International Journal of System Signal Control and Engineering Application 4 (1): 10-17, 2011
ISSN: 1997-5422

Neuro-Fuzzy Based Constant Frequency-Unified Power Quality Conditioner

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Abstract: The aim of this study is to maintain the constant frequency in the utility using constant frequency unified power quality conditioner with neuro-fuzzy logic controller. A Constant Frequency Unified Power Quality Conditioning system (CF-UPQC) consists of a Unified Power Quality Conditioner (UPQC) and a matrix converter based frequency changer. UPQC is a combination of series active and shunt active filter. The series active filter and shunt active filters are used to compensate the voltage, current imbalance and harmonics. Frequency converter (matrix converter) is used to regulate the supply frequency when it varies beyond the power quality limit. The performance of the CF-UPQC is compared with neuro-fuzzy controller against conventional controller.

Key words: CF-UPQC, matrix converter, active filter, neuro fuzzy logic controller, Matlab/Simulink, India

INTRODUCTION

Unified power quality conditioner is an advanced concept in the area of power quality control (Fig. 1). The basic working principle of unified power quality conditioner is based on series active filter and parallel active filter power converters that shares a common DC link (Watanabe and Aredes, 2002). Unified power quality conditioner is used to compensate voltage sag, voltage swell (Aredes and Fernandes, 2009) and current harmonics (Benslimane *et al.*, 2006). It is also used to compensate an impact on the reactive power (Chung and Deohan, 2005) through series voltage source inverter and shunt voltage source inverter. In order to avoid the switching oscillation, passive filters are replaced at the output of each inverter. At the output of shunt inverter, a high pass 2nd order LC filter is placed and the output of series inverter low pass second order LC resonance filter is allocated (Graovac *et al.*, 2000).

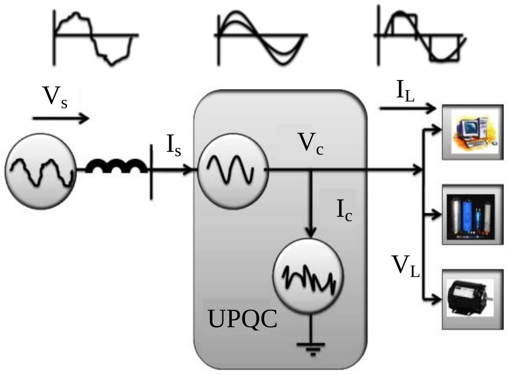

Fig. 1: Basic configuration of unified power quality conditioner

UPQC controller provides the compensated voltage through the UPQC series inverter and conditioning the current through the shunt inverter by instantaneous sampling of source voltage and load current. The reference current is compared with the shunt inverter output current (I_{a-c}) and they are fed in to hysteresis type (PWM) current controller. There are some problems with UPQC. UPQC cannot compensates supply frequency variations. As the supply frequency changes, the UPQC will not compensate or regulate the supply frequency as there is no device to regulate the supply frequency. To overcome, this problem CF-UPQC is introduced recently using PI controller.

FREQUENCY QUALITY INDICES

Power quality is the set of limits or conditions of electrical properties that allows electrical devices to function in their planned manner without the loss of performance (Monedero *et al.*, 2007). Without the proper power, an electrical utility or load may malfunction, fail permanently or not operate at well. The main power quality problems are voltage sag, voltage swell, voltage harmonics, current harmonics and supply frequency variations (Mishra *et al.*, 2008). The deviation of the power system fundamental frequency from its specified nominal value is defined as power frequency variation. If the balance between generation and demand is not maintained, the frequency of the power system will deviate because of change in the rotational speed of electromechanical generator. The amount of deviation and its duration of the frequency depend on the load characteristic and the response of the generation control

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system to load changes. Faults of power transmission system can also cause frequency variation outside of the accepted range for normal steady state operations of the power system.

Effects of variation of voltage and frequency on the performance of induction motors: Induction motors are time operated on circuits of voltage or frequency other than for which the motors are rated. Under such conditions, the performance of the motor will vary from the rating. The following is a brief statement of some operating results caused by small variations of voltage and frequency and it also indicates the general changes produced by the variations in operating conditions.

