Constant Frequency-Unified Power Quality Conditioner

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***Abstract*—The aim of this paper is to maintain the constant frequency in the utility using constant frequency unified power quality conditioner.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 which is composed by UPQC and matrix converter has been verified based on the simulation results.**

***Key Words*—CF-UPQC, Matrix Converter, Active filter,Matlab/ Simulink**

I. INTRODUCTION

Unified power quality conditioner is an advanced concept in the area of power quality control. The basic working principle of unified power quality conditioner is based on series active filter and parallel active filter power converters that share a common DC link [1].Unified power quality conditioner is used to compensate voltage sag, voltage swell [2],and current harmonics [3]. It is also used to compensate an impact on the reactive power [4] through series voltage source inverter and shunt voltage source inverter. In order to avoid the switching oscillation, passive filters are placed at the output of each inverter. At the output of shunt inverter a high pass second order LC filter is placed and the output of series inverter low pass second order LC resonance filter is allocated [5]. 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,I_b,I_c) and are fed to hysteresis type (PWM) Current controller. There are some problems with UPQC. UPQC cannot compensate 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 supply frequency.

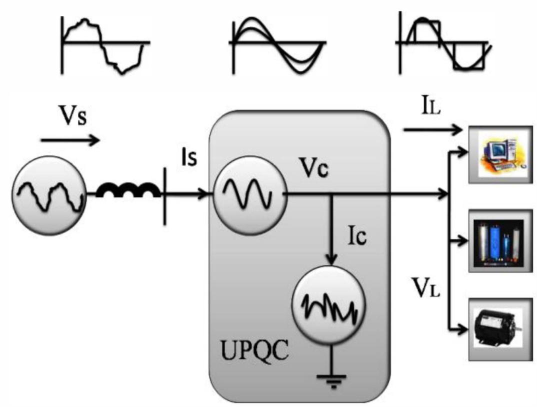

Figure.1: Basic Configuration of Unified Power Quality conditioner

II. 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 loss of performance[6]. 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[7]. As mentioned the above power quality issues are mitigated by using unified power quality conditioner except supply frequency variation. Supply frequency is an important issue in power quality. In order to characterize the power system frequency under normal operating condition the following indices are used

$$\Delta f = f - f_r \quad (1)$$

Where f_r is the rated frequency (50 or 60) Hz and f is the real frequency.

The relative frequency deviation

$$\%\varepsilon f = f - f_r / f_r * 100 \quad (2)$$

The integral deviation during the delay required to ensure appropriate of clock synchronized to the electrical network frequency

$$I_f = \int_0^{24} \Delta f . dt \quad (3)$$

According to the standard En 50160/2006rated frequency of supply voltage is 50Hz.Under normal operation conduction the mean value of the fundamental frequency measured over loss stay within the following range.

50 Hz$\pm$1%.ie 49.5-50.5Hz for 99.5%of the year

50 Hz$\pm$4%.ie 47-52Hz for 100%of the time.

But normally the power frequency may not be exactly 50Hz within the time interval. The fundamental frequency output is the ratio of the number of integer cycle counted clearing 10s time interval divided by the cumulative value of the integer value. The step taken to maintain the frequency with in required limits render deviation from the normalized value. In this way an analysis is of the influence of frequency variation on the final customer is only for a reduced interval about $\pm$3Hz of the rated value and for rather short period [8]. Within the reduced variation field (40%)a considerable number of static customers are not affected by the system variation(rectifier, resistance, ovens, electric arc etc)but 60%of the consumers (fans, motors etc) are affected by the frequency variations. The change in supply frequency hardly occurs in large distribution systems based on ground faults. If there are some major disturbances or very heavy load fluctuating continuously, then frequency variation will be occurs[9]. But large frequency variations are possible on electrical systems used on heavy sudden load and emergency supply systems for factories and hospitals. Such large frequency variations are possible on low power systems where diesel engines and gas turbines are used as prime movers

