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Matrix Converter Based Unified Power Quality Conditioner (MUPQC) for Power Quality Improvement in a Utility

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Abstract: This study proposes a new approach of unified power quality conditioner which is made up of a matrix converter without energy storage devices to mitigate the current harmonics, voltage sags and swell. By connecting the matrix converter output terminals to the load side through series transformer and the input side of matrix converter is connected to the supply side with step up transformer. So, a matrix converter injects the compensation voltage on the load-side, so it is possible to mitigate the voltage sag/swell problems, resulting in an efficient solution for mitigating voltage and current related power quality problems. Thus, the proposed topology can mitigate the voltage fluctuations and current harmonics without energy storage elements and the total harmonic distortion produced by the system also very low. It also reduced volume and cost, reduced capacitor power losses, together with higher reliability. The Space-Vector Modulation (SVM) is used to control the matrix converter. Matlab/Simulink based simulation results are presented to validate the approach.

Key words: Matrix converter, unified power quality conditioner, current harmonics, voltage sag/swell, non linear load, Matlab/Simulink

INTRODUCTION

Power quality is the set of limits of electrical properties that allows electrical system to function in proper manner without significant loss of performance like Flexible AC Transmission System (FACTS) the term custom power devices use for distribution system (Sahoo and Thyagarajan, 2009). Just as facts improve the reliability and quality of power transmission system, the custom power enhances the quality and reliability of power that is delivered to customers. The main causes of a poor power quality are harmonic currents, poor power factor, supply voltage variations, etc. (Siahkali, 2008). In recent years, the demand for the quality ofelectric power has been increased rapidly. Power quality problems have received a great attention or a large increase of the load current like starting a motor or transformer energizing.

Unified Power Quality Conditioner (UPQC) is one of the best customs power devices used to compensate both source and load side problems (Babu and Dash, 2012) in a distribution system. It consists of shunt and series converters connected back to back to a common DC link. It can perform the functions of both D-statcom and DVR.

Figure 1 shows a basic system configuration of a general UPQC consisting of the combination of a series active power filter and shunt active power filter (Fujita and Akagi, 1998). The main aim of the series active power filter is harmonic isolation between a distribution system and a load. It has the capability of voltage flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer Point of Common Coupling (PCC). The shunt active filter is used to absorb current harmonics, compensate for reactive power and negative-sequence current and regulate the DC-link voltage between both active power filters (Kesler and Ozdemir, 2009).

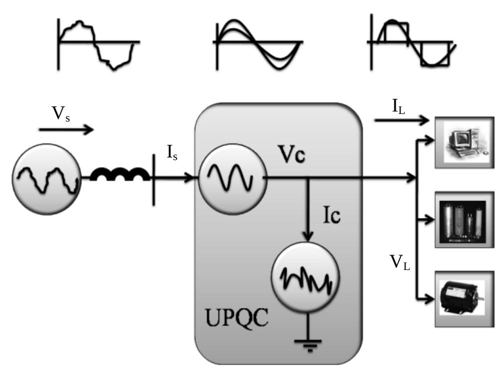

Fig. 1: Basic structure of unified power quality conditioner

Unified power quality conditioner consists the DC bus and its DC capacitor must be designed. DC capacitor achieves two goals, i.e., to comply with the minimum ripple requirement of the DC bus voltage and to limit the DC bus voltage variation during load transients. But the proposed matrix converter based UPQC there is no need of DC capacitor.

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The series active filter is controlled by the voltage source converter. But voltage source converter has some drawback. Due to switching loss, capacitor leakage current, etc., the source must provide not only the active power required by the load but also the additional power required by the VSI to maintain the DC-bus voltage constant. Unless these losses are regulated, the DC-bus voltage will drop steadily. Moreover, VSC based converter produces more harmonics and switching losses high.

In this study, a matrix converter based unified power quality conditioner compensates voltage sag and swell and current harmonics compared to conventional VSC based unified power quality conditioner.

MATRIX CONVERTER

In this study, a matrix converter based unified power quality conditioner instead of VSC based unified power quality conditioner is proposed. Although, matrix converter was initially introduced as an AC Driver, due to its advantages may be used in voltage compensation applications and control the frequency regulation (Lorzadeh *et al*., 2010) (Fig. 2).

