Matrix Converter Power Quality Issue Compensation Using Adaptive PLL based Controller in Unified Power Quality Conditioner

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Abstract: This study proposes an efficient adaptive based PLL controller for unified power quality conditioner to minimize the power quality impact present in the matrix converter instead of passive filter. A matrix converter produces significant harmonics and nonstandard frequency components into load. The proposed approach eliminates the total harmonic distortion efficiently and also mitigates sag, swell present in the matrix converter's load voltage. Due to smaller THD, the harmonic pollution in the power system will be reduced and the power quality will be increased. The proposed approach and controller has been tested and validated on the matrix converter using Matlab/Simulink software. The simulation results are shown to demonstrate the advantages of the proposed scheme.

Key words: Matrix converter, unified power quality conditioner, power quality, voltage harmonics, voltage sag and voltage swell, adaptive controller

INTRODUCTION

A matrix converter is a 3-3 phase configuration with direct AC-AC converter topology (Wheeler *et al.*, 2008), the matrix converter has several advantages over traditional rectifier-inverter type power frequency converters. It provides sinusoidal input and output waveforms. It has inherent bi-directional energy flow capability, the input power factor can be fully controlled. Finally, it has minimal energy storage requirements which allows to get rid of bulky and lifetime-limited energy-storing capacitors. In spite of the advantages, the matrix converter has also some disadvantages. It has a maximum input output voltage transfer ratio limited to $\cong 87\%$ for sinusoidal input and output waveforms. It requires more semiconductor devices than a conventional AC-AC indirect power frequency converter. Since, no monolithic bi-directional switches exist and consequently discrete unidirectional devices are arranged so, it can be used for each bi-directional switch and produces higher order harmonics (Yacamini and Oliveira, 1978). The matrix converter consists of nine bi-directional switches that allows any output phase to be connected to any input phase. The general architecture of matrix converter is shown in Fig. 1. Since, nine bi-directional switches are used in the matrix converter, it can assume 512 (2^9) different switching state combinations. However, not all of them can be employed. Regardless of the control method used, the choice of the matrix converter switching
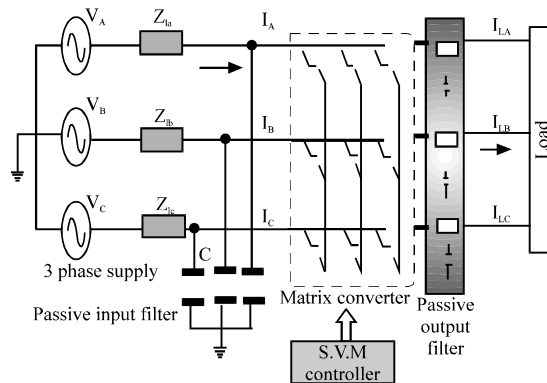

Fig. 1: General architecture of matrix converter

states combinations (from now on simply matrix converter configurations) to be used must be comply with two basic rules.

Taking into account that the converter is supplied by a voltage source and usually feeds an inductive load, the input phases should never be short-circuited and the output currents should not be interrupted. From a practical point of view, these rules imply that one and only one bi-directional switch per output phase must be switched on at any instant.

By this constraint in a 3-3 phase matrix converter only 27 switching combinations are permitted. The conventional compensation of harmonic reduction in the matrix converter is achieved by adding input parallel

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passive filters and series filters. But these filters are not working well when the supply frequency varies.

POWER QUALITY ISSUES IN MATRIX CONVERTER

Generally, 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. Without the proper power, an electrical utility or load may malfunction, fail permanently or not operate at well. Ideally, voltage is fed by a utility as sinusoidal having a magnitude and a frequency given by international standards or system specifications with an impedance of zero ohms at all frequencies. Generally, electrical power source is ideal and it can deviate in the following ways.

