Mitigation of Power Quality Problems of Grid Connected System with UPQC using Adaptive Neuro Fuzzy Inference System (ANFIS)

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Abstract: ***Mitigation of a three-phase three wire Unified Power Quality Conditioner (UPQC) controlled with Adaptive Neuro Fuzzy Inference System (ANFIS) based controller is presented in this project. UPQC is a custom power device which is integrated by series and shunt active power filters (APF) sharing a common dc bus capacitor. The shunt and series APFs are realized with the help of three – phase, three leg voltage source converters that are sharing a common DC capacitor. The fundamental voltages, currents are extracted by modified synchronous reference frame technique; switching pulses for both the filters are generated by conventional hysteresis based controller. The capacitance voltage is balanced by ANFIS based controller. Performance of the ANFIS based control algorithm of shunt active filter with series active filter is evaluated in terms of eliminating the power quality problems in a three phase, three-wire distribution system with non-linear and unbalanced load conditions. Adaptive Neuro Fuzzy logic control is used for dc capacitance balancing. System taken for test and the control algorithm are implemented with the help of Sim power systems and ANFIS editor of MATLAB / SIMULINK.***

Keywords: ANFIS, APF, Non Linear Load, UPQC

1. Introduction

Power Quality studies have emerged as a significant topic because of the extensive use of sensitive electronic equipments [6]. A broad definition of power quality that includes the definitions of technical quality and supply continuity states that the limits specified in the standards and regulations should not be exceeded by electrical PQ or in other words frequency, number and interval of interruption, interruption in voltage, sine waveform and voltage unbalance [3]. Nowadays power quality is definitely a big issue and the inclusion of advanced devices, whose functioning is extremely sensitive to the quality of power supply, makes it especially important [7]. Due to the increasing anxiety over supplying pure electrical energy to the consumers in the availability of non- sinusoidal waveforms, PQ has gained much interest in recent years. [9]. Huge number of non-linear loads and generators on the grid, especially systems based on power electronics like variable speed drives, power supplies for IT-equipment and high efficiency lighting and inverters in systems producing electricity from renewable energy sources have made electrical energy systems, voltages and specifically currents extremely irregular [8]. Degradation or impairment can occur in the electrical equipments connected to the system as a result of poor PQ [2]. The increased anxiety has resulted in measurement of changes in PQ, analysis of power disturbance characteristics and generation of solutions to the PQ problems [4]. Any apparent problem in voltage, current that gives rise to any frequency variations leading to breakdown or malfunction of customer equipment is termed as the PQ problem [1] [10]. A PQ problem can be caused by several events. As a switching operation within the facility to a power system may be associated with the cause of a fault event located hundreds of miles away from that place, analysis of these events is frequently difficult [12]. PQ problems include short disruptions, long disruptions, voltage sags and swells, harmonics, surges and transients, unbalance, flicker, earthing defects and electromagnetic compatibility (EMC) problems [5]. Undesirable effects like extra heating, intensification of harmonics because of the existence of power factor correction capacitor banks, decrease of transmission system efficiency, overheating of distribution transformers, disoperation of electronic equipment, improper functioning of circuit breakers and relays, incorrectness in measuring device, interference with communication and control signals etc are caused by these PQ problems [17]. Lessening the PQ problems and supporting the functioning of sensitive loads are possible because of Power Electronics and Advanced Control technologies [13]. The quality and reliability of electric power distribution systems are reported to be improved by Custom Power Devices (CPDs). Three major CPDs are D-statcom, DVR and UPQC. One of the foremost custom power devices that are competent of alleviating the consequence of power quality problems at the non linear load is the UPQC [14] [15]. In addition to removal of harmonics, recompense for reactive power, load current unbalance, source voltage sags, source voltage unbalance and power factor correction are provided by UPQCs [11] [18]. In power distribution systems or industrial power systems, UPQC has the outstanding potential to enhance the quality of voltage and current at the position of installation. Generally, an UPQC is comprised of two voltage source inverters (VSIs) sharing with one DC link capacitor. Here, the main problem is that the discharging time of DC link capacitor is very high. To mitigate this problem, an enhanced ANFIS based UPQC is proposed.