With a 10% increase or decrease in voltage given on the nameplate, the heating at rated horsepower load may increase. Such operation for extended periods of time may accelerate the deterioration of the insulation system.

In a motor of normal characteristics at full rated horsepower load, a 10% increase of voltage given on the nameplate would usually result in a lowering of power factor. A 10% decrease of voltage below that given on the nameplate would usually give an increase in power factor. The locked-rotor and breakdown torque will be proportional to the square of the voltage applied. An increase of 10% in voltage will result in a decrease of slip of about 17% while a reduction of 10% will increase the slip about 21%. Thus if the slip at rated voltage were 5%, it would be increased to 6.05% if the voltage were reduced 10%.

A frequency higher than the rated frequency usually improves the power factor but decreases locked-rotor torque and increases the speed and friction and windage loss. At a frequency lower than the rated frequency, the speed is decreased, locked-rotor torque is increased and power factor is decreased. For certain kinds of motor load such as in textile mills, close frequency regulation is essential.

If variation in both voltage and frequency occur simultaneously, the effect will be superimposed. Thus if the voltage is high and the frequency is low, the locked-rotor torque will be greatly increased but the power factor will be decreased and the temperature rise increased with normal load.

The foregoing facts apply particularly to general purpose motors. They may not always be true in connection with special-purpose motors, built for a particular purpose or as applied to very small motors.

While general-purpose alternating-current poly phase 2, 4, 6 and 8 pole, 60 Hz integral-horsepower induction motors are not designed to operate at their 60 Hz ratings on 50 Hz circuits, they are capable of being operated satisfactorily on 50 Hz circuits if their voltage and horsepower ratings are appropriately reduced. When such 60 Hz motors are operated on 50 Hz circuits, the applied voltage at 50 Hz should be reduced to 5/6 of the 60 Hz horsepower rating of the motor. The other performance characteristics for 50 Hz operation are as follows:

Speed: The synchronous speed will be 5/6 of the 60 Hz synchronous speed and the slip will be 6/5 of the 60 Hz slip.

Torque: The rated load torque in pound-feet will be approximately the same as the 60 Hz rated load torque in pound-feet. The locked-rotor and breakdown torques in pound-feet of 50 Hz motors will be approximately the same as the 60 Hz locked-rotor and breakdown torques in pound-feet.

Locked-rotor current: The locked-rotor current (ampere) will be approximately 5% <60 Hz locked-rotor current (amperes). The code letter appearing on the motor nameplate is used to indicate locked-rotor KVA per horsepower applies only to the 60 Hz rating of the motor.

Service factor: The service factor will be 1.0. Figure 2 shows the proposed improved configuration of constant Frequency- unified power quality conditioner. This modified unified power quality conditioner concepts enables the PWM converter to perform active filtering purpose and matrix converter also performs the function of frequency regulator. The compensation principle of the CF-UPQC will be explained in the coming sections B-D. The proposed unified power quality conditioner has to satisfy the following requirements. Reactive power is