Variations in the peak or RMS voltage are important to different types of equipment and load. When the RMS voltage increases beyond the nominal voltage by 10-80% for 0.5 cycles to 1 min, the phenomena is called as swell (Kusko and Thompson, 2007). Sag is the opposite action: the RMS voltage is below the rated voltage by 10-90% for 0.5 cycles to 1 min (Fuchs and Mosoum, 2008). Variations in the wave shape are usually known as harmonics (Heydt, 1995). Overvoltage occurs when the nominal voltage increases >110% for >1 min (Paul *et al.*, 2011).

Under voltage occurs when the nominal voltage falls or <90% for >1 min (Heydt, 1995). The input voltage directly reflects the output voltages of matrix converter (Wheeler *et al.*, 1993). Sag swell over voltage and under voltage occurs in the input voltage and to the reference with the above factors, the output voltage of the matrix converter also distorts. Next is the important harmonic source is AC/DC converters/inverters and AC/AC converter like matrix converter. Many low-power single-phase converters/inverters and high-power 3 phase converters/inverters are being used in electrical power systems. Harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency (Karaca and Akkaya, 2009). In matrix converter, two types of harmonics such as voltage harmonics and current harmonics are produced and it is given in Eq. 1 and 2:

$$\text{For voltage}: \text{THD}v = 100\sqrt{\frac{v_h^2}{v_1}} \qquad (1)$$

$$\text{For current}: \text{THD}i = 100\sqrt{\frac{I_h^2}{I_1}} \qquad (2)$$

Equation 1 and 2, I_h and v_h are current and voltage harmonics, respectively. There are many nonlinear loads drawing non sinusoidal currents from electrical power systems. These non sinusoidal currents pass through different impedances in the power systems and produce voltage harmonics. These voltage harmonics propagate in the power systems and affect all of the power system components. Most of the other electrical loads are sensitive to harmonics. Matrix converters produce harmonics. This harmonics may lead to their improper operation. Passing harmonic currents through the utility lines cause interference with the communication circuits near the transmission lines and may cause a malfunction in these circuits. On the other hand, harmonics cause disturbance in sensitive loads in power systems such as sensitive medical devices, control circuits and computers (De la Rosa, 2006). Control circuits that work on current or voltage zero crossing have higher sensitivity to harmonics and may not work properly in the presence of harmonics.

THE PROPOSED UPQC BASED COMPENSATION SCHEME FOR MATRIX CONVERTER

The Unified Power Quality Conditioner (UPQC) is a versatile device which could function as series active filter and shunt active filter. UPQC can simultaneously fulfill different objectives like maintaining a balanced sinusoidal (harmonic free) nominal voltage at the load, eliminating harmonics in the source currents, load balancing and power factor correction. In Fig. 2, the 3 phase, 3 wire UPQC system consists of the sconverter VSC$_1$, input filter
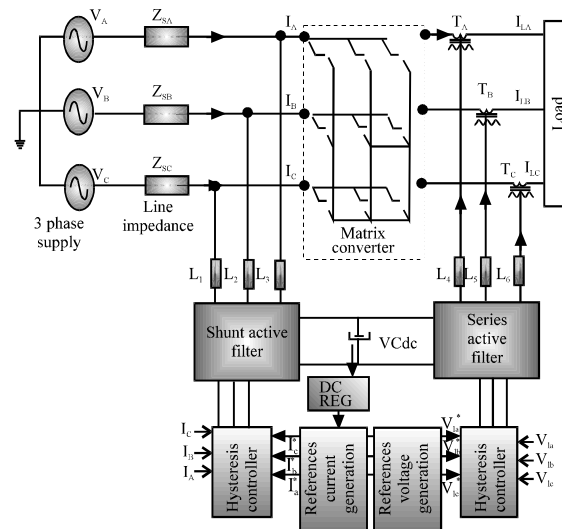