2. UPQC Control Strategy

UPQC mainly includes three parts: the series active power filters, shunt active power filters and energy storage capacitors. The series and shunt active power filter couples together through the DC-link energy storage capacitors.

Series APF connected to the grid and load by coupling transformer is mainly used to adjust the load voltage amplitude and compensate the power supply voltage sag in the controlled voltage source mode. Shunt active filter connected to the load is used to compensate load currents.

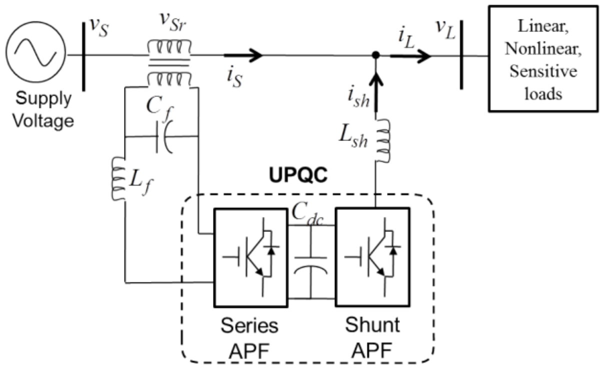

Figure 1: Topology of UPQC

A. Series APF

The Series APF is also known as the Static Synchronous Series Compensator (SSSC). It is a three leg three phase Graetz bridge converter with a DC side and a three phase AC side. The three phase AC side is connected across one side of a three phase transformer and the other side of this transformer is in series with the three phase AC bus bar as shown in Fig. 1. The objectives of the SSSC are, To insert a series voltage along the AC bus bar. This series insertion of voltage at appropriate phase and magnitude can help compensate sag or swell in the bus voltage. Voltage sag and swell can be smoothened by the SSSC such that the voltage across the load is fairly constant. The fluctuations in voltage across the load can adversely affect the power delivered to the load. Under conditions of voltage sag and swell propagated from the source side, the responsibility of maintenance of constancy of voltage across the load and hence the delivery of the required power to the load rests with the SSSC. Insertion of the compensating series voltage can be carried out only from a real power source and, as such, the DC side of the SSSC should be connected across a DC link where there is a possibility of drawing real power. In the case of UPQC the DC link is maintained at desired DC potential and the energy stored in the DC link is backed up by the STATCOM in real time. A PWM generator generating synchronized switching pulses switches the six switches of the SSSC. The objectives of the SSSC can be achieved by appropriately supplying the switching pulses. The generation of the switching pulses is governed by the three phase reference signal that is produced by the contribution of two controllers. The control objectives of the two controllers influence the generation of the reference signal and this leads to the operation of the SSSC meeting out its requirements.

B. Shunt APF

The shunt converter is a three leg three phase Graetz bridge converter with a DC side and a three phase AC side. The three phase AC side is connected across the three phase AC bus bar at the point of common coupling through a voltage transformer and a series reactor as shown in Fig. 1. A PWM generator generating synchronized switching pulses switch the six switches of the three leg shunt converter. The objectives of the shunt convertor can be achieved by appropriately supplying the switching pulses. The generation of the switching pulses is governed by the three phase reference signal that is produced by the contribution of two controllers. The control objectives of the two controllers influence the generation of the reference signal and this leads to the operation of the convertor meeting out its requirements. There are two controllers associated with the shunt converter. The shunt converter is a three leg three phase Graetz bridge converter with a DC side and a three phase AC side. The three phase AC side is connected across the three phase AC bus bar at the point of common coupling through a voltage transformer and a series reactor. [3]. A PWM generator generating synchronized switching pulses switch the six switches of the three leg shunt converter. The objectives of the shunt convertor can be achieved by appropriately supplying the switching pulses. The generation of the switching pulses is governed by the three phase reference signal that is produced by the contribution of two controllers. The control objectives of the two controllers influence the generation of the reference signal and this leads to the operation of the convertor meeting out its requirements [4]. There are two controllers associated with the shunt converter.