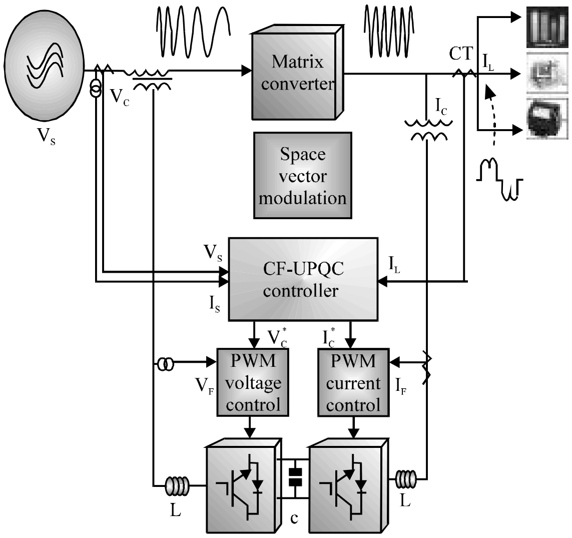

Fig. 2: Proposed configuration of CF -UPQC

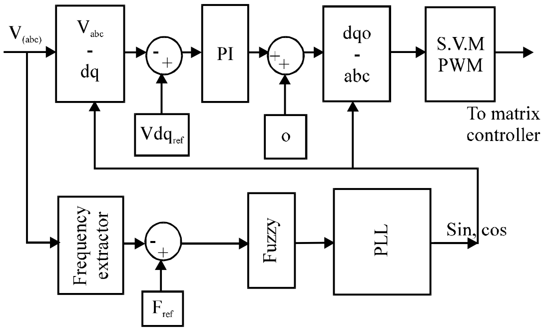

Fig. 3: Proposed neuro-fuzzy based control system of the frequency changer block (CF-UPQC)

maintained at minimum value. The load voltage should be maintained at the rated supply voltage. Maintain the input current with very low harmonic content. Assure the supply frequency is permissible within the power quality limits. The simulations result will be presented to validate the proposed CFUPQC. Modified configuration of UPQC consists of shunt active filter, series active filter, matrix converter shown in Fig. 3. CFUPQC is similar to the UPQC expect the frequency changing section. The frequency converter is achieved by matrix converter. The main advantage of frequency converter is as follow. Matrix converter can only increase or decrease the frequency instead of cyclo-converter. Here there is no dc storage element. So, losses are minimized and harmonics also minimized. UPQC has the potential drawbacks in the hybrid filtering performance as its filter in characteristics depends on load impedance and supply frequency. CF-UPQC's matrix converter regulates the frequency of supply voltage. CF-UPQC series active filter is used for compensating the voltage harmonics and voltage imbalance.

The CF-UPQC consists of Parallel Active Filter (PAF) that eliminates load harmonics and compensates load reactive power. In addition, the shunt active filter converter supplies the AC to DC power and is fed to common DC link. The control equation is as:

$$I_{pf} = G.I_L \rightarrow \left|G(j\omega)\right| = \begin{cases} 0, & \omega=\omega l \\ 1, & \omega=\omega h \end{cases} \quad (1)$$

Where:

G = The control function

ω = Fundamental frequency

I_L = The load current

I_{pf} = The parallel filter input current components for compensation are extracted from load current and load voltages using dq theory while the converter is a current controlled device using 20 kHz clocked hysteresis band

Series Active Filter (SAF) compensates supply harmonics flicker, voltage sag/swell and unbalance load harmonics to flow in to the parallel filter. Control equation is as:

$$U_{sf} = K.G.I_{sh} + U_{comp} \quad (2)$$

Where:

K = Regulator gain

U_{sf} = The series filter voltage

I_{sh} = Harmonic supply current

U_{comp} = Compensation voltage needed to remove supply voltage imperfection

I_{sh} = Extracted to dq theory

CF-UPQC frequency regulator system-neuro fuzzy controller: The matrix converter consists of nine bidirectional switches arranged in three groups, each being associated with an output line. This bi-directional switches arrangement connects any of the input lines to any of the output lines. A matrix with elements S_{ij}, representing the state of each bi-directional switch (on = 1, off = 0) can be used to represent the matrix output voltages (Vu, Vv, Vw) as function of inverters. At the same time, series active filter compensate the voltage problems. Figure 3 shows the control system of the frequency regulator. The matrix converter is controlled by space vector modulation. The reference voltage is used to control the regulation of output frequency. The supply frequency $V_{f(abc)}$ is sensed by the frequency counter. It is compared with the reference frequency $V_{f(ref)}$ and extract the error value. The compensated value is produced by the Neuro fuzzy controller and the compensated frequency is fed to the Phase Locked Loop (PLL). When the supply frequency is varied beyond the power quality limit, the frequency controlling system (matrix converter) changes the required PLL frequency from Neuro-fuzzy controller. The detailed fuzzy control system is described below. The conventional control (PI), system is not suitable for non linear systems.

In recent years, ANN's have generated considerable interest in the field of engineering as problem-solving tools. The fundamental element is a neuron which has multiple inputs and a single output. Each input is multiplied by a weight, the inputs are summed and this quantity is operated by the transfer function of the neuron to generate the output. The output is sometimes referred to as an activity level. In this study, the multilayer Feed Forward NN (FFNN) in Fig. 4.