The matrix converter has implemented in several custom power devices like constant frequency unified power quality conditioner (Paul *et al*., 2011), universal power quality conditioner (JenoPaul *et al*., 2011), dynamic voltage restorer (Lozano *et al*., 2010), shunt active filter (Heris *et al*., 2012).

A matrix converter can operate as a four quadrature AC-AC converter circuit. The output voltage, frequency and its amplitude and also the input power factor can be controlled by utilizing the proper modulation method (SVM).

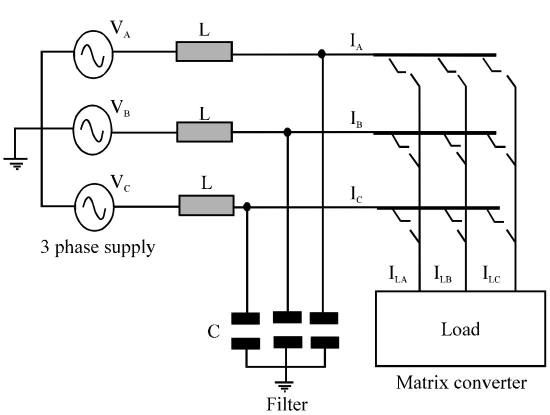

Fig. 2: Basic structure of matrix converter

PROPOSED UNIFIED POWER QUALITY CONDITIONER

The proposed unified power quality is designed using a matrix converter is shown in Fig. 3. I_{abc} are the smoothing inductor. C_{abc} is the smoothing capacitor. One step up transformer is used for step up the matrix converter input voltage. So, the matrix converter injects the significant current to PCC.

In this study, the step up transformer was simply modeled by a current source and the focus was put on the control of the input current for the active filtering function. Because matrix converter transfer ratio is limited to 0.876. The control strategy features two cascaded control loops.

In series part a series active filter is designed using the same matrix converter topology. Series filter removes the ripples. The series transformer also called injection transformer which injects the appropriate voltage to the load to compensate the voltage and removes the harmonics. Figure 4 shows the fundamental working principle of a series active filter. V_{pcc} is the point of common coupling. $V_s\angle 0$ is the source voltage. $I_c\angle\beta$ is the injected current for current harmonic mitigation.

$A_m\angle\alpha_m$ is the matrix converter amplitude and its phase angle. $V_{inj}\angle\gamma = 90$ is the injection voltage for voltage compensation. UPQC's series active filter work as isolators instead of generators of harmonics and hence, they use different control strategies. Now, here UPQC's series active filters working as controllable voltage sources. With this approach, the evaluation of the reference voltage for the series filter is required. This is

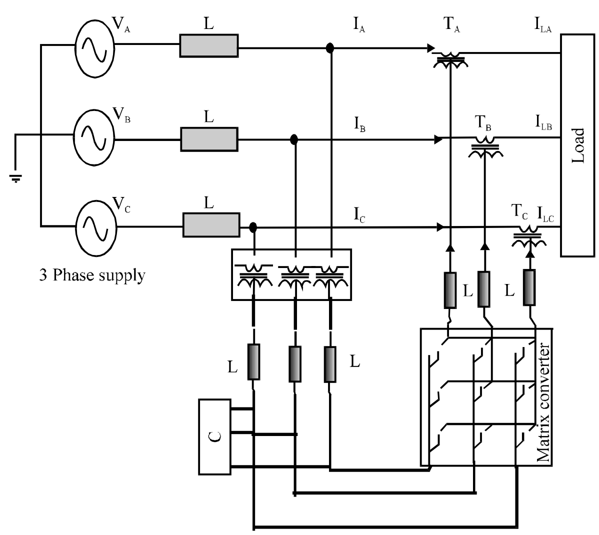

Fig. 3: Proposed unified power quality conditioner

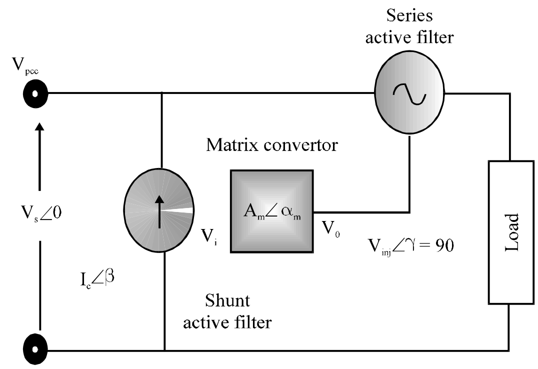

Fig. 4: Fundamental representation of matrix converter based unified power quality conditioner

normally quite complicated because the reference voltage is basically composed by harmonics and it then has to be evaluated through precise measurements of voltages and/or current waveforms. Another way to get the reference voltage for the series filter is through the various control theory. However, this solution has the drawback of requiring a very complicated control circuit (several analog multipliers, dividers and operational amplifiers).

