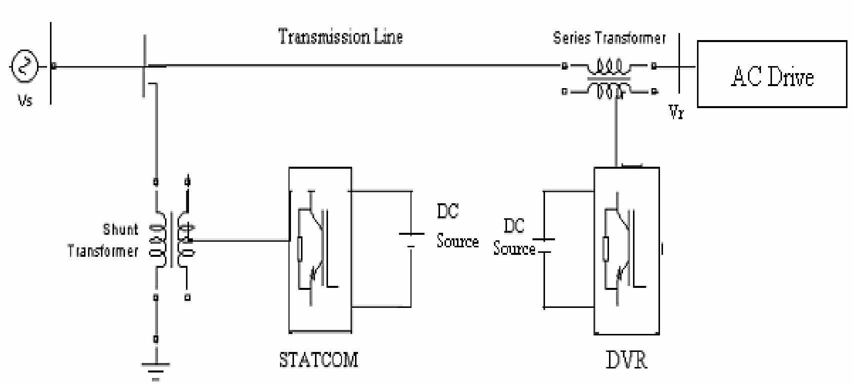


Figure 1: Power System supplying AC Drives

2 SYSTEM MODELLING

The proposed system shown in Fig. 1 consists of two buses, ac inverter connected to sending end as STATCOM with its own dc battery, a 3 phase ac inverter connected in series as a DVR to load bus. The AC drive connected to load bus and shown in Fig. 2, consists of a 3-phase PMSM motor, fed by a power conditioning unit consisting of a 3-phase diode rectifier and a 3-phase voltage source inverter composed of with 6 IGBTs.

2.1 Modelling AC Drive:

The Park equations of a PMSM are:

$$Vq = Rs\, Iq + p\, \lambda q + \omega \lambda d \tag{1}$$

$$Vd = Rs\, Id + p\, \lambda d - \omega\, \lambda q, \tag{2}$$

$$\lambda q = Lq\, Iq \tag{3}$$

$$\lambda d = Ld\, Id + \lambda m. \tag{4}$$

Where:

Vd, Vq: d and q- axis components of stator phase voltage
Rs: stator resistance
p: d/dt

Ld, Lq: d- and q- axis stator self inductance
λm: peak flux linkage due to permanent magnet.
ω:angular velocity rad/sec

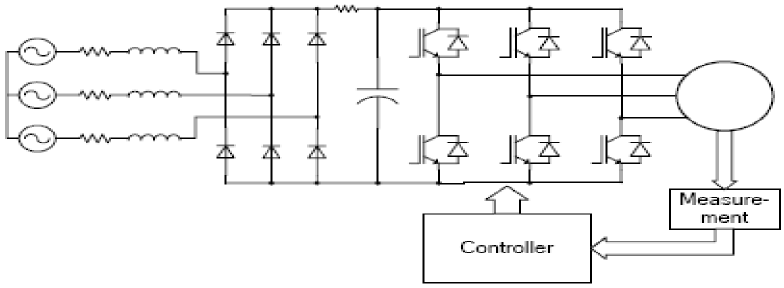


Figure 2: PMSM Drive

Equations (1) to (4) are used to model the PMSM in MATLAB/Simulink. The 3-phase inverter, implemented in Simulink consists of IGBTs, where the rectifier consists of diodes. PI controllers are adjusted for speed control of the drive. The PMSM drive represents the load to the power system under investigation. Varying reference speed changes the equivalent load and allows testing the response of the OUPFC under different conditions and harmonics due to switching IGBTs.

2.2. Transmission Line Model

The OUPQC is placed between two busses referred to as the sending bus and the receiving bus. The VSC at the sending bus is connected in shunt and will therefore be called the shunt voltage source. The second source, the series voltage source, is placed between the sending and the receiving busses. For mathematical analysis, an equivalent transmission line shown in Fig.3.

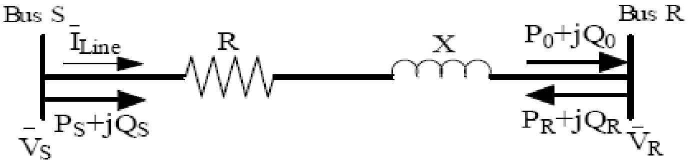


Figure 3: Equivalent Power System

For the system shown in Figure (3) the RMS voltages of the sending and receiving buses are:

$$\overline{V_s} = V_s \angle \delta_s \tag{5}$$

and

$$\overline{V_R} = V_R \angle \delta_R \tag{6}$$

I_{line} is phasor current on the line, R and X are resistance and reactance of the line respectively δs and δr are the phase angles of sending and receiving ends respectively.
The complex power injected into the sending bus:

$$S_S = P_S + jQ_S = \overline{V_S}\,\overline{I^*_{line}} \tag{7}$$

where P_S and Q_S are the real and reactive powers injected into the sending bus,
* denotes conjugate complex value.
The line current can be written as**:**

$$\overline{I_{line}} = \frac{\overline{V_S} - \overline{V_R}}{R = jX} = (\overline{V_S} - \overline{V_R})(G + jB) \tag{8}$$

where

$$G = \frac{R}{R^2 + X^2} \quad \text{and} \quad B = \frac{X}{R^2 + X^2}$$

Combining equations (5) to (8), the following expressions for the real and reactive powers injected into the sending bus are obtained:

$$P_S = V_S^2 G - V_S V_R G \cos(\delta_S - \delta_R) - V_S V_R B \sin(\delta_S - \delta_R)$$

$$Q_S = -V_S^2 B - V_S V_R G \sin(\delta_S - \delta_R) + V_S V_R B \cos(\delta_S - \delta_R)$$

Similarly, the real and reactive powers received at the receiving bus are:

$$P_o = -P_R = -V_R^2 G + V_S V_R G \cos(\delta_S - \delta_R) - V_S V_R B \sin(\delta_S - \delta_R)$$

$$Q_o = -Q_R = V_R^2 B - V_S V_R G \sin(\delta_S - \delta_R) - V_S V_R B \cos(\delta_S - \delta_R)$$

For typical transmission line X>>R. Therefore, the conductance G is usually neglected and suseptance B is replaced by B=-1/X. Using these approximations, the expression for real power transmitted over the line form the sending to the receiving bus becomes

$$P_s = -P_R = -V_s V_R B \sin(\delta_s - \delta_R) = \frac{V_s V_R}{X} B \sin(\delta_s - \delta_R) = \frac{V_s V_R}{X} B \sin\delta = P_o(\delta)$$

The angle $\delta = \delta_s - \delta_R$ is called the power angle.

The reactive power sent to the line from the sending bus and received from the line at the receiving bus are

$$Q_s = -V_S^2 B + V_S V_R B \cos(\delta_s - \delta_R) = \frac{V_S^2 - V_S V_R \cos(\delta_s - \delta_R)}{X}$$

$$-Q_R = V_R^2 B - V_S V_R B \cos(\delta_s - \delta_R) = \frac{-V_R^2 + V_S V_R \cos(\delta_s - \delta_R)}{X} = Q_o(\delta)$$

2.3 OUPQC Model

The conventional UPFC is the combination of two voltage source converters (VSC); one converter connected to the power system through a shunt transformer**,** while the second converter is inserted into the transmission line via a series transformer. The converters are connected by a common DC link. For the OUPFC proposed in this paper the common DC link is replaced by separate DC source in each converter, which allows shutting down any of two converters if not needed. This scheme also helps in reducing maintenance cost. It also allows individual dealing with each customer.

The main objective of the series converter is to produce an ac voltage of controllable magnitude and phase angle, and inject this voltage at fundamental frequency into the transmission line, exchanging real and reactive power at its ac terminals through the series connected transformer. The shunt converter provides the required real power at the dc terminals; thus, real power flows between the controller shunt and series ac terminals through the common dc link. The two converters and associated transformers are simulated with Matlab Simulink. The controllers (PI and FL) are designed for each converter, and the proposed system is tested under different fault conditions.

3 OUPQC CONTROL SCHEMES

The objective of OUPQC controlled by PI controllers and FL controllers is to enhance system stability by fast recovery from symmetrical, unsymmetrical ground faults,and voltage swells, and fast damping of low frequency oscillations. Controllers are designed for the proposed system load, AC drive, and its performance with each controller deduced and compared.

PI Control Scheme

The PI controller is designed for stabilizing power system voltage magnitude and frequency, which may be deteriorated by above mentioned faults or harmonics. A PI controller is designed for shunt converter , another for the series converter. Simulation results will be demonstrated side by side with FLC results for clear comparison.

Fuzzy Logic Control Scheme

Fuzzy logic is close in spirit to human thinking and natural language than other logical systems. It provides an effective means of capturing the approximate and inexact nature of systems (Saribulut, 2008- Dash, 2000). As the UPFC models are complex to derive, nonlinear equations are involved, and the equipment has a wide range of operation, it is plausible to think on a control strategy that could be based on a model-free approach. The basic structure of a fuzzy logic controller is presented in Fig. 4. In this paper, the kernel of the control is to substitute the conventional PI controllers explained above. This is done to maintain the simplicity and for comparing the overall performance of the fuzzy controller against conventional PI controller. The FLC objective is to track the reference voltage of the 3-phase system. The minimum-maximum method is applied for fuzzification, and the weighted center of area method is applied for de-fuzzification.