It has one hidden layer. The bias unit whose activity level is fixed at one is connected to all neurons in the hidden and output layer to adjust the weighted sum input of each neuron. The number of neurons in the input and the output layer is determined by each application and

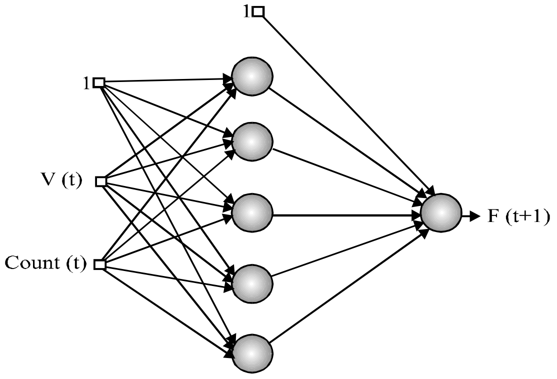

Fig. 4: The developed network architecture

the number of neurons in the hidden layer must be adjusted during the learning phase so that the network can be trained efficiently. The activity level of the jth neuron is obtained as:

$$v_j = f_j(net_j) = f_i[\sum_i(\omega_{ji}x_i) + b_j]$$

Where:

v_j = Activity level (output) of the jth neuron (net_j) input of the jth neuron
f_i = Transfer function of the jth neuron
ω_{ji} = Connection weight from the ith neuron to the jth neuron
x_i = Activity level of the ith neuron in the prior layer
b_j = Connection weight from the bias unit to the jth neuron

The sigmoid function is used as the transfer function in this study. The back propagation algorithm is used to train the network. The connection weights such as ω_{ji} and b_j are adjusted so that the average squared error between the network output and the desired output (target) for a given reference input is minimized. Learning continues iteratively until the sum of the squared error is below a certain goal. The incremental change of weight from the ith neuron to the jth is computed by:

$$\Delta\omega_{ij}(t+1) = \eta\delta_j o_i + \alpha\Delta\omega_{ij}(t)$$

Where:

$\Delta\omega_{ij}(t+1)$ = Incremental change in the weight ω_{ij} at time t
η = Learning rate (usually a constant)
α = Momentum (usually a constant)

Fuzzy logic is a function to the diagnosis of induction motor stator and phase conditions based on the amplitude features of stator currents. This method has been chosen because fuzzy logic has proven ability in mimicking human decisions and the stator voltage and phase condition monitoring problem has typically been solved. Fuzzy rules and membership functions are constructed by observing the data set. For the measurements related to the stator currents, more insight into the data is needed so membership functions will be generated for zero, small, medium and big. For the measurement related to the stator condition, it is only necessary to know if the stator condition is good, damaged or seriously damaged. Once the form of the initial membership functions has been determined, the fuzzy if-then rules can be derived. In this study, two faults have been investigated: stator voltage unbalance and open phase.

These rules have been optimized so as to cover all the healthy and the faulty cases. For the study, we have obtained the following 14 if-then rules:

Rule 1: If I_a is Z Then CM is SD
Rule 2: If I_b is Z Then CM is SD
Rule 3: If Ic is Z Then CM is SD
Rule 4: If I_a is B Then CM is SD
Rule 5: If I_b is B Then CM is SD
Rule 6: If Ic is B Then CM is SD
Rule 7: If I_a is S and I_b is S and I_c is M Then CM is D
Rule 8: If I_a is S and I_b is M and I_c is M Then CM is D
Rule 9: If I_a is M and I_b is S and I_c is M Then CM is D
Rule 10: If I_a is M and I_b is M and I_c is M Then CM is G
Rule 11: If I_a is S and I_b is S and I_c is S Then CM is G
Rule 12: If I_a is S and I_b is M and I_c is S Then CM is D
Rule 13: If I_a is M and I_b is S and I_c is S Then CM is D
Rule 14: If I_a is M and I_b is M and I_c is S Then CM is D