Fig. 2: Proposed UPQC based compensation for matrix convertor

inductance L_{1-3}, input filter capacitor $1C_{11-13}$, DC-link Capacitor CDC, the converter VSC_2, output filter inductance L_{4-6}, output filter capacitor C_{21-23}, series transformer (T_{A-C}), load and so on. The converter VSC_1 output voltage $V(a-c)$ between source voltage $V_{s(a-c)}$ and load voltage $V_{L(a-c)}$ through inductance L_1 and transformer T_s which is called series converter. The converter VSC_2 output compensated current $I_{(a-c)}$ between source current $I_{s(a-c)}$ and load current $I (a-c)$ through filter inductance $L_{(1-3)}$ and filter capacitor $C_{(1-3)}$ which is called as parallel converter. It can be seen that the series converter and the parallel converter in Fig. 2. Space vector modulation control is used to control the matrix converter.

Modeling and analysis of UPQC-matrix converter: Figure 3 shows the fundamental representation of UPQC with matrix converter. UPQC is a combination of a shunt and a series compensator cascaded via a DC link capacitor which facilitates the sharing, the active power between the two. Shunt active filter of the UPQC is modeled as a controlled current source and the series active filter is modeled as a controlled voltage source. Bus voltage V_m is taken as the source.

The supply generator side voltage is represented as V_M. I_M is the source current. V_{PCC} is the intermediate bus voltage and V_{inj} is the voltage injected by the series active filter of the UPQC.

The supply side voltage is in phase with the PCC voltage. I_S is the supply current which is in anti-phase with the load side voltage. I_c is the current injected from the shunt active filter of the UPQC. The load terminal voltage is represented as V_L. I_L is the load current. The dynamics of the DC link capacitor is ignored in the modeling of the UPQC. This has been done in the assumption that the DC link capacitor voltage stays constant all the time. Series active filter compensates the
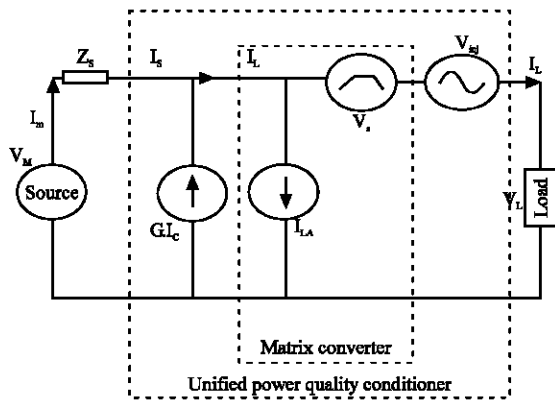

Fig. 3: Fundamental representation of UPQC with matrix converter

harmonic voltage source and it is placed in between the matrix converter and load. If the series active filter is controlled as:

$$V_{inj} = KGI_S \qquad (3)$$

Where:
V_{inj} = Series active filter
I_s = Source current
G = Equivalent transfer function

The source current is:

$$I_S = \frac{V_S - V_L}{Z_S + Z_L + KG} \qquad (4)$$

K>>1 purequirese operating condition for the series active filter to compensate for a harmonic source:

Z_s = Source (line) impedance
I_L = Equivalent harmonic current source
Z_L = Equivalent impedance on the input side of matrix converter

which may include passive filters and power-factor correction capacitors and G is the equivalent transfer function of the active filter including the detection circuit of harmonics and the delay of the control circuit.

In general, G has the function of notching the fundamental component that is $|G|_h = 0$ at the fundamental and $|G|_h = 1$ for harmonics. All the equations are represented in per unit. From Fig. 3, the following equations are obtained from the shunt part of UPQC:

$$I_C = GI_L \qquad (5)$$

$$I_S = \frac{Z_L}{Z_S + \dfrac{Z_L}{1-G}} \cdot I_{LO} + \frac{V_S}{Z_S + \dfrac{Z_L}{1-G}} \qquad (6)$$

$$I_L = \frac{\dfrac{Z_L}{1-G}}{Z_S + \dfrac{Z}{1-G}} \cdot I_{LO} + \frac{1}{1-G}, \frac{V_S}{Z_S + \dfrac{Z_L}{1-G}} \qquad (7)$$