3. Mathematical Model of UPQC

A UPQC distribution system is shown in Fig. 2. Vs is the source voltage, Vse is series converter voltage compensation, Ish is shunt converter current compensation and VL is the load voltage. It consist of load that supplied by a source voltage through a feeder system. Feeder impedance Zs is a combination of R and XL. The shunt converter injects the current Ish such that the source current is balanced and distortion free irrespective of IL. The series converter and shunt converter can control the load voltage and source current. Due to the voltage distortion, the system may contain negative phase sequence and harmonic components [8]. With respect to the basic topology the UPFC and the UPQC are similar. However the objectives of these two make differences in the control scheme implemented and this makes the total difference between the two. The objectives of the UPFC are included among the other objectives of the UPQC.

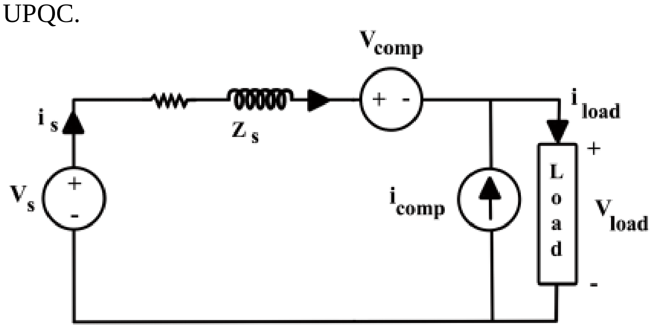

Figure 2: UPQC Distribution System

To obtain a balance sinusoidal load voltage with fixed amplitude V, the output voltages of the series converter should be given by

$$V_{se} = (V - V_p)Sin(\theta + \theta_P) - V_n(t) - \sum_{k=2}^{\alpha} V_K(t) \quad (1)$$

V_p : Positive Sequence Voltage Amplitude Frequency

θ_P : Initial Phase of Voltage for Positive Sequence

V_n : Negative Sequence Component

The shunt converter acts as a controlled current source and its output components should include harmonic, reactive and negative-sequence components in order be to compensate these quantities in the load current, when the output current of shunt converter is kept to be equal to the component of the load as given in the following Equation (2).

$$I_L = I_p Cos(\theta + \theta_P) Sin\phi_P + I_n + \sum_{k=2}^{\alpha} I_L(k) \quad (2)$$

As seen from the above equations that the harmonics, reactive and negative sequence current is not flowing into the power source. Therefore, the terminal source current is harmonic-free sinusoid and has the same phase angle as the phase voltage at the load terminal.

ϕ_P : Initial Phase Current for Positive Sequence

$$I_S = I_p Sin(\theta - \theta_P) Cos\phi_P \quad (3)$$

The source side three phase voltages, Va, Vb and Vc are sinusoidal in nature. And these quantities are to be converted into equivalent DC quantities and then used in the controllers. The conversion of the three phase sinusoidal voltages denoted as Vabc into Vd ,Vq and Vo in the rotating frame is known as D-Q transformation or Park transformation. The vector (Va Vb Vc) can be transformed into another vector (Vd Vq Vo) with the help of a transformation matrix. It can be viewed that,

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} Sin\theta & Sin(\theta - \frac{2\pi}{3}) & Sin(\theta + \frac{2\pi}{3}) \\ Cos\theta & Cos(\theta - \frac{2\pi}{3}) & Cos(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (4)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} Sin\theta & Cos\theta & 1 \\ Sin(\theta - \frac{2\pi}{3}) & Cos(\theta - \frac{2\pi}{3}) & 1 \\ Sin(\theta + \frac{2\pi}{3}) & Cos(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix} \quad (5)$$

The elements of the vector (Va, Vb, Vc) and the elements of the transformation matrix are time varying but the elements of the output vector (Vd ,Vq ,Vo) are not time varying. However, any change in the amplitude of either of Va, Vb or Vc is reflected in the elements of the vector (Vd, Vq, Vo). Park transformation is the conversion of the three phase system of voltages which are 120^o displaced and varying in a sinusoidal fashion into another system of three elements which are just constants. However, in the transformed system the element Vo is zero if the three phase system is balanced. The elements Vd and Vq are orthogonal in nature such that they do not have any influence on each other. In a typical control system both Vd and Vq can be changed individually without affecting the other.