Control system of the shunt CF-UPQC: Figure 5 shows the shunt inverter controlling block diagram of CF-UPQC using synchronous reference frame theory where the load currents $I_{a\text{-}c}$ are given. The measured currents of load are transferred into dqo frame using sinusoidal functions through dqo synchronous reference frame conversion. The sinusoidal functions are obtained through the grid voltage using Phase Locked Loop (PLL). Here the currents are divided into ac and dc components:

$$I_{id} = \overline{I}_{id} + \tilde{I}_{id} \quad (3)$$

$$I_{iq} = \overline{I}_{iq} + \tilde{I}_{iq} \quad (4)$$

In Eq. 3 and 4, i_d and i_q are the real and reactive components. AC components and DC elements can be derived by low pass filter. $\bar{I}_{id}$, $\bar{I}_{iq}$ are the dc components and $\tilde{I}_{id}$, $\tilde{I}_{iq}$ are the ac components of I_{id}, I_{iq}. The control algorithm corrects the systems power factor and compensates all the current harmonica component by generating the reference currents given in equation:

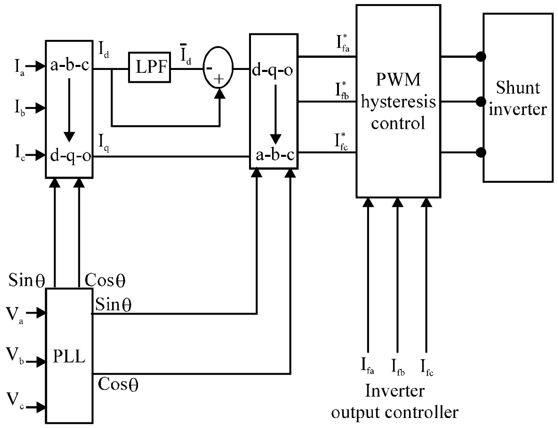

Fig. 5: Control system of the shunt CF-UPQC

$$I^*_{fd} = I_{id} \tag{5}$$

$$I^*_{fq} = \overline{I}_{iq} \tag{6}$$

The reference current is transferred in to (a_b_c) frame through reverse conversion of synchronous reference frame. Resulted reference current (I^*_{fa-fc}) and the output current of shunt inverter (I_{fa-fc}) are fed to the hysteresis band controller.

Now, the required controlling pulses are generated and the required compensation current is generated by the inverter applying these signals to shunt inverters power switch gates.

CF-UPQC series inverter control system: Figure 6 shows the CF-UPQC series inverter controlling block diagram using synchronous reference frame control theory. In this method, the required value of load phase voltages in d and q-axis is compared with the load voltage and the result is consider as the reference signal. The supply voltage detected (V_{abc}) is detected and transformed into the synchronous dqo reference frame using:

$$v_{t\_dqo} = T^{dqo}_{abc}\, v_{t\_abc} \tag{7}$$

The compensating reference voltage in the synchronous dqo reference frame is defined as:

$$v^{ref}_{sf\_dqo} = v_{t\_dqo} - v^{exp}_{l\_dqo} \tag{8}$$

The compensating reference voltage in Eq. 8 is then transformed back into the (a_b_c) reference frame. Resulted reference voltage (v^*_{fa-fc}) and the output current of shunt inverter (v_{fa-fc}) are fed to the hysteresis band controller. The required controlling pulses are generated and the required compensation voltage is generated by the series inverter.