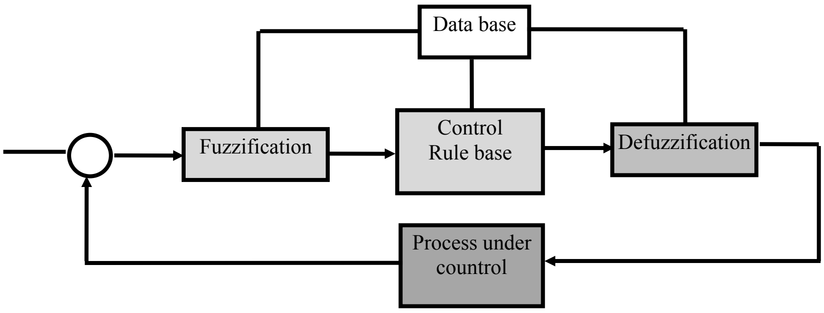


Figure 4: Basic Structure of FLC

To track the performance of the system for the sake of adjusting grid voltage, two variables are used as inputs to the FLC. The first input is the error in grid voltage, and the second input is the change of error. The output of the FLC is chosen to be the change of PWM signal applied to the switches of series and shunt converters.

In adjusting the system voltage via the OUPQC, four FLC, two for each inverter, are designed. Each inverter employs one FLC for the d-axis voltage component, and the other FLC for the q-axis voltage component. All controllers are of fixed structure in rules and member ships, but the only change is in the gain of input and output. The system uses seven triangular memberships for each variable as in Fig 5. The control rules of the system are defined in the following table:

		error						
		NL	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
Change of error	**NL**	**NL**	**NL**	**NL**	**NL**	**NL**	**NL**	**Z**
	NM	**NL**	**NL**	**NM**	**NM**	**NM**	**Z**	**PS**
	NS	**NL**	**NM**	**NS**	**NS**	**Z**	**PS**	**PM**
	Z	**NL**	**NS**	**NS**	**Z**	**PS**	**PS**	**PL**
	PS	**NM**	**NS**	**Z**	**PS**	**PS**	**PM**	**PM**
	PM	**NS**	**Z**	**PS**	**PM**	**PS**	**PM**	**PM**
	PL	**Z**	**PM**	**PS**	**PL**	**PM**	**PM**	**PM**

Where, N≡ negative, P≡ positive, L ≡large, M≡ medium, S≡ small, and Z ≡ zero

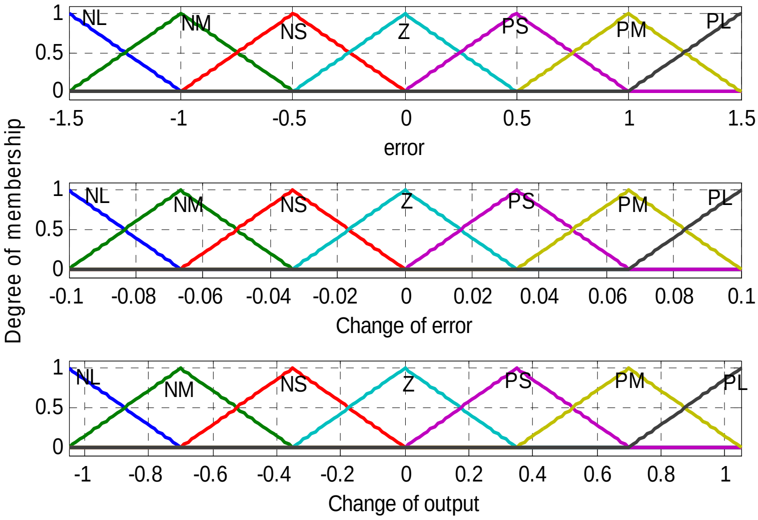


Figure 5: Membership functions for state 2I/P&1O/P.

4 SIMULATION RESULTS AND DISCUSSION FOR 3-PHASE GROUND FAULTS

The performance of the considered power system with the employed UPQC is evaluated for both designs, i.e. with PI controllers, and with fuzzy controllers, using the Matlab software package. A 3- phase voltage to ground fault is assumed at t=0.2 sec for 0.1 sec duration, as shown in Fig.6. The simulation results are given in Figs. 7 to Fig.11. Always Figure (a) represent system performance with PI Controller and Figure (b) represent system performance with Fuzzy Controller.

Fig.7 shows the voltage recovery after 3-phase voltage to ground fault, while Fig.8 shows the line current profile after fault recovery. It is obvious that the system with the fuzzy controller results in smoother voltage and current waveforms than the system with PI controller. This indicates that the line voltage has less harmonic contents in the system controlled by the FLC. This result is further proven from THD values of Fig.9, showing that the harmonic contents increase considerably due to the fault in case of PI controlled system, while it is much lower in FLC system (THD is 10% less in case of Fuzzy Logic Controlled system).