4. ANFIS Controller

ANFIS system is the implementation of PI, Fuzzy and Neural controller. Fig. 3 shows the proposed controller for unified power quality conditioner with ANFIS controller. The ANFIS controller implemented in this article is of the model described as above whose fuzzifier section comprise the input signals error (E) and change in error signal (CE) whose membership functions are selected as Gaussian membership function and are classified into seven functions namely Negative Big (NB); Negative Small (NS); Zero (ZE); Positive Small (PS);Positive Medium (PM). As for the first step a set of four fuzzy logic controllers are designed two each for the STATCOM and the SSSC respectively.

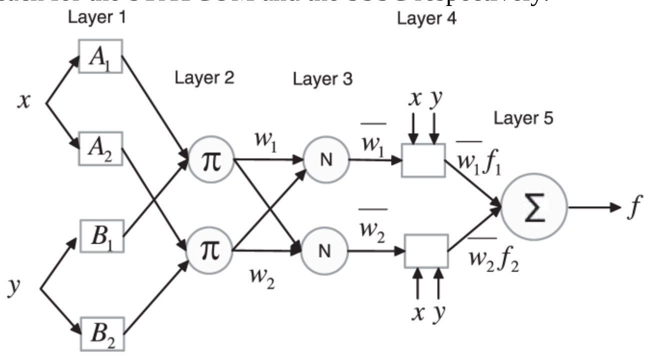

Figure 3: ANFIS architecture

Fig. 3 ANFIS structure The ANFIS structure of is shown above. The ANFIS structure used here have 7 rules. The rules are created by using one input. One input is DC link error Voltage and output is regulated DC output voltage. From membership function plots of both inputs, rules are created. Combining fuzzy logic and neural networks is a powerful tool in controlling, forecasting and modeling of composite systems such as photovoltaic systems. ANFIS constructs an input output mapping is based on both human knowledge and generated input output. The flow chart of the ANFIS system shown in Figure 4. In this process pair of input-output data sets under different weather conditions is collected by simulation and trained by ANFIS controller.

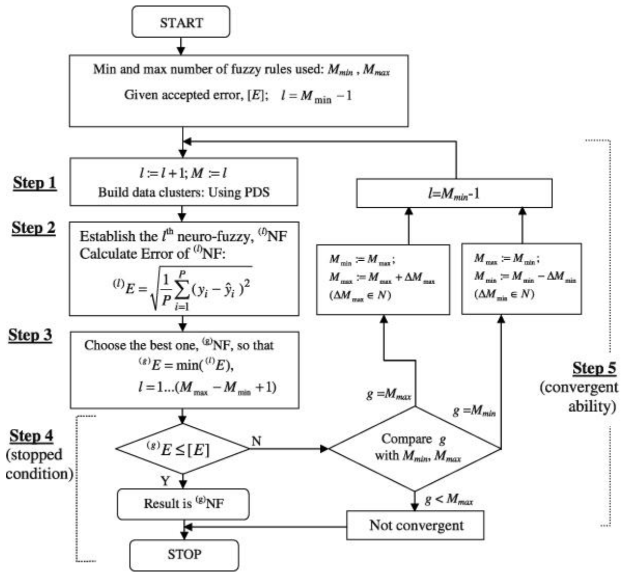

Figure 4: ANFIS UPQC system flow chart

Step-1: At first the initialization of the input variables called the parameters is done which is in a binary form and the input variables are fuzzy field. Step-2: After input fuzzification, output fuzzification is done by applying fuzzy operators like AND, OR operators. Step-3: Membership functions are defined and are computed to track the given input/output data. Step-4: The parameters associated with the membership function changes through the learning process. Step-5: Fuzzy rules are created basing on the input output relationship of the system. Step-6: After creating rules, aggregation of various outputs is done and then the resulted functions are de fuzzyfied to get an optimal output. Step-7: The obtained output is then trained by applying it to the Neural network through the back propagation method. Step-8: The error is minimized by performing various iterations in the Neural network and we get an optimized output.