Focusing on harmonic:

$$\left|\frac{Z_L}{1-G}\right|_h > |Z_S|_h \qquad (8)$$

$$I_C = I_{Lh} \qquad (9)$$

$$I_{LH} = I_{LOh} + \frac{V_{Sh}}{Z_L} \qquad (10)$$

where, the subscripts, h and f represent the harmonic components and the fundamental components respectively. Modulus represents the magnitude of a transfer function. G can be predesigned and determined by the active filter while Z_s and Z_L are determined by the system, i.e., parameters of the ac source and the load side of the matrix converter. The control objective to be achieved during the normal working condition is that the shunt active filter of the UPQC must provide the reactive power required by the generator, connecting transformer or any other inductive device. During any abnormal condition, the series active filter of the UPQC should regulate the incoming voltage and compensate for any voltage sag or swell and the shunt active filter should continue to provide the reactive power and at the same time, it should maintain the DC link capacitor voltage at a constant value.

Analysis and the coordination control scheme of shunt active filter

Control strategy of UPQC: The control strategy is basically the way to generate reference signals for both shunt and series active power filter of UPQC. The compensation effectiveness of the UPQC depends on its ability to follow with a minimum error and time delay to calculate the reference signals to compensate the distortions, unbalanced voltages or currents or any other undesirable condition.

Selection of the controlling method: UPQC is vastly studied by several researches as an infinite method for power quality conditioner. Different UPQC controlling methods can be classified in three following classes: Time-domain controlling method, frequency domain controlling method and new techniques. Fourier method is one of the method can be named as frequency-domain methods. The methods such as P-Q theory (Fuchs and Mosoum, 2008), ZVS instantaneous reactive power (Heydt, 1995), algorithms based on the synchronous d - q reference frame, instantaneous power balance method (Paul *et al.*, 2011), synchronous detection algorithm, direct detection algorithm and notch filter based controlling methods are belongs to the time domain methods.

Dead beat control, space vector modulation and wavelet conversion are some of the new techniques (Heydt, 1995). Controlling methods are based on three general standards such as load characteristics, required accuracy and application facility. All the methods end in

to a similar result when the reference signal is calculated under balanced and sinusoidal condition. Otherwise each method end into a different results under unbalanced and non sinusoidal conditions.

Dead beat controlling method presents the best operation among the others but more expense should be paid for its calculations. Among the introduced methods the adaptive control method seems to be more appropriate. The fact is that it needs the sinusoidal and balanced voltage and it is not sensitive to voltage distortions and it is relatively simple. In result, the response time of the control system shortens.

Controller design: The control system of the proposed system is shown in Fig. 1. This comprises of three following parts:

• Reference signal generation (PLL)
• Shunt inverter control
• Series inverter control

REFERENCE SIGNAL GENERATION OF THE CONTROLLER (PLL)

The critical problem of a unified power quality conditioner is to find an algorithm which can obtain an accurate harmonic reference signal for control purpose. Conventional control algorithms such as the instantaneous reactive power theory (Karaca and Akkaya, 2009) or instantaneous symmetrical components (De la Rosa, 2006), the shunt and series AF currents/voltages are sensed and controlled to match their respective computed reference components, there by increasing the number of sensors and computational delays. In this study, a detecting method based on adaptive noise cancelling theory is used and it is adopted to measure the harmonic components of the nonlinear load current and load voltage is implemented. Let the load current, input frequency and terminal voltage be the input to the PLL.