The active and reactive power profiles during and after fault recovery are shown in Fig.10. These profiles reveal the high reactive power consumption during fault with FLC, which is lower for PI controller. However the power factor given in Fig.11 is same for both systems. In spite of its average high with values of .9, the fault effect is obvious in PI Controller system, where dips and crests take place in power factor (PF) curve.

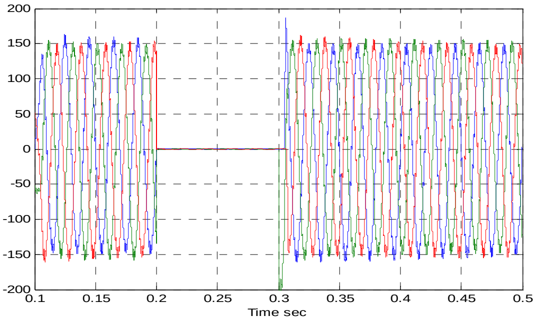
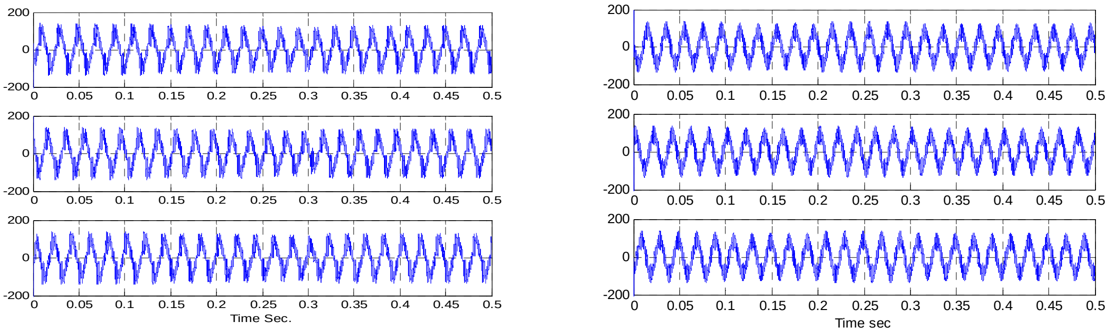
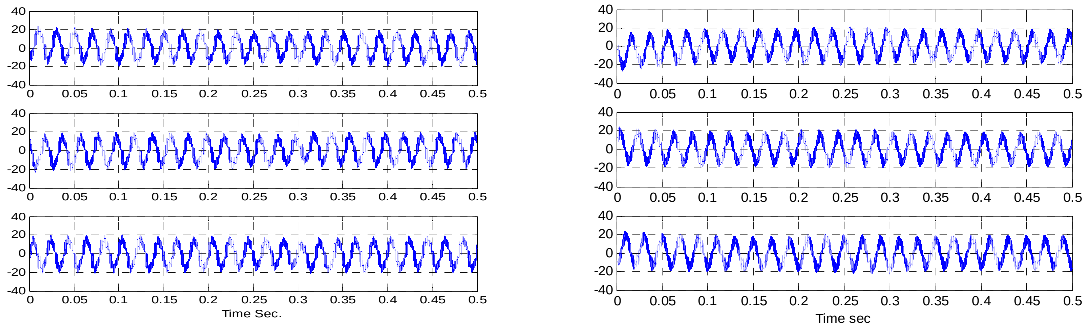