THE CONTROL SYSTEM OF MATRIX CONVERTER BASED UNIFIED POWER QUALITY CONDITIONER

Series part control system of UPQC: The output terminal voltage and input terminal current consider the low frequency transformation function and set a sinusoidal input voltage as follows (Fig. 5):

$$\bar{v}_{abc} = V_i \begin{bmatrix} \cos(\omega_0 t + \alpha_0) \\ \cos(\omega_0 t + \alpha_0 - 2\pi/3) \\ \cos(\omega_0 t + \alpha_0 + 2\pi/3) \end{bmatrix} \quad (1)$$

$$\bar{v}_{ABC} = D\bar{v}_{abc} = (aD_1 + (a-1)D_2)\bar{v}_{abc} = qV_i \begin{bmatrix} \cos(\omega_0 t + \alpha_0) \\ \cos(\omega_0 t + \alpha_0 - 2\pi/3) \\ \cos(\omega_0 t + \alpha_0 + 2\pi/3) \end{bmatrix} \quad (2)$$

Where, ϕ is the output (or load) angle. Using Eq. 2, the MC output currents can be written as follows:

$$\bar{i}_{abc} = D^T \bar{i}_{ABC} = qI_o \left(a \begin{bmatrix} \cos(\omega_i t + \varphi_i) \\ \cos(\omega_i t + \varphi_o - 2\pi/3) \\ \cos(\omega_i t + \varphi_o + 2\pi/3) \end{bmatrix} + (1-a) \begin{bmatrix} \cos(\omega_i t + \varphi_o) \\ \cos(\omega_i t + \varphi_o - 2\pi/3) \\ \cos(\omega_i t + \varphi_o + 2\pi/3) \end{bmatrix} \right) \quad (3)$$

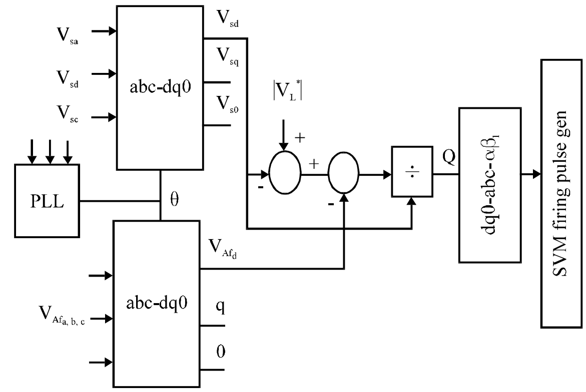

Fig. 5: Reference voltage generation for matrix converter based series active filter

Assume the desired input current to be:

$$\bar{i}_{ABC} = I_o \begin{bmatrix} \cos(\omega_0 t + \alpha_0 + \varphi_0) \\ \cos(\omega_0 t + \alpha_0 + \varphi_0 - 2\pi/3) \\ \cos(\omega_0 t + \alpha_0 + \varphi_0 + 2\pi/3) \end{bmatrix} \quad (4)$$

where, φ_i is the input displacement angle:

$$\bar{i}_{abc} = I_i \begin{bmatrix} \cos(\omega_i t + \alpha_i + \varphi_i) \\ \cos(\omega_i t + \alpha_i + \varphi_i - 2\pi/3) \\ \cos(\omega_i t + \alpha_i + \varphi_i + 2\pi/3) \end{bmatrix} \quad (5)$$

Reference voltage generation: The ratio of the maximum (RMS) value of the input voltage to the maximum (RMS) values of the output voltage is defined as:

$$Q = \frac{V_o}{V_i} \quad (6)$$

Q, that is, where V_o and V_i are the maximum (RMS) amplitude of output and input voltages, respectively. Considering V^*_{Af} to be the amplitude of active filter's reference voltage, the value of Q can be calculated as:

$$Q = \frac{V^*_{Af}}{V_s} \quad (7)$$

To find V^*_{Af}, the difference between ideal and actual load voltages is calculated and then divided by the grid voltage as shown in Fig. 6. The SVM firing pulse generator" uses the following equation to calculate the on-time of matrix converter switches:

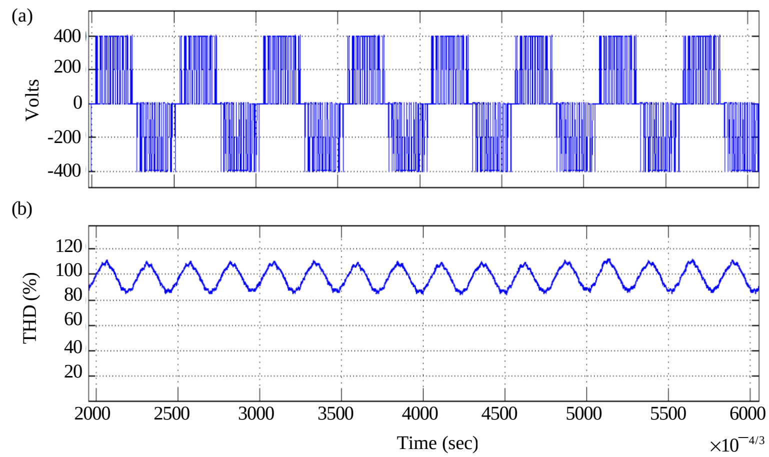

Fig. 6: a) VSC converter output voltage; b) total harmonic distortion in percentage

$$m_{ij(t)} = \frac{1}{3} + \frac{2}{3} Q\cos\left(\omega_i t - 2(j-1)\frac{\pi}{3}\right) \times \left\{\cos\left(\omega_o t - 2(i-1)\frac{\pi}{3}\right) - \frac{1}{6}\cos(3\omega_o t) + \frac{1}{2\sqrt{3}}\cos(3\omega_i t)\right\} - \frac{2}{9\sqrt{3}} Q\left\{\cos\left(4\omega_i t - 2(j-1)\frac{\pi}{3}\right) - \cos\left(2\omega_i t - 2(j-1)\right)\frac{\pi}{3}\right\} \quad (8)$$

Where:

i and j = The number of input and output phases(a: 1, b: 2, c: 3)

ω_i and ω_o = The input and output voltage angular speeds

Reference current generations: The load current is measured and transformed from the fixed abc-reference frame to the rotating dq-reference frame using the relation (Eq. 9) and the angle of the voltage at the Point of Common Coupling (PCC):

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (9)$$

Since, the rotating dq-reference frame is based on the angle of the voltage at the PCC, the d and q load current components represent, respectively the active and reactive components of the load current. The control objective is to compensate all the load current components except for the fundamental active load current component. Therefore, a High Pass Filter (HPF) is introduced to filter out the fundamental component of the active current. Only the harmonic and reactive components remain in the current reference. The active current that is produced by the transformer also needs to be added to the active current reference as the matrix converter. Finally, obtained the references are d^*_{mc}, q^*_{mc} and which are provided to the outer current control loop. All entities marked with asterisk are reference values as opposed to real/measured values.

Table 1: Simulation parameter of matrix converter based UPQC

Parameters	Values
V_{source}	440 V
L_s	2 mh
L_f	0.5 mh
c_f	200 µf
R_f	0.1 Ω
C_i	2 µf
Matrix converter switching frequency	1200 Hz
Power system frequency	60 Hz

Current control: The previous study explained calculate the current references. To control the current, researchers use Eq. 10:

$$L_f \frac{d}{dt}\overline{i_{mc}} = \overline{v_{pcc}} - \overline{v_c} \quad (10)$$

When Eq. 8 is converted into the rotating dq-reference frame, cross-coupling terms appear as shown in Eq. 9 which must be compensated. When transforming to the rotating dq reference frame again cross coupling terms appear:

$$C_f \frac{d}{dt}\begin{bmatrix} v_{c-d} \\ v_{c-q} \end{bmatrix} = \begin{bmatrix} i'_{mc,d} \\ i'_{mc,q} \end{bmatrix} - \begin{bmatrix} i_{mc,d} \\ i_{mc,q} \end{bmatrix} - \omega C_f \begin{bmatrix} -v_{c,q} \\ v_{c,d} \end{bmatrix} \quad (11)$$

$$L_f \frac{d}{dt}\begin{bmatrix} i_{mc-d} \\ i_{mc-q} \end{bmatrix} = \begin{bmatrix} v_{pcc} \\ 0 \end{bmatrix} - \begin{bmatrix} v_{c,d} \\ v_{c,q} \end{bmatrix} - \omega L_f \begin{bmatrix} -i_{mc,q} \\ i_{mc,d} \end{bmatrix} \quad (12)$$

Table 1 shows the system parameters of the proposed matrix converter based UPQC.