Three phase distorted supply voltages are sensed and given to the PLL which generates sine terms. The sensed supply voltage is multiplied with a suitable value of gain before being given as an input to the PLL. Here, K = 1 ... N be the gain value assigned for controlling (Fig. 4). Here, I_L is the load current, V_T is the load voltage, ω is the output signal of the adaptive detecting circuit and f is the fundamental reference frequency which is in phase with ac source voltage. From the theory of ANC and (Wheeler *et al.*, 1993) as the input sinusoidal reference signal, i.e., the fundamental component of the system voltage has the same frequency and in phase with the
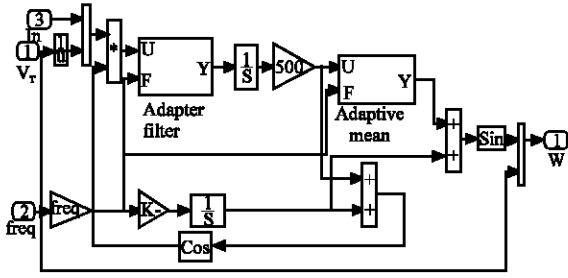
Fig. 4: Porposed reference signal generation (PLL)

desired fundamental components of load current and load voltage, the dc component of the output of integrator will tune accordingly until they are equal in magnitude. The corresponding fundamental real components of the current and voltage are then extracted from the sampled load current and load voltage. Under the action of ANC loop in steady state, the output current I_f and the voltage V_s of detecting circuit have no larger include the fundamental real components, the dc component of the integrator output will keep a constant value which is in proportional to the magnitude of the fundamental real component of load:

$$I_f = I_L - kE_m \sin\omega t \ (K_0 + 1/\omega RC^t_0 I \ E_m \sin\omega t$$
$$= I_L - kK_0 \ E_m \sin\omega t - kK_1 \ E_m \sin\omega t$$

Where:

$$K_1 = 1/\omega \ RC \ I_f \ . \ E_m \ \sin\omega t d\omega t$$
$$V_s = V_L - kE_m \sin\omega t \ (K_0 + 1/\omega RC^t_0 V_s \ E_m \sin\omega t d\omega t$$
$$= V_s - kK_0 E_m \sin\omega t - kK_1 E_m \sin\omega t$$

Where:

$$K_1 = 1/\omega RC \ I_f \ . \ E_m \ \sin\omega t d\omega t$$

$$I_L = I_P + I_Q + I_H$$

$$V_L = V_P + V_Q + V_H$$

Where:

I_p = Fundamental active component load current
I_q = Fundamental reactive component of load current
I_h = Harmonic components in load current
V_p = Fundamental active component of load voltage
V_q = Fundamental reactive component of load voltage
V_h = nharmonic components in load voltage
K_1 = Proportional coefficient
K_0 = DC component of the integrator output

Then:

$$I_f = I_L - k.K_0 \ .E_m \ \sin\omega T$$
$$I_f = I_P + I_Q + I_H - kK_0 \ .E_m \ \sin\omega T$$

$$I_F = I_Q + I_H$$
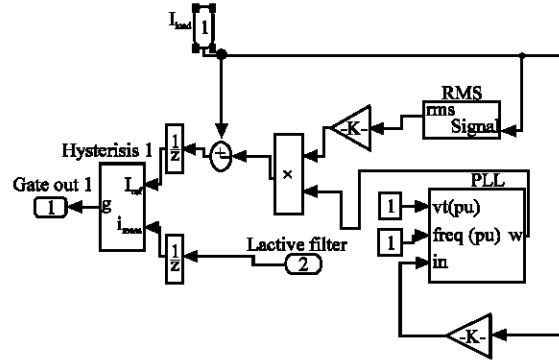$$I_P = k.K_0 \ .E_m \ \sin\omega T$$

Fig. 5: Proposed shunt control strategy

The output signal of the adaptive detecting current and voltage are just the reactive power and harmonic components of the nonlinear load voltage and current.