Figure 6: Ground Fault Profile



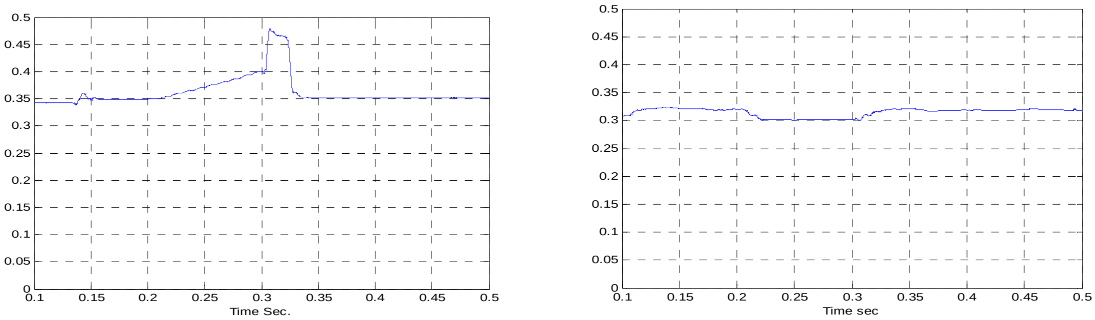
(a)PI Controller (b) FLC

Figure 7: Output Voltage



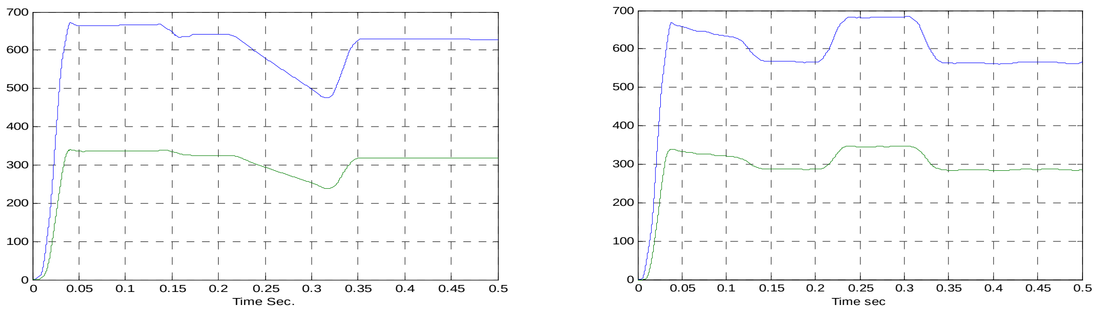
(a) PI Controller (b) Fuzzy Logic Controller

Figure 8: Line Current



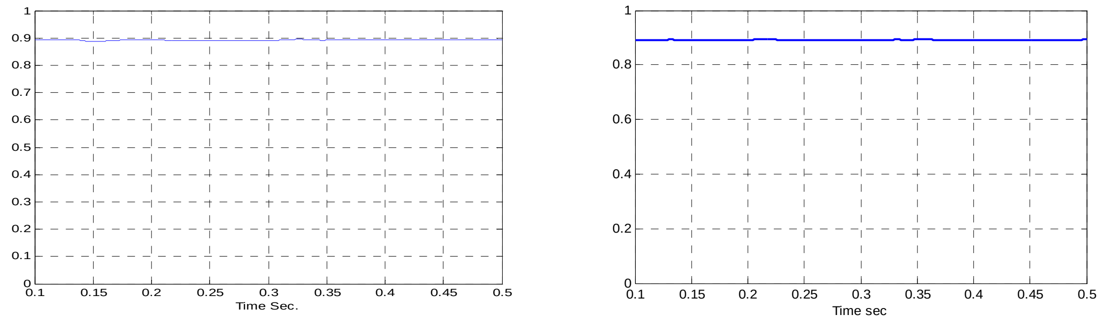
(a) PI Controller (b) Fuzzy Logic Controller

