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Matrix Converter Based Series Active Filter for Voltage Sensitive Loads

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Key words: Matrix converter, series active filter, voltage sensitive load, MATLAB, simulink

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Abstract: This study a proposed a new series active filter, based on a matrix converter without energy storage devices to mitigate the current harmonics. By connecting the matrix converter output terminals to the load side connected with series transformer and the input side of matrix converter is connected to the supply side. 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 related power quality problems. Thus, the proposed topology can mitigate the voltage fluctuations without energy storage elements and the total harmonic distortion produced by the system also very low. Space-Vector Modulation (SVM) is used to control the matrix converter. MATLAB/Simulink based simulation results are presented to validate the approach.

INTRODUCTION

There are several causes for voltage distortion, namely, nonlinear loads, some types of voltage sources and thunderstorms[1]. These problems cause instantaneous and long term effects on electrical equipment. The short term effects are malfunctioning, interferences and degradation of the performance of devices or equipments. Effects in the long run are, basically, overheating and premature aging of the electrical devices. If the mains voltage is undistorted but non linear loads are connected to the electrical grid, the current harmonics produced will cause voltage distortions in the line impedances and the voltage at the load terminals will also be distorted. With a distorted voltage, even linear loads absorb distorted currents[2]. Passive filters can be used to compensate some of the problems mentioned above, but they have some limitations. Passive filters only filter the frequencies for which they have been previously tuned, its operation cannot be limited to a certain load, resonances can occur and the electrical system can start to operate with capacitive power factor. Finally Passive filter cannot control the voltage power quality problem like sag/swell.

Recent developments in Active power filters have several advantages over passive ones: compensation is automatic, there is no risk of resonances, unity power factor (or any other desired value) can be achieved permanently and without disturbing the electrical network, they can compensate for phase unbalance and excellent performance can be achieved[3]. They can also be combined with passive filters (which may be already installed) in hybrid topologies, in order to diminish its rated power. Figure 1 shows the series active filter arrangement. Series active filter consists of an AC-DC converter, DC capacitor and VSC based inverter for injecting the voltage to the load.

The drawback of active filter is the DC bus capacitor must be designed[4]. It 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.

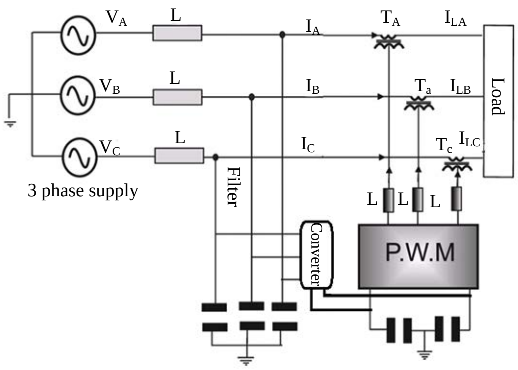

Fig. 1: Basic structure of series active filter

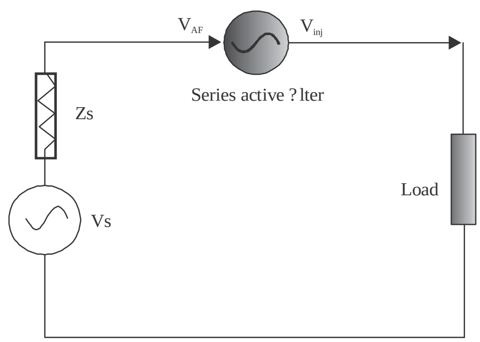

Fig. 2: Fundamental representation of series active filter

Figure 2 shows the fundamental representation of series active filter. Figure 2 shows the fundamental working principle of a series active filter. Zs is the source impedance. VAf is the active filter voltage Series active filters work as isolators. Now, series active filters working as controllable voltage sources. The evaluation of the reference voltage for the series filter is required. This is 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”[5]. However, the solution has the drawback of requiring a very complicated control circuit (several analog multipliers, dividers and operational amplifiers).