Control scheme of shunt inverter control: Figure 2 shows the UPQC shunt inverter block diagram using adaptive controller implemented in simulink. Where the sensitive load currents are I_{load}. The measured load currents are fed in to adaptive controller. The fundamental sinusoidal functions are obtained through the PLL using adaptive filters. Let the load current and the current of active filter be the input to the shunt firing unit. The gate signal obtained from this unit is the input to the IGBT. Thus, obtaining gate signal by means of hysteresis current controlling technique is performed. The gate signal is obtained by means of using hysteresis current controlling technique. To detect the current to be compensated, reference current should be obtained. PLL value is improved by means of RMS value. RMS load active current can be obtained by:

$$RMS \ (F(t)) = \sqrt{\frac{1}{T} \int_{t-T}^{T} f(t)^2}$$

The computed currents are then given to the hysteresis controller along with the sensed 3 phase current. The output of the hysteresis controller is the voltage of gate signal. In Voltage Source Inverter (VSI) of the shunt active filter, the shunt APF can be designed to operate as a controlled current source whose output current would be automatically controlled. Finally, the reference current wave form get generate and RMS value of the load current is multiplied. We get the actual undistracted current wave form with respect to the load current (Fig. 5). The error sigal will generate the RMS value of the reference current wave form into actual load current wave form the mean value taken by the current signal of shunt active filter:

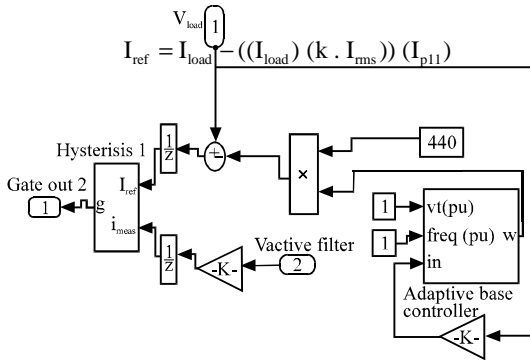$$I_{ref} = I_{load} - ((I_{load})(k \cdot I_{rms}))(I_{p11})$$

Fig. 6: Block diagram of proposed series control strategy

The two inputs are fed to the hysteresis band controller and the output fed to the IGBT control.

Control scheme of series inverter control: A simple control methodology is developed to control the series inverter control. The series filter is controlled such that it injects voltages (v_{ca}-v_{cc}) which cancels out the distortions and/or unbalance present in the supply voltages thus, making the voltages at the PCC (v_a-v_{Lc}) perfectly balanced and sinusoidal with the desired amplitude as shown in Fig. 6.

In other words, the sum of the supply voltage and the injected series filter voltage makes the desired voltage at the load terminals. The output of PLL is same for both shunt and series part. Let the load voltage and voltage of the active filter are the inputs to the series firing unit. The computed value of PLL is then multiplied with the desired peak value of the PCC phase voltage which becomes the 3 phase reference PCC voltages, the desired peak value is 440 V thus, it is given.

The computed voltages are then given to the hysteresis controller along with the sensed 3 phase PCC voltages. The output of the hysteresis controller is gate signals of the VSI of the series active filter. The hysteresis controller generates the gate signals such that the voltage at the PCC becomes the desired sinusoidal reference voltage. Therefore, the injected voltage across the series cancels out the harmonics present in the supply voltage. The complete system (converters, control circuitry and load) has been simulated using Simulink toolbox from Matlab 7.9.

SIMULATION RESULT

The simulations with Matlab/Simulink were performed for the purpose of analyzing the operation of the proposed system. The power circuit is modeled as a 3 phase 4-wire system. The circuit parameters that were used are shown in Table 1. In the simulation studies, the