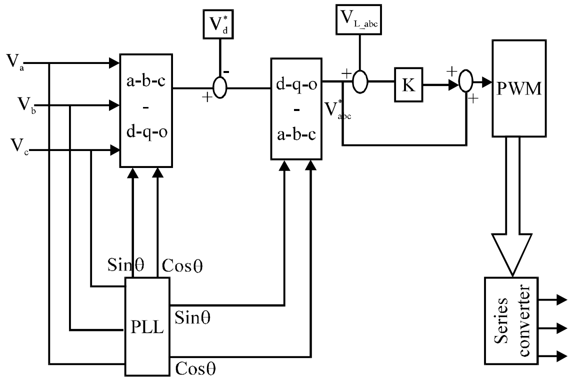

Fig. 6: Control system of the series CF-UPQC

SIMULATION RESULTS

The proposed system is simulated by Matlab software. In Fig. 7, the simulation of the matrix converter operation without input capacitor is shown. Here the line voltage is 440 V; the supply current is 200 Amperes. In this simulation, the input current wave shape is non-sinusoidal and it contains harmonics. The simulation time starts from 0.02-0.085 sec. Consider the simulation time is from 0.025-0.045 sec as the one cycle of the current wave form. Here the wave shape of this current is non sinusoidal and it contains harmonics. Figure 7a shows that the input voltage is harmonic free. Figure 7b shows the input current wave form of the matrix converter. Figure 7c shows the load voltage of the matrix converter output. Figure 7d shows the load current applied to the load. Here the load current is resistive load. Figure 8a shows the matrix converter output voltage. Simulation result shows that the matrix output voltage contains harmonics. Figure 8b shows the input current of series active filter part. This simulation shows that the series active filter takes the current sinusoidal .The matrix converter output voltage is 440 V. Figure 9a shows the total harmonic distortion in the source voltage. There is no harmonic present. Figure 9b shows the total harmonic distortion in the matrix converter output. The matrix converter produced 60%of voltage harmonics. In Fig. 9c, the THD is reduced at 1% by the proposed system.

Figure 10 shows the matrix converter is affected by swell. The voltage swell is present from 0.03-0.05 sec. The matrix converter reflects the input supply variations to the output supply. Figure 10a shows the supply input with sag voltage. Figure 10b shows that the supply current

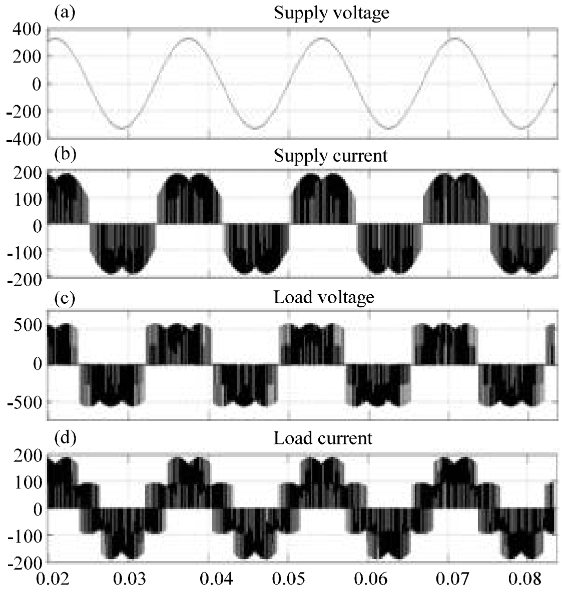

Fig. 7: a) System voltage (V_S); b) source current (I_s); c) load voltage (V_L) and d) load current (I_L) without filter

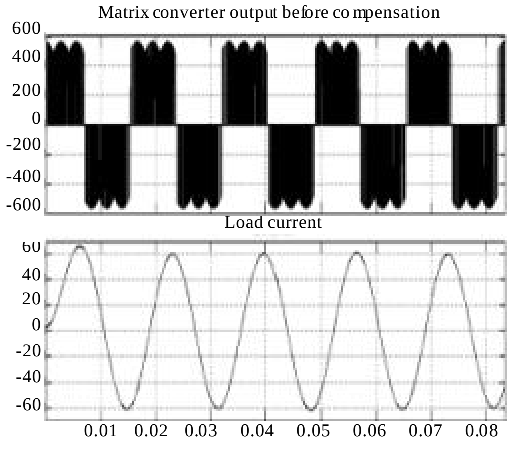

Fig. 8: a) Matrix converter output voltage before compensation and b) input load current of series active filter

drawn by load is also increased. Figure 10c shows the input voltage variations directly affected by the output voltage. When the sag voltage occurs, the load current is also increased without compensation and is shown in Fig. 10d.