A. Effects of Change in Supply Frequency on Torque and Speed

The asynchronous and synchronous driving motors connected the supply network used extendedly in individual acceleration have the power frequency changes. Depending on the mechanical characteristic speed of the motor and also depends on the supply frequency [10].The speed of asynchronous motors or synchronous motor unlimited drags to the electric power supply variations s proportional to the applied voltage frequency. The frequency variation leads to the necessary modification of the process production time throughout the supply with a reduced frequency, depressing the supply frequency capacitive circuit, transformer, and relay coil are affected.The torque is related to the motor output power and the rotor speed.AC motor characteristics require the applied voltage to be proportionally adjusted whenever the frequency is changed the motor changes to deliver the rated torque. For a case if a motor is designed to operate at 450 volts at 60 Hz, the applied voltage must be reduced to 230 volts when the frequency is reduced to 30 Hz. Thus the ratio of volts per hertz must be regulated to a constant value (450/60 = 7.67 V/Hz in this case). For optimum performance, voltage adjustment may be needed especially at low speeds.But a constant volt per hertz is the general formula. This ratio can be changed in order to change the torque delivered by the motor.

$$T_{load} = \frac{P_m}{\omega_m} NM \quad (4)$$

$$\omega_m = \frac{2\pi n_m}{60} \frac{rad}{sec.} \quad (5)$$

Lifetime of the bearings is also limiting the maximum speed of the motor. It is recommended to consult the motor manufacturer if more than 150 % speed is required by the application. The synchronous speed of an induction motor is based on the supply frequency and the number of poles in the motor winding and can be expressed as:

$$\omega = 2 * 60 f / \text{n} \quad (6)$$

Where

ω = pump shaft rotational speed (rev/min, rpm)

f = frequency (Hz, cycles/sec)

n = number of poles

The rotational speed at different frequencies and number of poles can be listed as:

TABLE I:AC Motor Synchronous (No Load) Speeds At Input Frequencies

Frequency	*Speed ω(4 pole)*
10	300
20	600
30	900
40	1200
50	1500
60	1800
70	2100

A. Effects of Change in Supply Frequency on Torque and Speed

The frequency also involved in horsepower ratting of the motor known asthis formula:

$$HP = \frac{rpm*T(torque)}{5252(constant)} \quad (7)$$

As mentioned the above chapter 1, the relation between the speed and its frequencyof the motor is based on the expression N = 120f/P.From this expression, it is prove that the speed of the motor is directly proportional to the supply frequency. So any decrease or increase inthe frequency will affect the speed of the motor [11].Suppose When a 50 Hz motor is made to run on 60 Hz supply: general practices in several countries have all house-hold items and equipments rated for 50 Hz power supply. So when such small domestic devices are connected to a 60 Hz power supply, they cause a severe problem. That is,

[(60Hz – 50 Hz)/ 50 Hz] * 100 = 20 %.

Thus all such equipments will run 20 % faster than their normal rated speed. This is not safety for the equipment as the insulations may be rated for lesser capacity and windings will burn-out. To run safely manner, should add a reduction gear or an expensive 50 Hz source. Also this 50 Hz motor will operate perfectly on a 60 Hz supply provided its supply voltage is stepped-up.60 Hz/ 50 Hz = 6/5 * 100 = 120 %. Suppose60 Hz motor connected to 50 Hz supply. It is same as the above, but instead of stepping-up the supply voltage, it is necessary to step-down the supply voltage.50Hz/ 60 Hz = 5/6 * 100 = 80 %.The speed of an induction motor is given as N = 120f/p (1-S). So obviously the speed of an induction motor can be controlled by varying any of three factors namely supply frequency f, number of pole P or slip S.Motor torque is directly propotional to supply frequency[12].

Motor torque=flux density*I

Flux density=K*(V/HZ)

Where K - motor constant

V - voltage

HZ - frequency

$$Motortorque = \left(K * \frac{v}{Hz}\right) * I \quad (8)$$

B. Effect of Change in Supply Frequency on transformer output

A transformer is a static piece of apparatus by means of which electric power in one circuit is transformed in to electric power of same frequency in another circuit.