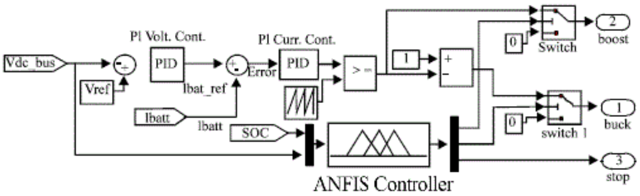

Figure 5: Simulation Model of ANFIS control

ANFIS is one of the recent controllers used for regulate dc-link voltage for UPQC. In this paper ANFIS based UPQC is on produced to regulate dc link voltage. This technique is used for the compensating current to eliminate the harmonics and it can be generated by the system. The membership function can be optimized by using fuzzy logic implemented network neuron. ANFIS can construct an input/output mapping and set up the data pairs based on both human knowledge in the form of fuzzy IF-THEN rules and simulation input output membership function and rules can be created using fuzzy logic. The various researches have been performed in the power quality maintenance. Some of the devices such as dynamic voltage restorer (DVR), uninterruptible power supplies (UPS) and many devices used for maintaining the quality power supply. But, these devices are capable of maintaining the power quality in the distribution network .Hence this paper, a new technique a neuro fuzzy based on Takagi Sugeno fuzzy inference system is introduced. The generated fuzzy rules can be trained by using the neural network and we get a desired output of an UPQC FACTS device, designed for both compensate both source side and load side problems.

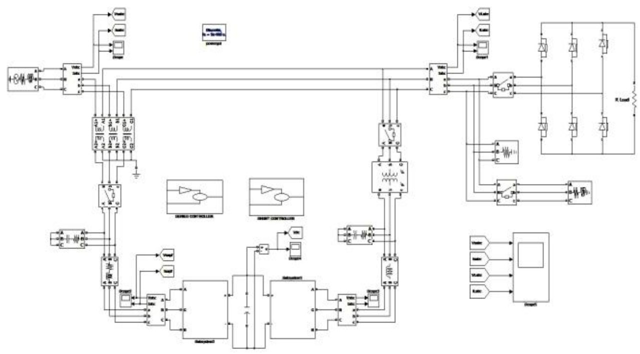

Figure 6: Simulation model of ANFIS based UPQC

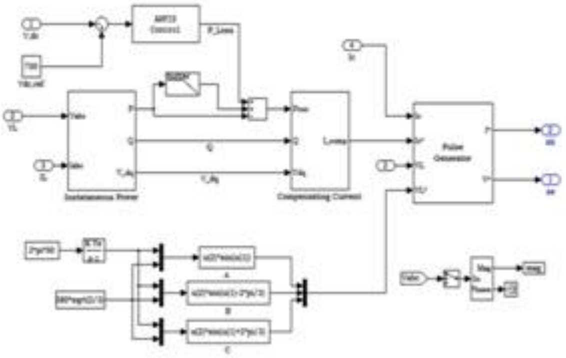

Figure 7: Simulation model of UPQC control

The UPQC combines shunt active filter and series active filter in a back to back connection, to reduce the power quality problems and power factor correction in a distribution network. Reactive can be performed. Hence this paper proposed Neuro fuzzy technique can be used to regulate DC link voltage of a DSTATCOM and load waveforms can be maintained as constant. The DC link capacitor voltage maintained as constant level. The training data set for ANFIS by varying the working date. There is 2000 training data set and 500 epochs are used to train the ANFIS reference model. The training error condensed to approximately 0.09%, Figure 5 is shown in flow chart for execution of ANFIS based controller. The deliberate ANFIS organizer has also two inputs voltage V_S, and V_L dc capacitor link voltage V_{DC}, and one output duty cycle (D). The two inputs V_S, V_L and V_{DC} variables produce a control signal D(t) which is execution to the inverter to adjust the duty cycle. The proposed controller is conscious to take advantage of simplicity and eliminate the slow converging, oscillation around the maximum voltage, and during transient period.

5. Simulation Results

The proposed control scheme is developed in MATLAB/ SIMULINK environment. Simulation parameters as specified have been used for this purpose. In order to introduce nonlinear load a three phase diode bridge with RL load on dc side is used. The simulation results for compensation of voltage sag/swell, compensation of current and voltage harmonics are presented

a) Voltage and Current Harmonic Compensation Analysis

The below Fig.8 shows the simulation result of voltage and current harmonic mitigation simultaneously. Fig. 8(a) shows the introduction of 5th (20%) and 7th (20%) order voltage harmonics at 0.1 sec for a duration of 0.11 sec into the source. voltage. This distortion is done deliberately to study the harmonic compensating capability of UPQC (with ANFIS) to source voltage. The series APF injects an out-of phase voltage with 5th and 7^{th} harmonic which is the difference between the desired load voltage and actual supply voltage after 0.1sec as realized in Fig. 8(b). The load voltage profile can be seen from which is free from any distortion. Current harmonics generated by the nonlinear load is compensated by the Shunt APF. The load current can be seen in Fig. 8(f). The shunt APF injects a current in such a manner that the source current (Fig. 8(e)) becomes sinusoidal. The improved source current profile is observed in Fig 8(d).