After the proposed compensation (UPQC), series active filter eliminates the swell problem and maintain the power quality in the matrix converter output as shown in the Fig. 11a, b. Figure 12 shows the system response when the supply frequency is decreased below the power

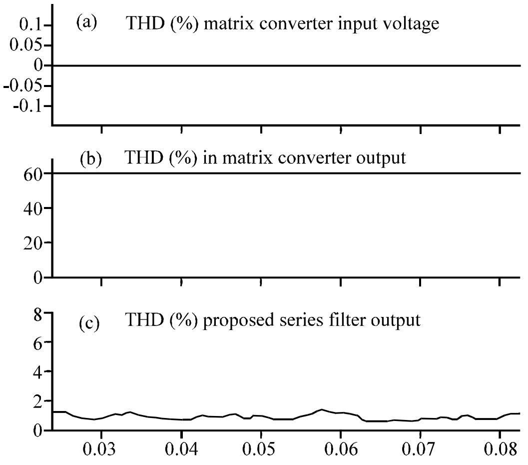

Fig. 9: a) Total harmonic distortion in matrix converter input voltage; b) total harmonic distortion in matrix converter and c) total harmonic distortion in matrix converter output current

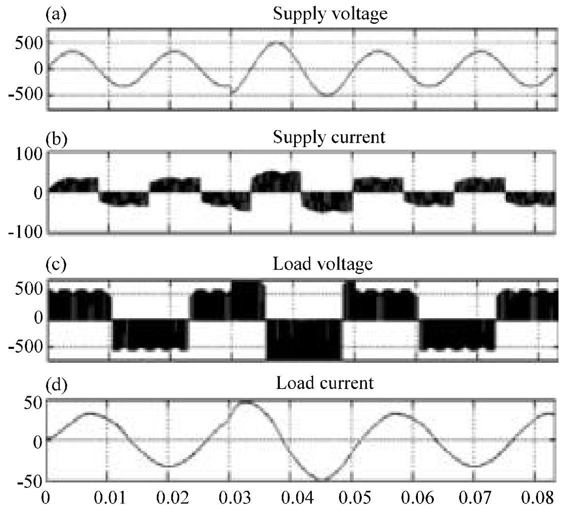

Fig. 10: a) Voltage swell in matrix converter input; b) supply current before compensation; c) matrix converter output voltage and d) matrix converter output current without UPQC

quality limits. It can be shown in Fig. 12a that the frequency decreases from 60-55 Hz, the PI control system regulates the load frequency as constant. As shown in Fig. 12b, the supply frequency varies but the output frequency remains almost constant.

Frequency variation starts from 0-0.4 sec linearly. Figure 13a shows the system response. The supply frequency is increased above the power quality limits. It can be seen that the frequency increases from 60-65 Hz. The PI system regulates the load frequency to a constant level. The frequency variation starts from 0-0.45 sec

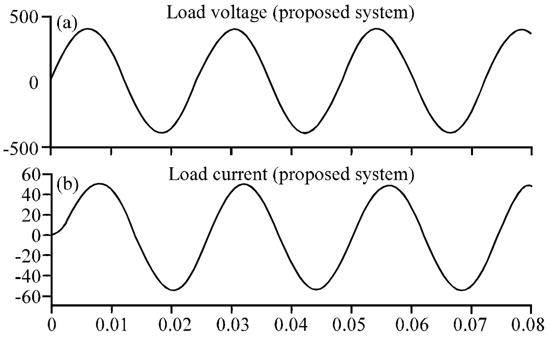

Fig. 11: a) Voltage swell occur in matrix converter output voltage and b) current with UPQC based compensation

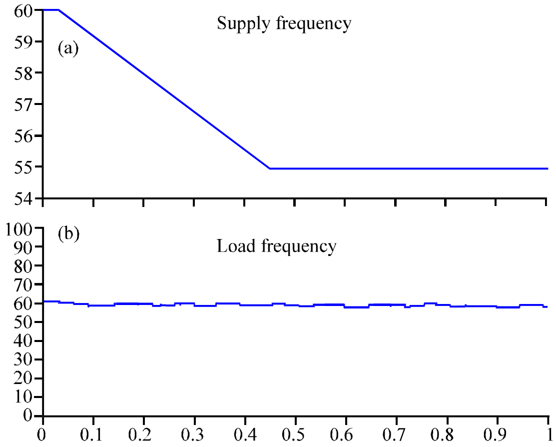

Fig. 12: a) Supply frequency falls below the power quality limit and b) output load frequency with conventional PI controller based compensation