SIMULATION RESULTS

In this research, three phase matrix converter based UPQC is used to compensate the voltage sag/swelland current harmonic. The source voltage is 440 Vrms, 60 Hz. Table 1 shows the proposed system's main parameters. It includes source impedance parameters L and C values for passive branche.

In simulation studies, the results are specified before and after applying the matrix converter based UPQC. Also, the calculated values of Total Harmonic Distortion.ll. The simulation is performed by the Matlab/Simulink Model in discrete form. The sample time of the discrete value is 3×10^{-4} sec.

Result For VSC based converter harmonic: Figure 6 shows the total harmonic distortion of the VSC based converter. Figure 6a shows the voltage source converter's output voltage. Figure 6b shows that its total harmonic distortion. It clearly shown the total harmonic distortion is >100%.

Result for matrix converter harmonic: Figure 7 shows the matrix converter output voltage and its harmonics. The matrix converter produces <40% of harmonicas shown in Fig. 7a and its corresponding matrix converter voltage is shown in Fig. 7b. So, the matrix converter produces the less harmonic compared the voltage source converters.

Proposed matrix converter based UPQC (voltage compensation): Figure 8 shows the single phase representation of the proposed Unified Power Quality Conditioner. The supply voltage is 400 V. Figure 8a shows the supply voltage at sag and swell conditions. At 0.1-0.2 sec the voltage sag accrued the voltage sag voltage is at 100 V.

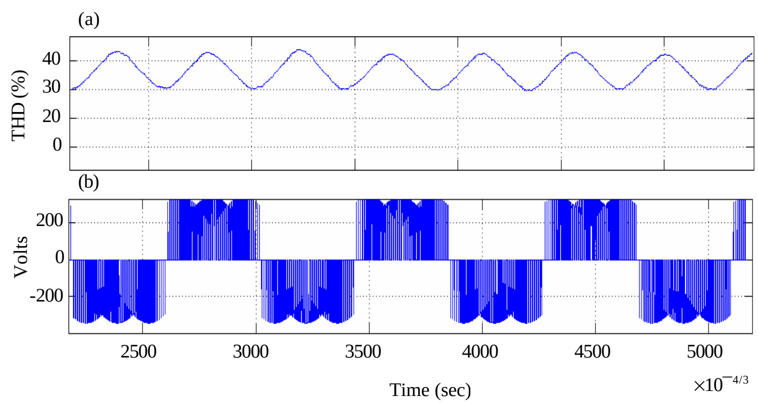

Fig. 7: a) Total harmonic distortion in percentage and b) matrix converter output voltage

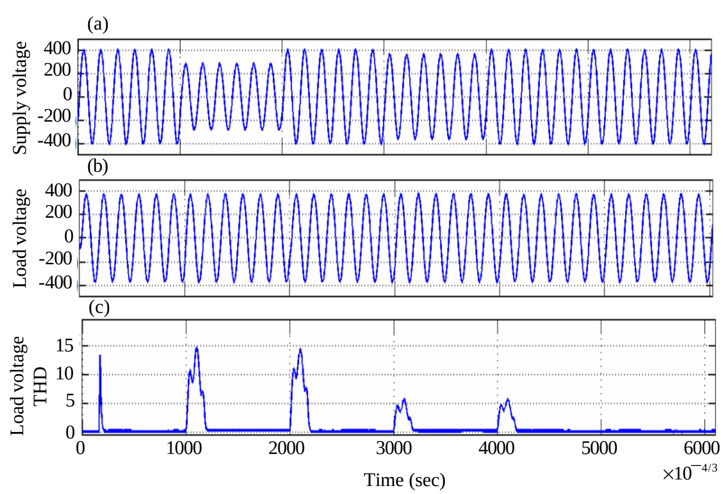

Fig. 8: a) Load voltage after proposed compensation; b) supply voltage and c) total harmonic distortion of load voltage