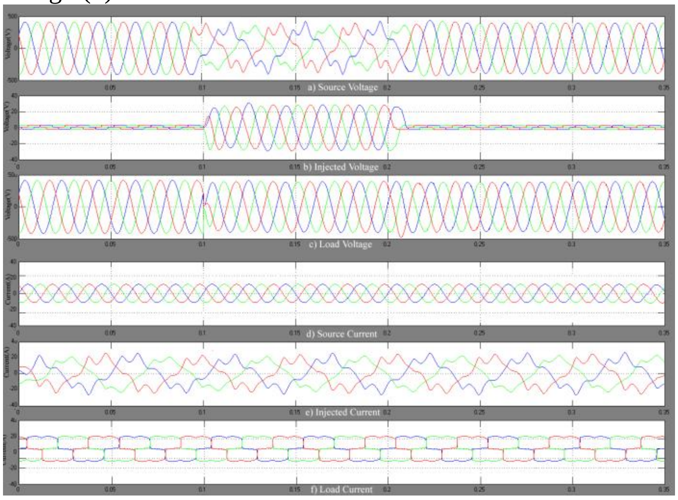

Figure 8: Simulated results of UPQC (a) Source Voltage (b) Series injected Voltage (c) Load Voltage (d) Source Current (e) injected Current (f) Load Current

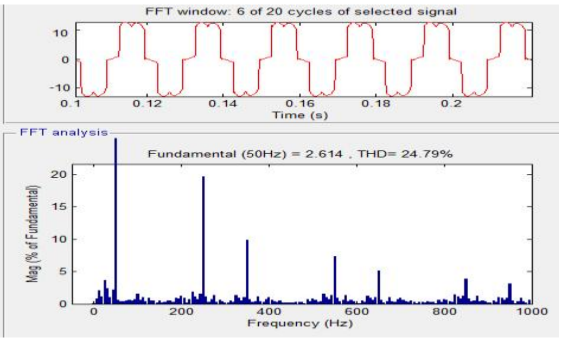

Figure 9 (a)

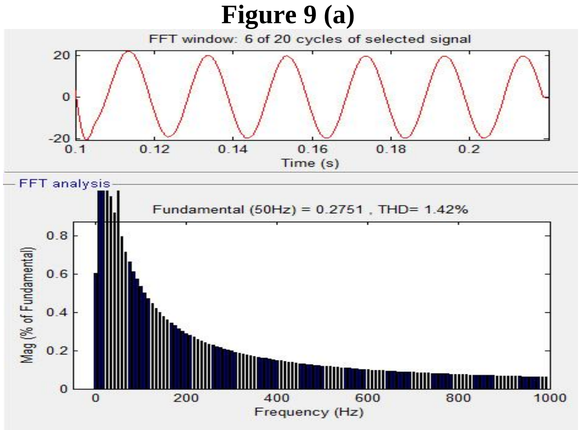

Figure 9 (b)

Figure 9: Total Harmonic Distortion (THD) (a)Load Current THD (b) Source Current THD

Fig. 9(a-b) shows the harmonic spectrum of load current and source current for phase-a after UPQC with ANFIS is put in operation. THD of load current is 24.79%. With shunt APF in operation there is a significant reduction in THD at source side current from, 24.79% to 1.42% Shunt APF is able to decrease the current harmonics entering into source side.