Figure 9: THD Harmonic



(a) PI Controller (b) Fuzzy Logic Controller

Figure 10: Active and Reactive Power

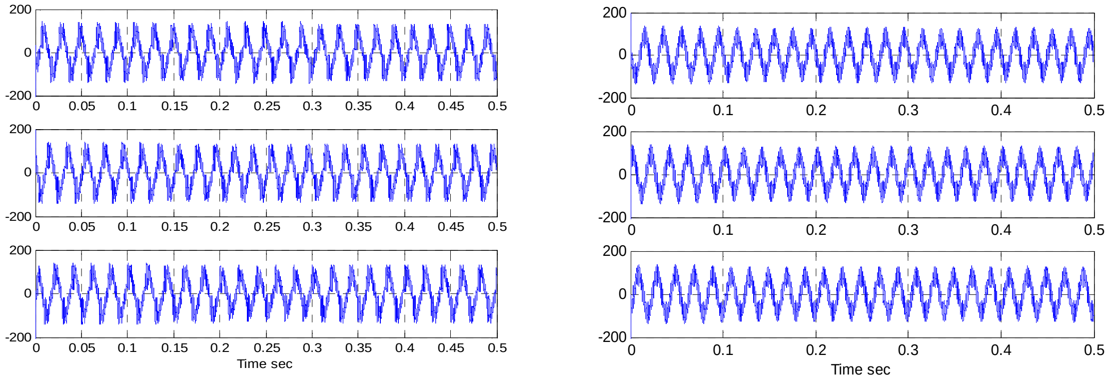


(a) PI Controller (b) Fuzzy Logic Controller

Figure 11: Power Factor

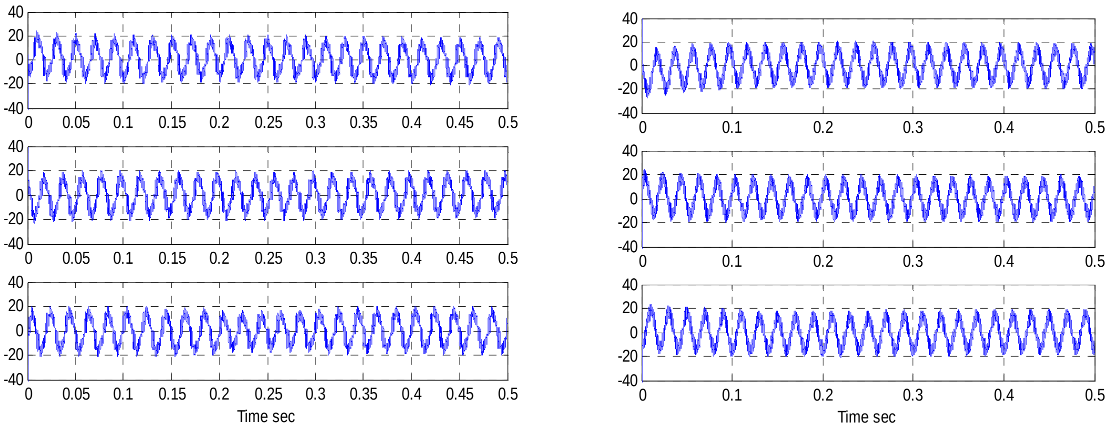
5 SIMULATION RESULTS AND DISCUSSION FOR UNSYMMETRICAL GROUND FAULT

The simulation results for single-phase ground fault are given in Figs. 12 to Fig.15. Fig. 12 and Fig.13 giving the line voltages and currents, reveal that voltage and current recovery is fast for both systems. However, the harmonic content in the waves of PI controlled system is higher than in FL controlled system as shown in THD values in Fig.14. The THD is higher by 20% in PI controller than the case of Fuzzy Logic Controller. The active and reactive power profiles during and after fault recovery are shown in Fig.15, showing a slightly higher consumption in active and reactive power in FL controlled system. Similar results are obtained for 2-phase ground fault, leading to same conclusion.



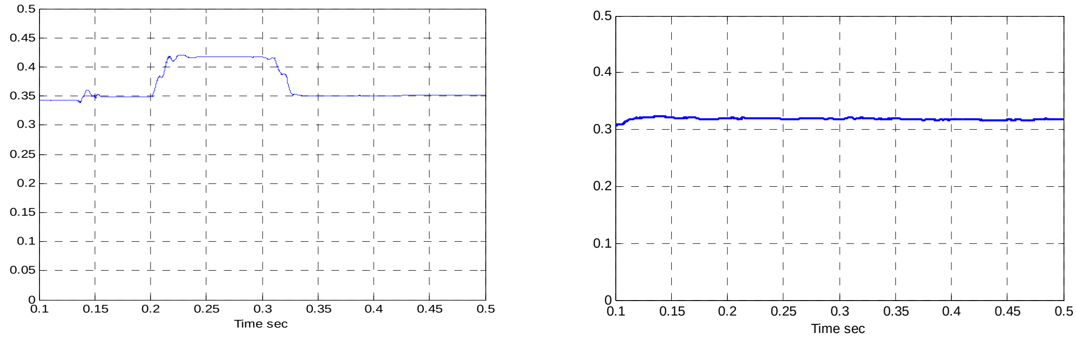
(a) PI Controller (b) Fuzzy Logic Controller

Figure 12: Output Voltage



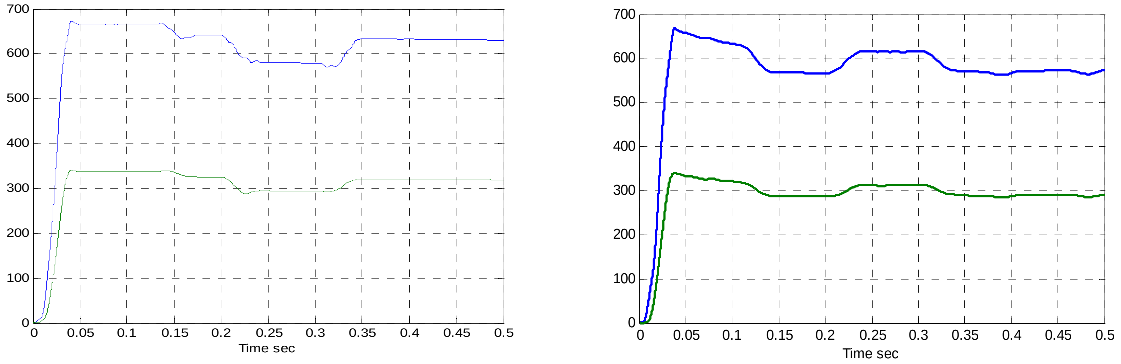
(a) PI Controller (b) Fuzzy Logic Controller