All the series active filter is controlled by the voltage source converter. But voltage source converter has some draw back present. Due to switching loss, capacitor leakage current, etc., the distribution 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.

MATERIALS AND METHODS

Matrix converter: In this study proposes a matrix converter based series active filter instead of a VSC based converter (Fig. 3).

After the invention of matrix converter is 1976, it has drawn significant attention. 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. The main application of the converter is in driving motors where the space and weight are premium. The main drawbacks of this topology are the need for fully controlled bi-directional switches and complex algorithm to perform commutation. Developing power matrix converter modules and high speed DSP processors have partially solved these problems A series active filter based on matrix converter topology is presented in this study. Although, matrix converter was initially introduced as an AC driver, due to its advantages may be used in voltage compensation applications. The matrix converter has several advantages listed below.

Sinusoidal input and output current waveforms with small distortion, adjustable input power factor regardless of the load, generally with unity power factor.

- Bilateral transformation of energy
- Elimination of energy storage components
- High-efficiency and fast-response
- Reduction of installation area and integration of more complex silicon structures in power modules
- Higher controllability
- The number of phases on input and output sides are independent of each other
- The waveform and the frequency on both sides are independent of each other
- A matrix converter can reproduce any waveform without using any additional power hardware

It can be used as a full four-quadrant power supply without any additional power hardware. Elimination of temperature sensitive electrolytic DC-link capacitors which results in higher reliability and higher operating temperature. A space vector modulation strategy which permits zero current commutation is employed to provide sinusoidal input and output currents for the matrix converter.

Proposed series active filter: The proposed series active filter is designed using a matrix converter is shown if Fig. 4. L_{abc} are the source impedance, l_{abc} is the smoothing inductor. $C_{(abc)}$ is the smoothing capacitor input of matrix converter is connected to the supply voltage and the output voltage is connected injection transformer (T_{abc}).

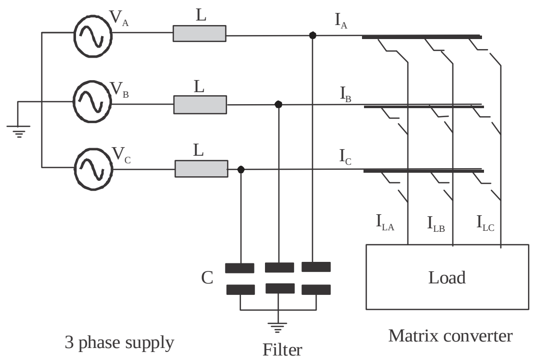

Fig. 3: Basic structure of matrix converter

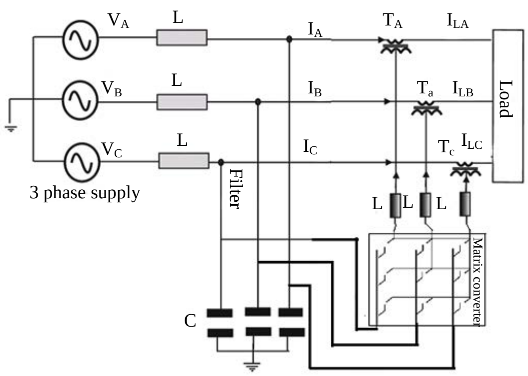

Fig. 4: Proposed series active filter

Figure 5 shows the schematic diagram of the proposed matrix converter. In the present paper a three-phase to the three-phase matrix converter is utilized to realize a series active filter as shown in Fig. 5. Bidirectional switches are implemented by common collector back to back IGBT and diode switch shells . By eliminating the energy storage unit, DC capacitor and minimizing the size of filters in the series active filter configuration, it is possible to pack all the modules into a small size equipment. The proposed series active filter requires more switching devices but it does not need a large electrolytic capacitor.