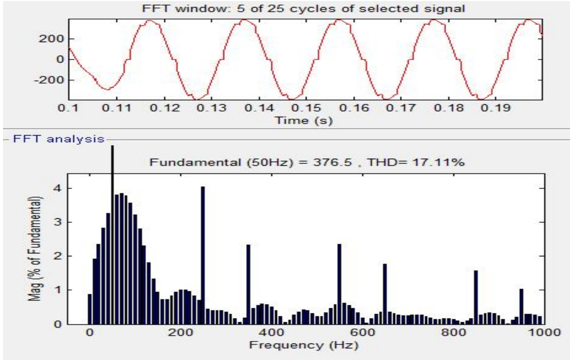

Figure 10 (a)

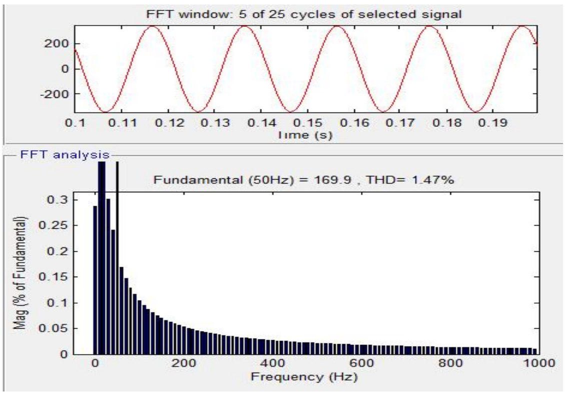

Figure 10 (b)

Figure 10: THD (a) Source Voltage (b) Load Voltage

Fig. 10(a-b) shows the harmonic spectrum of source voltage and load voltage for phase-a. THD of source voltage is 5.20%. With the UPQC (with ANFIS) there is a significant reduction in load voltage THD from 17.11% to 1.47%. Series APF prevents the harmonics from disturbing the load voltage.

b) Voltage Sag and Current Harmonic Compensation

The simulation result of voltage sag and current harmonic compensation is observed in Fig.11. A sag (20%) is introduced to the supply voltage at 0.1sec. and lasts till 0.21 sec. as shown in Fig. 11(a). Fig. 11(b) shows the injected in phase voltage from the series APF. This voltage is the difference between the desired voltage at the load side and the actual voltage at the source side. Thus, UPQC is able to maintain the desired level of the load voltage (Fig. 11(c)) so that the source side sag in voltage does not affect the load side voltage. The UPQC requires some supply of active power so that the in-phase voltage can be injected. This power is drawn from the source by shunt inverter, by taking extra current component to keep the DC link voltage at fixed level. If it is not maintained, the DC link voltage will drop to very low value in very few cycles. The current drawn by shunt inverter is shown in Fig. 11(e) (between time 0.1 sec. and 0.21 sec.), and the consequent increase in the magnitude of the source side current is also noticed accordingly in Fig. 11(d).

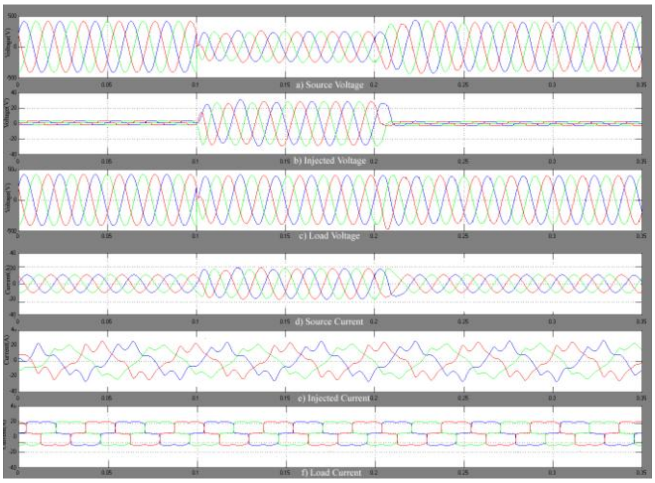

Figure 11: Simulated results of UPQC (a) Source Voltage (b) Series injected Voltage (c) Load Voltage (d) Source Current (e) injected Current (f) Load Current