Figure 13: Line Current



(a) PI Controller (b) Fuzzy Logic Controller

Figure 14: THD Harmonic



(a) PI Controller (b) Fuzzy Logic Controller

Figure 15: Active and Reactive Power

6 SYSTEM RESPONSES AFTER FREQUENCY OSCILLATION

A change in triggering of IGBT converter, connected to PM machine leads to oscillation of higher frequency than grid frequency. This change may be done to change reference speed or applied load. An oscillation of 300Hz associated with a swell in voltage is assumed for 0.3 seconds as shown in Fig.16. The parameters of FLC and PI are tuned to allow oscillation damping. Results are shown in Figs.17-19. Fig. 17 and Fig.18 prove fast damping of both output voltage and line current for the two controllers. Fig.19 showing active power (P) and reactive power (Q) response during fault prove the superiority of FLC over PI, since P and Q in case of FLC are slightly affected while high P and Q are drawn from grid in the case of PI controller.

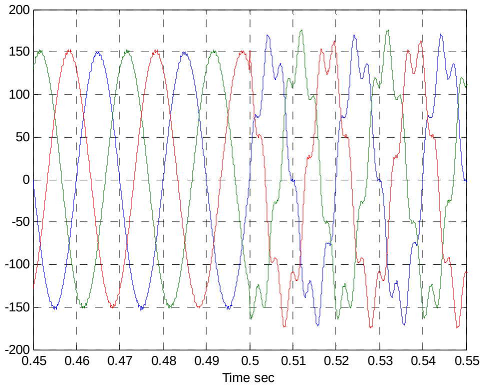
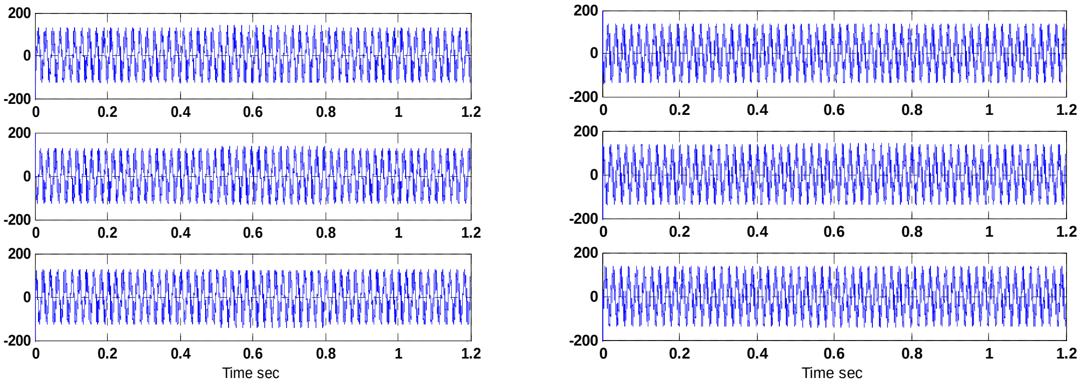
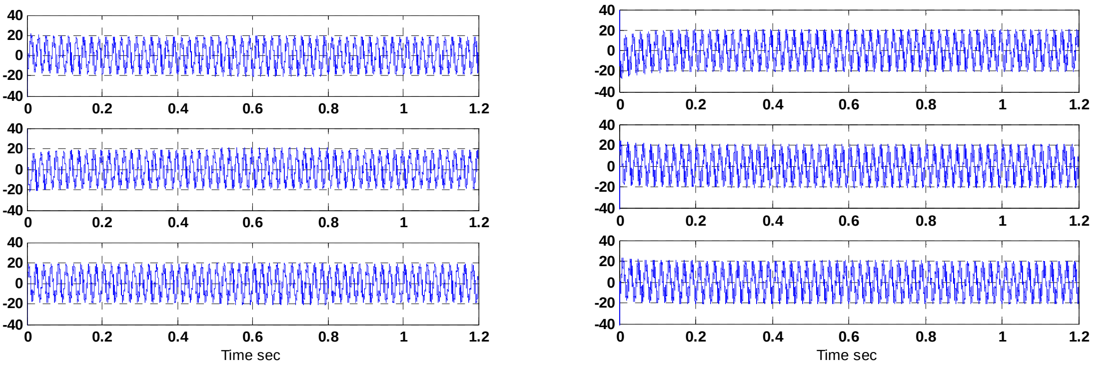