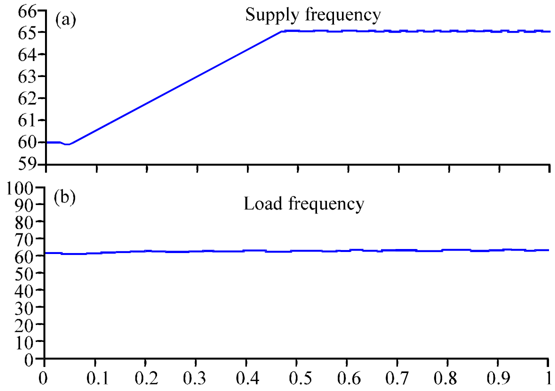

Fig. 13: a) Supply frequency rises above the power quality limit and b) load frequency with conventional PI controller based compensation

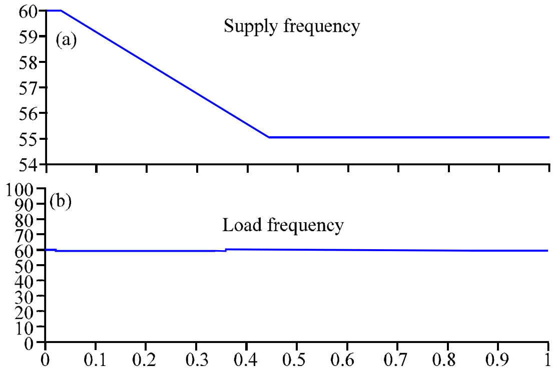

Fig. 14: a) Supply frequency falls below the power quality limit and b) output load frequency with proposed Neuro-fuzzy controller based compensation

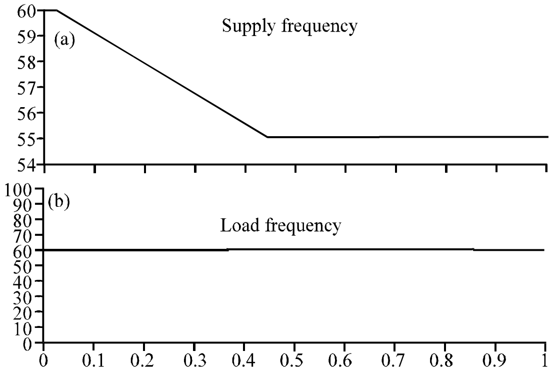

Fig. 15: a) Supply frequency rises above the power quality limit and b) load frequency with proposed neuro-fuzzy controller based compensation

linearly. From Fig. 12b, it can beinferred that the output frequency is almost constant even when the supply varies. Figure 14 shows the system response when the supply frequency is decreased below the power quality limits. It can be seen in Fig. 13a that the frequency decreases from 60-55 Hz, the proposed system regulates the load frequency constant. As shown in Fig. 13b, the supply frequency varies but the output frequency remains constant. Frequency variation starts from 0-0.4 sec linearly. Figure 15a shows the syst em response. The supply frequency is increased above the power quality limits. It can be seen that the frequency increases from 60-65 Hz. The proposed system regulates the load frequency to a constant level. The frequency variations starts from 0-0.45 sec linearly as shown in Fig. 14a. From Fig. 14b, it can be inferred that the output frequency is almost constant even when the supply varies.

CONCLUSION

This study has presented a model of custom power equipment, namely Constant Frequency Unified Power Quality Conditioner (CF-UPQC) with neuro-fuzzy controller. The study illustrates the operation and control of a CF-UPQC. This device is connected in between source and load. When a unbalanced and frequency sensitive load is supplied through CF-UPQC it will regulate the supply voltage, supply frequency and eliminates harmonics. The main aim of the CF-UPQC is to regulate supply frequency at the load terminal. The proposed method can regulate the supply frequency efficiently using matrix converter. The simulation results showed that the proposed neuro-fuzzy system has the ability to control almost compensates all the power quality issues compared to conventional controller.

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