The Rms value ofEMF induced in the transformer depends on the supply frequency

Induced emf in the primary winding

$$E_1 = 4.44 f N_1 B_m \text{A} \quad (9)$$

Similarly the rms value EMF induced in the transformer secondary winding is depends on the suplly frequency

$$E_2 = 4.44 f N_2 B_m \text{A} \quad (10)$$

whereN_1,N_2 are the number of turns in primary and secondary winding.

$$\emptyset_m = B_m * \text{A} \quad (11)$$

ie maximum flux in core in webers,f is the frequency of input Hz. Equation (11) shows when the supply changes the induced voltage is also changed. Most of the utlity load contains step down transformer. If the frequency changes, the suply voltage is also changed and may damage the equipment.

III. CONSTANT FREQUENCY - UNIFIED POWER QUALITY CONDITIONER (CFUPQC)

A. CF-UPQC structure

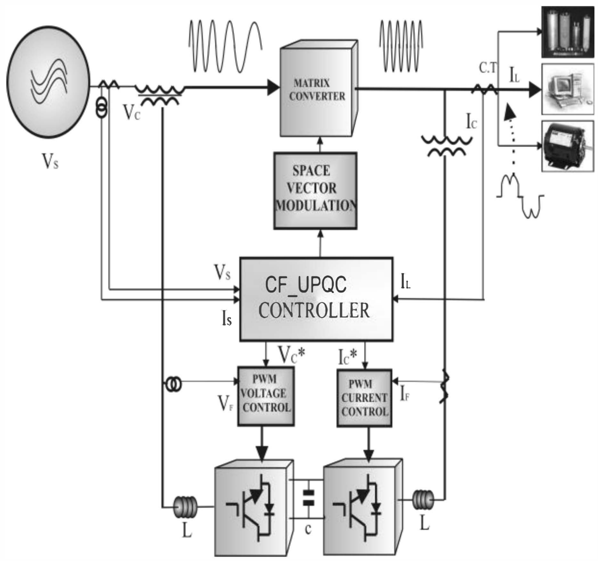

Figure.2: Proposed Configuration of CF -UPQC

Fig 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,C and D. The proposed unified power quality conditioner has to satisfy the following requirements. Reactive power is 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. Matrixconverter 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

$$I_{pf}=G.I_L \rightarrow |G(j\omega)| = \begin{cases} 0, \omega=\omega 1 \\ 1, \omega=\omega h \end{cases} \quad (12)$$

Where G is the control function, ω is fundamental frequency.I_L is the load current, $I_{pf}$is 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

$$U_{sf} = K.G.I_{sh} + U_{\text{comp}} \quad (13)$$

Where K is regulator gain, $U_{sf}$is the series filter voltage, I_{sh} are harmonic supply current and U_{comp} is compensation voltage needed to remove supply voltage imperfection. I_{sh} are extracted to dq theory.

B .CF-UPQC Frequency RegulatorSystem

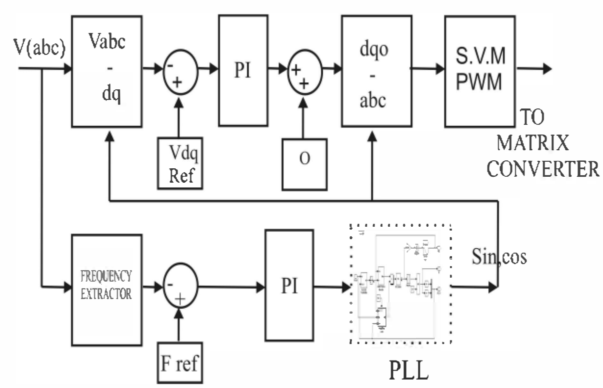

Figure.3: Control System of the Frequency changer block (CF-UPQC)