Table 1: The circuit parameters

| Source	Parameters		Values
Load			
	Voltage	V_{Sabc}	510 V_{rms}
	Frequency	F	50 Hz
	3 phase load resistance	R_L	2 Ω
DC link			
	Voltage	V_{dc}	900 V
	Capacitor	C_1,c_2	2200 μF
Series active power filter			
	Ac line inductance	LC_{abc}	0.5 mH
	Filter resistance	RC_{abc}	2 Ω
	Filter capacitor	CC_{abc}	100 μF
	Switching frequency	F_{pwm}	20 kHz
Shunt active filter			
	Ac line inductance	LC_{abc}	5 mH
	Filter resistance	RC_{abc}	2 Ω
	Filter capacitor	CC_{abc}	100 μF
	Switching frequency	F_{pwm}	20 kHz
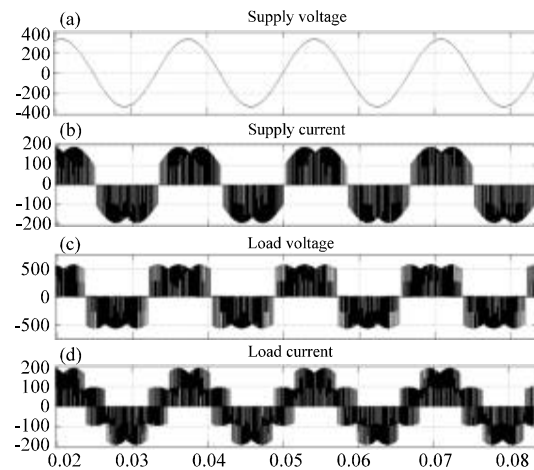
Fig. 7: System voltage (V_S), source current (I_s), load voltage (V_L) and load current (I_L) without filter

results are specified before and after UPQC system is operated. In Fig. 7, the simulations of the matrix converter operates without input capacitor is shown in Fig. 7. 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 0.025-0.045 sec search is the one cycle of the current waveform. Here, the wave shape of this current is non sinusoidal and it contains harmonics.

Figure 8 shows the UPQC based quality control scheme. Figure 8a shows the input voltage is 520 V frequency is 50 Hz. Simulation starts at 0-0.08 sec.

The simulation result (Fig. 8a) show the input voltage is harmonic free (Fig. 8b) shows the input current waveform of the matrix converter in a proposed control scheme. Figure 8c shows the load voltage proposed
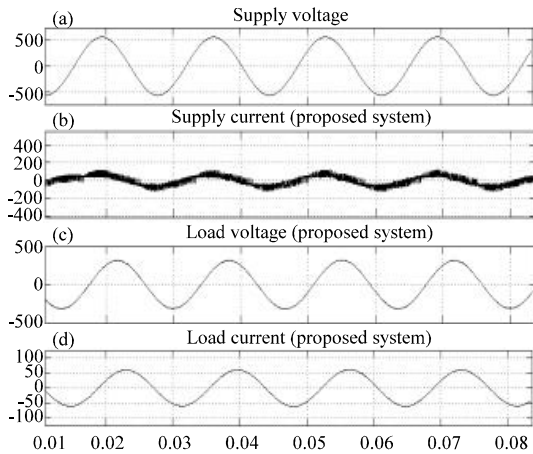
Fig 8: a) Input supply voltage; b) Supply current in proposed system; c) Matrix converter output voltage (proposed compensation); d) Load current compensation (proposed controller)
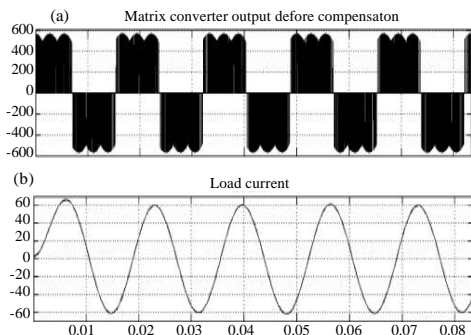

Fig. 9: a) Matrix converter output voltage before compensation and b) Input load current of shunt active filter

system applied. Figure 8d shows the load current applied in the proposed system. Here, the load current is a resistive load. Figure 9a shows the matrix converter output voltage the simulation result shows the matrix output voltage contain harmonics. Figure 9b shows the input current of the series active filter part. This simulations show's that the series active filter takes the current sinusoidal and the matrix converter voltage is 440 V.

In Fig. 10, the real and reactive power maintained constant as shown in the simulation result. Figure 11a shows the total harmonic distortion in the source voltage. There is no harmonic present.