Figure 16: Oscillation 3 phase voltage



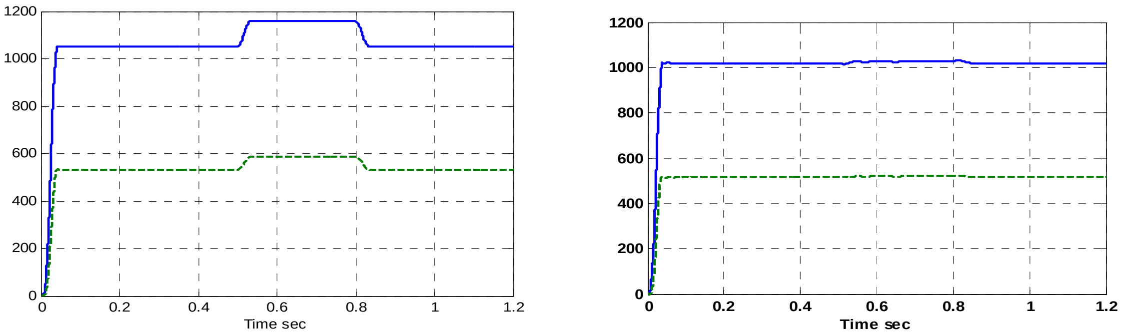
(a) PI Controller (b) Fuzzy Logic Controller

Figure 17: Output Voltage



(a) PI Controller (b) Fuzzy Logic Controller

Figure 18: Line Current



(a) PI Controller (b) Fuzzy Logic Controller

Figure 19: Active and Reactive Power

7 SWITCHING POSITIONS OF DVR & STATCOM

To conclude the optimum position of the two devices, positions of DVR & STATCOM are switched. DVR is connected to grid side while STATCOM is connected to load side, a 3-phase short circuit fault is assumed and system response tested using PI controller. Voltage waveforms shown in Fig.20 reveal the slow voltage recovery, which consequently affected P&Q shown in Fig.21 where stable condition are reached after approximately twice the time needed when STATCOM was connected to grid side.

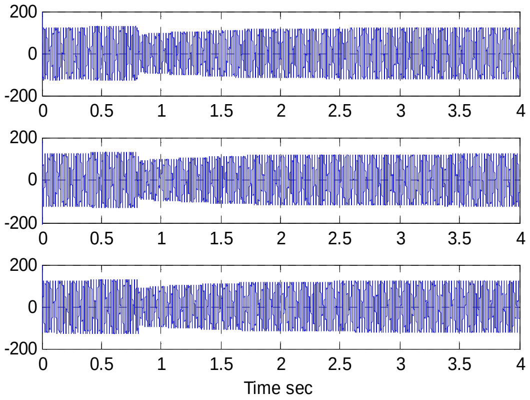


Figure 20: Output voltage

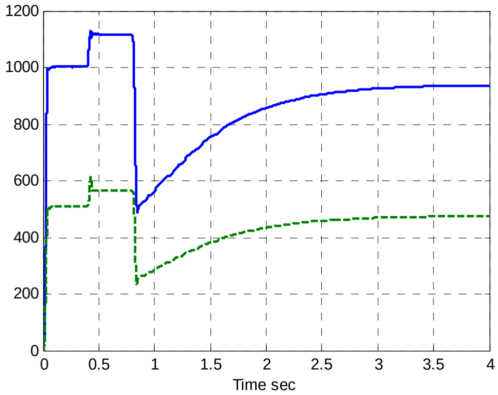


Figure 21: Active and Reactive Power

8 CONCLUSION

A new UPQC scheme is proposed where the shunt and series converters are separated with individual storage. This scheme is defined as OPEN UPQC (OUPQC). The fault ride through (FRT) ability of a fuzzy logic-Controlled OUPQC is investigated and compared with the FRT of a PI- Controlled OUPQC. First, both systems are modeled, and simulation results obtained. The performance of the two systems are presented and compared for symmetrical 3 phase ground faults, for un-symmetrical ground faults, oscillations associated with voltage swell, and switching positions of STATCOM and DVR. Comparison included time taken for fault recovery, voltage and current waveforms, harmonic level in waveforms (THD), and active and reactive power consumption. Results revealed faster FRT and lower harmonics for FL-based OUPQC in case of symmetrical faults. However, active and reactive power consumptions are comparable in both systems.

For unsymmetrical faults, the voltage and current waveforms for the PI-controlled system are highly distorted. This is not the case in FL-controlled system where these waveforms are smoother with 40% lower THD. However, the active and reactive power consumptions during fault are higher in FL-controlled system. These results led to conclude that FL-controlled system is preferred than PI- controlled system due to its faster FRT and lower THD, in spite of its slightly higher power consumption during unsymmetrical faults.

FLC proved to be more effective than PI controller in damping low frequency oscillation associated with voltage swell, where fast voltage recovery and minimum variation in P and Q took place.

Reversing positions of DVR and STATCOM with assumed 3-phase fault to ground led to longer time for voltage recovery, and consequently the active and reactive power are stabilized after twice time needed when DVR was connected to the load side.

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