The matrix converter consists of nine bidirectionalswitches arranged in three groups, each beingassociated with an output line. This bi-directional switchesarrangement connects any of the input lines to any of theoutput lines. A matrix with elements S*ij*, representing the state of each bi-directional switch (*on=1, off=0*), can be usedto represent the matrix output voltages (v_u, v_v, v_w) as function of Inverters. At the same time series active filter compensate the voltage problems.Fig 3 shows the control system of the frequency regulator. The matrix converter is controlled by space vector modulation. The modulation reference voltage is used to control the regulation of output frequency. The supply frequency $vf_{(abc)}$is sensed by the frequency counter. It is compared with the reference frequency $vf_{(ref)}$and extract the error value. The compensated value is produced by the PI controller and compensated frequency is fed to the phase locked loop(PLL).When the supply frequency is variedbeyond the power quality limit the frequency controlling system(matrix converter) changesthe required PLL frequency from PI controller.

c. Control system of the CF-UPQC shunt Part

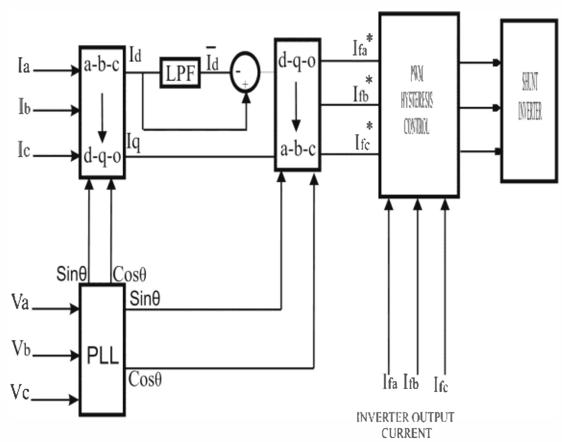

Figure.4: Control System of the Shunt CF-UPQC

In the Fig (4) shows the shunt inverter controlling block diagram of CFUPQC using synchronous reference frame theory where the loads current are $I_a,I_b and\ I_c$is given. The measured currents of load are transferred in to dqo frame using sinusoidal functions through dqo synchronous reference frame conversion. The sinusoidal functions are obtained through the grid voltage using phase lockedloop (PLL). Here the currents are divided in to ac and dc components

$$I_{ld} = \bar{I}_{ld} + \tilde{I}_{ld} \quad (14)$$

$$I_{lq} = \bar{I}_{lq} + \tilde{I}_{lq} \quad (15)$$

The equation (14) and (15) $i_d$and $i_q$are the real and reactive components. AC components and DC elements can be derived by low pass filter.$\bar{I}_{ld}$, $\bar{I}_{lq}$ are the dc components and $\tilde{I}_{ld}$, $\tilde{I}_{lq}$ are the ac components of I_{ld}, I_{lq}. The control algorithm corrects the systems power factor and compensates all the current harmonica component by generating the reference currents given in equation

$$I_{fd}^* = \tilde{I}_{ld} \quad (16)$$

$$I_{fq}^* = \bar{I}_q \quad (17)$$

The reference current is transferred in to (a_b_c) frame through reverse conversion of synchronous reference frame. Resulted reference current $(I_{fa,}^*I_{fb,}^*I_{fc,}^*)$ and the output current of shunt inverter (I_{fa}, I_{fb}, I_{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.

d) CFUPQC *Series Inverter Control System*

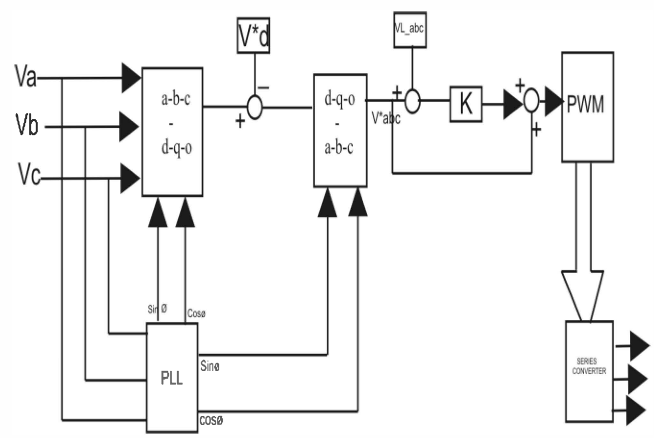

Figure.5: Control System of the Series CF-UPQC

Fig.5. 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 axis 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 in to the synchronous dqo reference frame using