Figure 11b shows the total harmonic distortion in the matrix converter output. The matrix converter produced 60%of voltage harmonics shown in Fig. 12c, the THD reduced at 1% of proposed system.
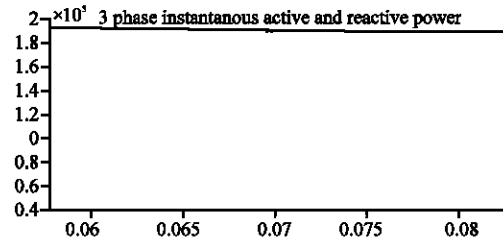

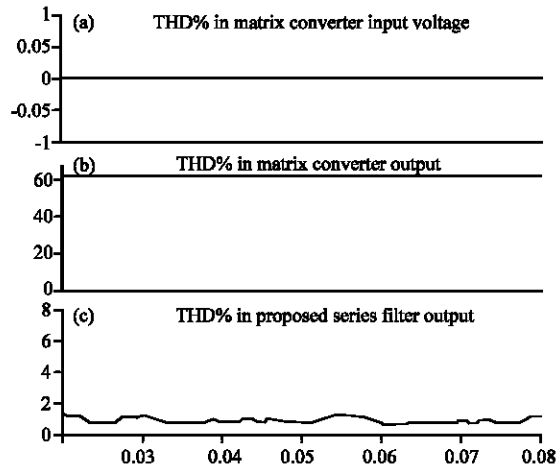Fig. 10: Real and reactive compecsation on proposed PLL based UPQC compensator in matrix converter

Fig. 11: a) Total harmonic ditortion matrix converter input voltage; b) Total harmonic distortion in matrix converter and c) Total harmonic distortion in matrix converter output current
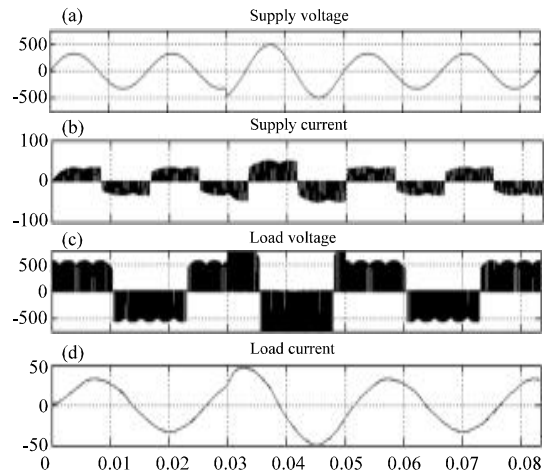

Fig. 12: a) Voltage swell occurred in matrix converter; b) Output current: c) Voltage without compensation

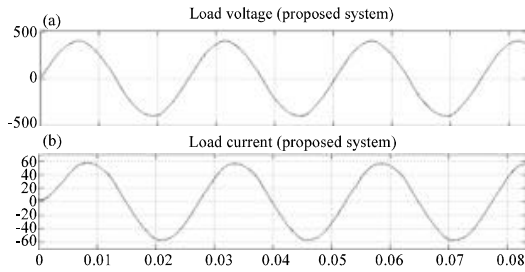Figure 12a-c shows when the matrix converter is affected by swell. The voltage swell present from

Fig. 13: a) Voltage swell occurred in matrix converter; b) output current, voltage with adaptive PLL controller based compensation

0.03-0.05 sec. After the proposed compensation series active filter eliminates the swell problem, it maintains the power quality in the matrix converter output as shown in Fig. 13 a, b.

CONCLUSION

This study proposed an efficient adaptive PLL based controller for unified power quality conditioner to compensate current and voltage variation and harmonic mitigation in matrix converter. The simulation result shows that when unbalance and nonlinear occurs in load current or unbalance and sag in the source voltage, the proposed controller eliminates the impact of distortion and unbalance of the load current on the power line, making the power factor to unity. Meanwhile, the series compensator isolates the load voltages and source voltage. Shunt compensator provides three phase balanced and rated voltages for loads.

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