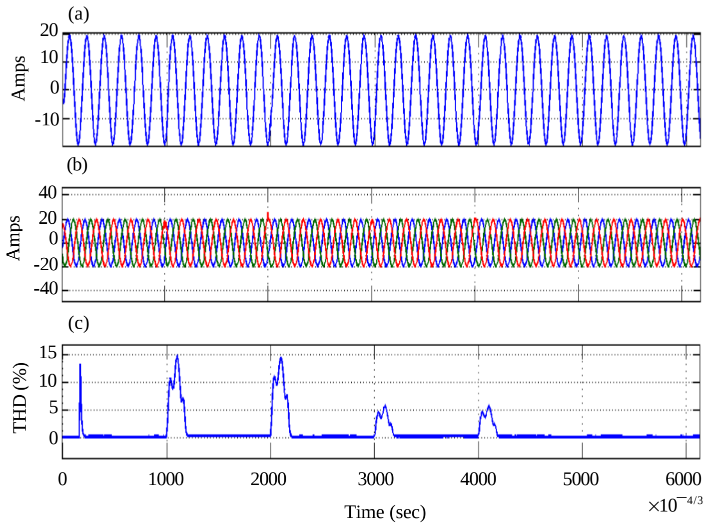

Fig. 9: a) Load current after compensation; b) load current after compensation (3 phase) and c) total harmonics distortion of load current

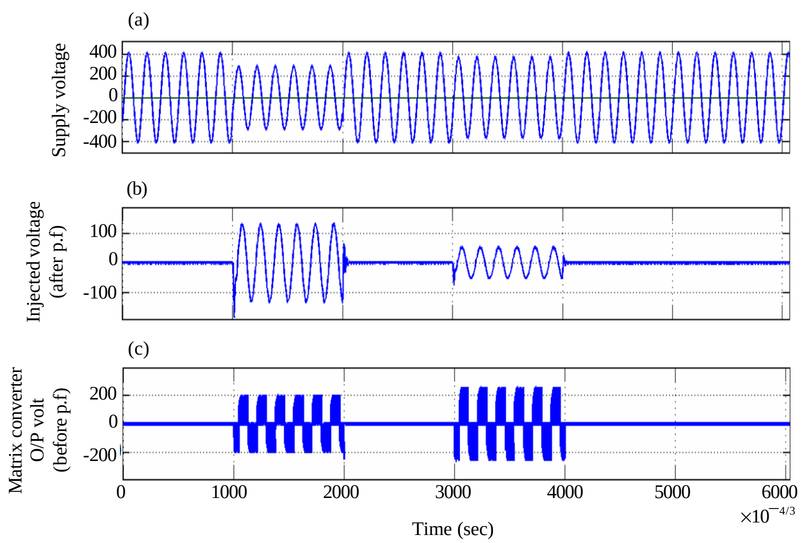

Fig. 10: a) Supply voltage; b) injected voltage through a transformer and c) injected matrix converter voltage

Moreover, the voltage swell accrued at 0.3-0.4 sec of 50 V. Figure 8b shows the matrix converter based compensation compensates the voltage sag and swell. Figure 8c shows the output of the proposed UPQC and its total harmonic distortion. It contains only <2% of harmonic present.

Proposed UPQC based compensation (current harmonics): Figure 9 shows the minimization of load current harmonic based on matrix converter based UPQC compensation. Total current per phase is 20 amperes. In Fig. 9a and b, 3 phase current is shown. Figure 9c shows the total current distortion. The harmonic level is <1% as shown in Fig. 9.

Result for proposed UPQC injected voltages for voltage compensation: Figure 10 shows the voltage injection through proposed unified power quality conditioner. Figure 10a shows the fluctuated voltage. Figure 10b shows the corresponding injected voltage through the series transformer. Figure 10c shows the matrix converter output voltage with out any smoothing filter.

CONCLUSION

This study investigated the use of matrix converter based unified power quality conditioner to mitigate the voltage sag/swell and current harmonics. This study analyzed the matrix converter based unified power quality conditioner and found that matrix converter produces less harmonic distortion compared to the voltage source converter. The proposed UPQC's series active filter handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to correct any abnormalities in the supply voltage to keep the load voltage balanced and constant at the nominal value. Based on simulation results the matrix converter based UPQC also mitigates the current harmonics efficiently with low total harmonic distortion. The matrix converter proved to be efficient for active filtering purposes compared to conventional voltage source converter. In this study, the performance of a matrix converter based UPQC mitigating voltage sags/swells and current harmonics which is demonstrated with the help of Matlab/Simulink.

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