$$v_{t\_dqo} = T_{abc}^{dqo} v_{t\_abc} \quad (18)$$

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

$$v_{sf\_dqo}^{ref} = v_{t\_dqo} - v_{l\_dqo}^{exp} \quad (19)$$

The compensating reference voltage in (19) is then transformed back into the (a_b_c) reference frame .Resulted reference voltage ($v^*_{fa,}vi^*_{fb,}v^*_{fc,}$) and the output current of shunt inverter (v_{fa}, v_{fb}, v_{fc}) are fed to the hysteresis band controller. The required controlling pulses are generatedand the required compensation voltage is generatedby the series inverter.

IV. SIMULATION RESULTS

The proposed system, simulation results is simulated by MATLAB software.

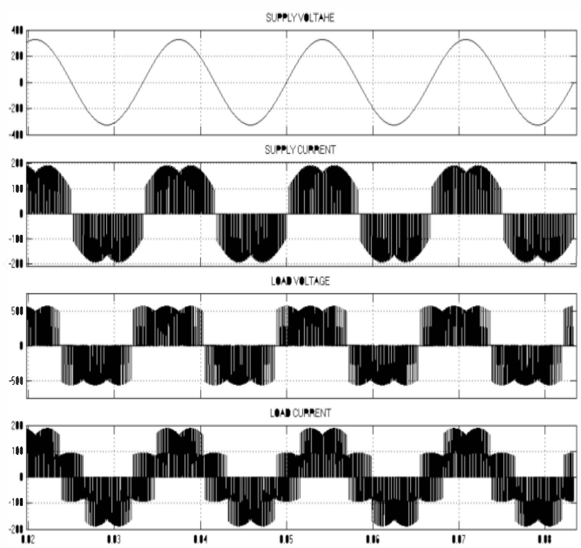

Figure. 6: (a) System voltage (v_S) ,(b)source current (Is),(c) load voltage(V_L)and (d) load current(I_L) without filter

In Fig.6 the simulation of the matrix converter operation without input capacitor is shown. Here the line voltage is 440v; the supply current is 200 Amperes. In this simulation the input current wave shape is non sinusoidal and it contains harmonics. The simulation time start from 0.02 to 0.085sec.Consider the simulation time 0.025 sec to 0.045 sec as the one cycle of the current wave form. Here the wave shape of this current is non sinusoidal and it contain harmonics. The simulation result Fig.6.(a) shows the input voltage is harmonic free. Fig.6.(b)shows the input current wave form of the matrix converter. Fig.6(c) shows the load voltage of the matrix converter output. Fig.6(d) shows the load current applied the load. Here the load current is resistive load

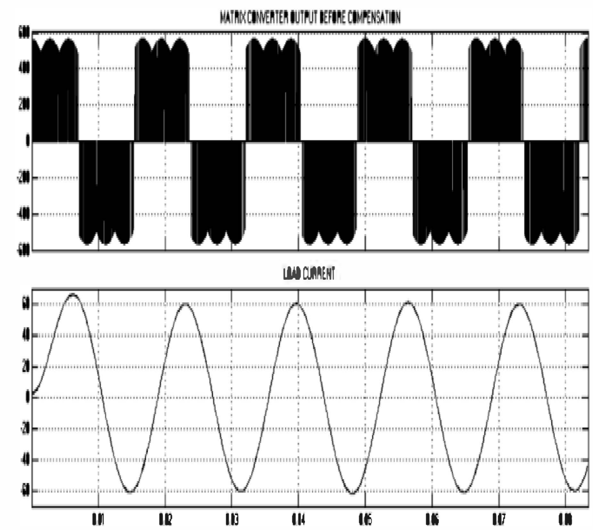

Figure.7.(a) Matrix converter output voltage before compensation(b)input load current of series active filter

Fig.7.(a) shows the matrix converter output voltage.Simulation result shows that the matrix output voltage contains harmonics. Fig. 7 (b) shows the input current of series active filterpart. This simulation show's that the series active filter takes the current sinusoidal .the matrix converter output voltage is 440v.