c) Voltage Swell and Current Harmonic Compensation

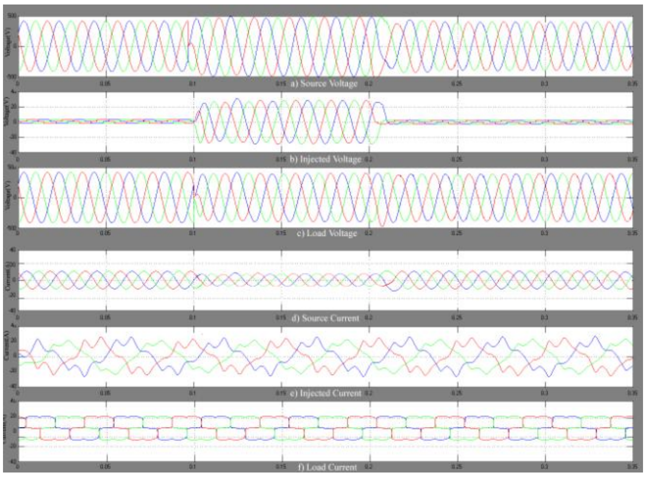

Figure 12: Simulated results of UPQC (a) Source Voltage (b) Series injected Voltage (c) Load Voltage (d) Source Current (e) injected Current (f) Load Current

The simulation result of voltage swell compensation is shown in Fig. 12. A swell (20%) is introduced to the supply voltage at 0.1 sec. and lasts till 0.21 sec as shown in Fig. 12(a).The voltage sag and swell conditions are opposite to each other. Therefore, during a source side voltage swell, the series APF now injects out-of phase voltage equal to the difference between the desired voltage at the load side and the actual voltage at the source side (Fig. 12(b)). Hence, the UPQC cancels the increased source voltage that may appear at the load side and keeps the desired level of the load voltage (Fig. 12(c)). The increase in source side voltage reflects that the utility is supplying some extra power to the load. This may damage equipments and loads due to the increase in current drawn by them. At the same time, the rise in source voltage results in the increase of the DC link voltage. Under aforesaid situation, out-of phase fundamental current component is injected by the shunt APF (Fig. 12(e)) between instants 0.1sec and 0.21 sec. to keep fixed DC link voltage level. Accordingly there is a consequent decrease in the magnitude of the source
side current (Fig. 12(d)).

d) Comparison and Performance analysis

The performance analysis of the ANFIS based controller for the UPQC can be appreciated by comparing the results of the multiple controllers. Performance analysis of PI, Neural Network and ANFIS controller which are modulated with the UPQC are shown in Table 1. From the results, THDs are maintained within the permissible limits. The source voltage under distorted condition from 0.1sec to 0.21sec undergoing sag condition which is shown in Fig. 11(a). The source voltage with sag/swell before compensation has THDs of 17.11% (Fig. 10(a)) in R phase. The load voltage with sag/swell after compensation has THDs 1.47% (Fig. 10(b) in R phase respectively. An unbalanced created in load condition, the shunt compensator forces the load current to be sinusoidal in nature.

Table 1: Performance Analysis of PI, Neural and ANFIS controller

Quantity/ R phase	PI controller		Neural Network		ANFIS controller	
	THD %	Magnitude	THD %	Magnitude	THD %	Magnitude
Source Voltage	27.3	410	24.7	410	17.11	410
Load Voltage	1.74	412	1.63	410	1.47	412
Load Current	25.8	22	24.7	22	24.79	22
Source Current	2.61	23	1.92	22	1.42	23

The Load current before compensation have THDs of 24.71%. The source current after compensation have THDs of 1.42%. In the case of ANFIS controller the THD of load voltage is 1.47% and source current THD is 1.42%. Hence in different controllers operation, from Table 1, it is clear that ANFIS controller gives better performance in terms of reduced THDs in voltage and current after compensation. The THD within the limit specified in the IEEE 519-192.

6. Conclusion

The intelligent unified controller for the UPQC using ANFIS has been developed. The simulation model in the MATLAB/SIMULINK environment has been tested and the test results prove the efficiency of the novel method. The acceptable results for the proposed system summarized as follows. The control of voltage sag, swell, and reactive power is compensated. It is seen from the simulation result that the THD for the output voltage of the proposed system is very low, compared with conventional controllers. The simulation results show that the UPQC with PI Controller Compensates 85% of voltage transients during fault condition. While UPQC with Adaptive Neuro Fuzzy controller (ANFIS) Compensates for almost 98% of voltage transients. Hence as compared to the response obtained with PI Controller or Neural controller, Adaptive Neuro Fuzzy controller (ANFIS) based controller have great advantage of flexibility.

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