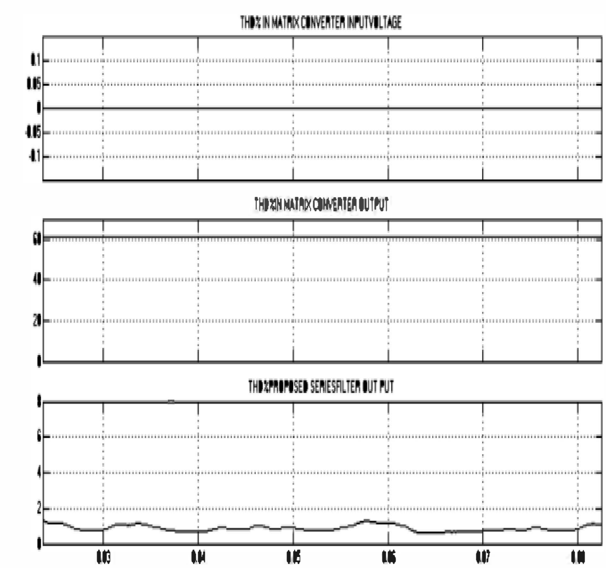

Figure .8. (a) Total harmonic distortion matrix converter input voltage,(b)total harmonic distortion in matrix converter,(c) total harmonic distortion in matrix converter output current

Fig.8(a) shows the total harmonic distortion in the source voltage. There isno harmonic present. Fig.8(b) shows the total harmonic distortion in the matrix converter output. The matrix converter produced60%of voltage harmonics as shown in figure.In Fig. 8(c) the THD is reduced at 1% by the proposed system

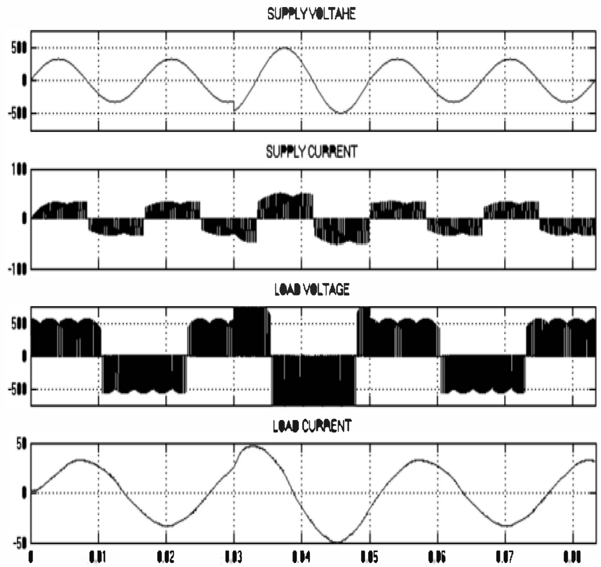

Figure.9(a) voltage swell in matrix converter input, (b) supply current before compensation, (c) matrix converter output voltage, (d) matrix converter output current without UPQC.

Fig 9 shows when the matrix converter is affected by swell. The voltage swell present at 0.03 to 0.05sec. The matrix converter reflects the input supply variations to the output supply. Fig. 9 (a) shows the supply input with sag voltage. FromFig. 9(b) it can be inferred that the supply current drawn by load is also increased. Fig. 9(c) shows how the input voltage variations directly affect the output voltage. When the sag voltage occurs, the load current is also increased without compensation and is given inFig.9 (d).

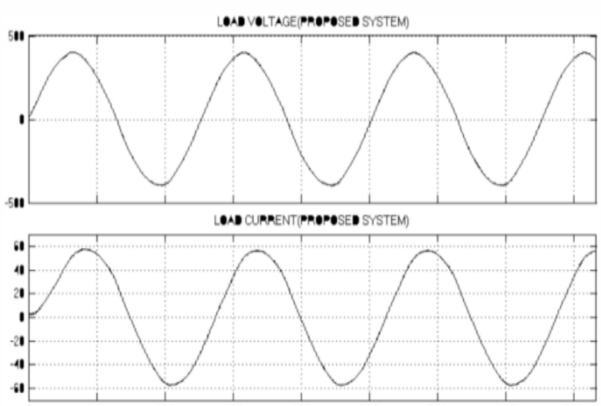

Figure. 10–avoltage swell accord in matrix converter output voltage, (b) current with UPQC based compensation

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.10 (b)

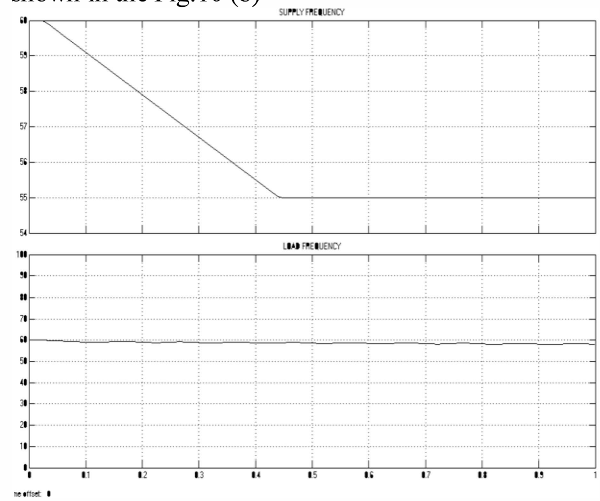

Figure. 11 –(a) supply frequency fall below the power quality limit(b) output load frequency with proposed compensation.

Fig.11 shows the system response when the supply frequency is decreased below the power quality limits. It can be seen in Fig.11 (a)that as the frequency decreases (from 60 Hz to 55 Hz the proposed system regulate the load frequency constant.As shown in Fig.11 (b) the supply frequency varies but the output frequency remains almost constant. Frequencyvariation starts from 0 sec to 0.4 sec linearly as shown in Fig.11 (a).

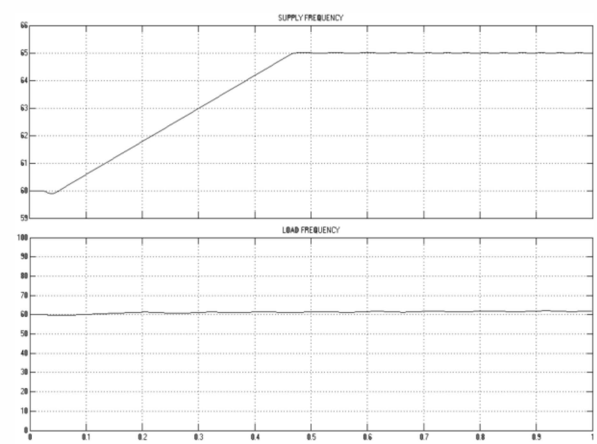

Figure. 12–(a) supply frequency rise above the power quality limit (b) load frequency with proposed compensation.

Fig.12(a) shows the system response. The supply frequency is increasedabove the power quality limits. It can be seen that as the frequency increases (from 60 Hz to 65 Hz. The proposed system regulates the load frequency to a constant level. The frequency variations start from 0 sec to 0.45 sec linearly as shown in Fig. 12 (a). From Fig. 12.b it can be inferred that the output frequency is almost constant even when the supply varies but

V. CONCLUSION

This paper has presented a model of custom power equipment, namelyconstant frequency unified power quality conditioner (CF-UPQC).The paper illustrates the operation and control of a CF-UPQC.This device is connected in between source and load. When aun-balanced, 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 system has the ability to control almost compensate all the power quality issues.

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