Control system: The output terminal voltage and input terminal current consider the low frequency transformation function (Eq. 1) and set a sinusoidal input voltage as follows:

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

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

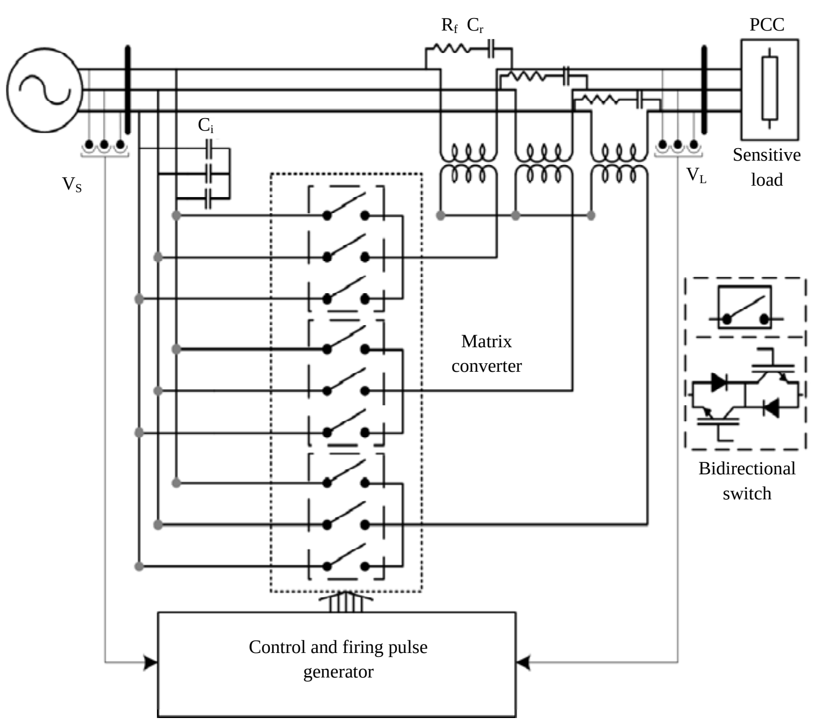

Fig. 5: Schematic diagram of series active filter

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

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

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 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 Enhanced Venturini Method (EVM) has been used to generate the firing pulses of the matrix converter switches[6]. In this method, 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 block indicated by "EVM firing pulse generator" uses the following equation to calculate the on-time of matrix converter switches:

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

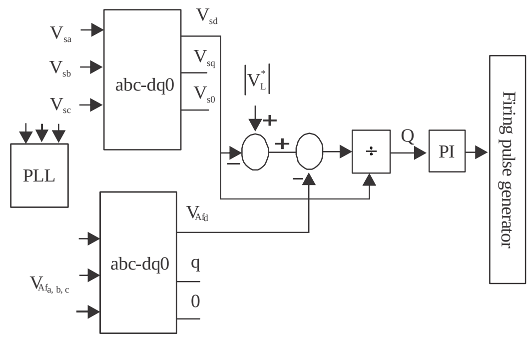

Fig. 6: Reference voltage generation for matrix converter based series active filter

where, i and j are the number of input and output phases (a:1, b:2, c:3), ω_i and ω_o are the input and output voltage angular speeds. Considering n as the series transformer voltage ratio:

$$V_{AF} = nQV_s \quad (9)$$

During voltage sag, error! bookmark not defined must be hold so:

$$V_s + nQV_s \geq 1\text{p.u} \quad (10)$$

The maximum obtainable value of Q is √3/2. Hence, the minimum source voltage that active filter can compensate is:

$$V_{s(min)} \geq \frac{1}{1+\sqrt{3}/2\, n}\text{pu} \quad (11)$$

By defining Vs and λ as ideal source voltage and sag depth, respectively, Vs = (1-λ)VS^*_s the maximum compensable sag depth can be calculated as:

$$\lambda_{max} = V^*_s - V_{s(min)} = \frac{\frac{\sqrt{3}}{2}n}{1+\frac{\sqrt{3}}{2}n}\text{p.u} \quad (12)$$

So, the maximum compensable sag depth is 0.866 p.u. in the presence of transformer. Whereas and without the transformer (n = 1) the load voltage will drop if a sag depth >0.46 p.u. occurs. Considering the power balance equation for a matrix converter (Pin = Pout), we have:

$$V_s I_i = \frac{1}{n}V_{af}I_{out} \quad (13)$$

where, I_{in} and I_{out} are input and output currents of matrix converter, V_{af} is the injected active filter voltage:

Table 1: Simulation parameter

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	600 Hz
Power system frequency	60 Hz

$$\frac{I_i}{I_{out}} = Q \tag{14}$$

get. Hence, the maximum input current of:

$$I_{i(max)} = n\frac{\sqrt{3}}{2}I_L$$

matrix converter is considering the load voltage to be constant due to overcompensation, Eq. 11 shows that for compensating deep converter. Replacing V_{Af} from (Eq. 9) in Eq. 13 yields, $I_{out} = nL_L$ using the transformer voltage ratio, I_{out} can be written $I_i = nQI_L$ as where, I_L is the load current. Table 1 shows the system parameters of the proposed matrix converter based series active filter.

RESULTS AND DISCUSSION

In this research, three phase matrix converter based series active filter is used to compensate the voltage sag/swell. The source voltage is 440 Vrms, 60 Hz. Table 1 shows the proposed system main parameters. It includes source impedance parameters L and C values for passive branches used.The system has been simulated VSC based series active filter and the proposed matrix converter based series active filter separately. In simulation studies, the results are specified before and after applying the matrix converter based active filter. Also, the values for total harmonic distortion before compensation and after compensation using, existing series active filter and the proposed matrix converter based series filter are given. All the simulation is performed by the MATLAB simulink model in discrete form. The sample time of the discrete value is 3×10-4 sec. Figure 7 shows the total harmonic distortion of the VSC based converter. Figure 7a shows the voltage source converter's output voltage. Figure 7b shows that its total harmonic distortion. It clearly displayed the total harmonic distortion is >100 %.

Result for VSC based converter harmonic

Result for matrix converter harmonic: Figure 8 shows the matrix converter output voltage and its harmonics. The matrix converter produces <40% of harmonic as shown in Fig. 8a and its corresponding matrix converter voltage is shown in Fig. 8b, so, the matrix converter produces the less harmonic compared the voltage source converters.

Result for with conventional series active filter based compensation (voltage sag condition): Figure 9 shows the load voltage and its total harmonics distortion after the VSC based series active filter enabled. Figure 9a shows the supply voltage. The voltage is 440 v at 0.32 sec the voltage is decreases (voltage sag) due to additional load. So, the amplitude of voltage goes to decreases. Figure 9b shows the load voltage after the VSC based series active filter enabled. After VSC series active filter implementation the voltage sage is mitigated at 0.32 sec. Figure 9c shows the total harmonics of load voltage. VSC based converter's HD is 8%.

Result for with conventional series active filter based compensation (swell condition): Figure 10 shows the voltage swell mitigation using conventional VSC based series active filter. Figure 10a shows the supply voltage. It sinusoidal at 0.6 sec the voltage sag accures abd at 0.78 sec the voltage swell accrued. The magnitude of supply voltage is 440 volts. Figure 10b shows the load voltage after compensation. This wave form also sinusoidal and the voltage is sag and swell free. But it contains harmonics. Figure 10c shows the total harmonics distortion is 8%. the swell simulation time start 0.78-1.2 sec.

Result for matrix converter based series active filter based compensation (at sag condition): Figure 11 shows the matrix converter based shunt active filter to mitigate the voltage swell efficiently with low harmonic distortion compared to conventional active filter. Figure 11a shows the supply voltage and the wave form is sinusoidal. At 0.31 sec the voltage sag accrued Fig. 11b shows the wave form of load voltage after proposed compensation. The wave for also sinusoidal and the harmonic content is low. Figure 11c shows the total harmonic distortion level. The total harmonic distortion level is 3.5% only.

Result for matrix converter based series active filter based compensation(at swell condition): It is clear from Fig. 12b that the load voltage is effectively maintain constant when voltage swell accrued byusing the matrix converter based series active filter. Figure 12c shows that the proposed matrix converter based series active filter THD of the load voltage is only 3.5%.

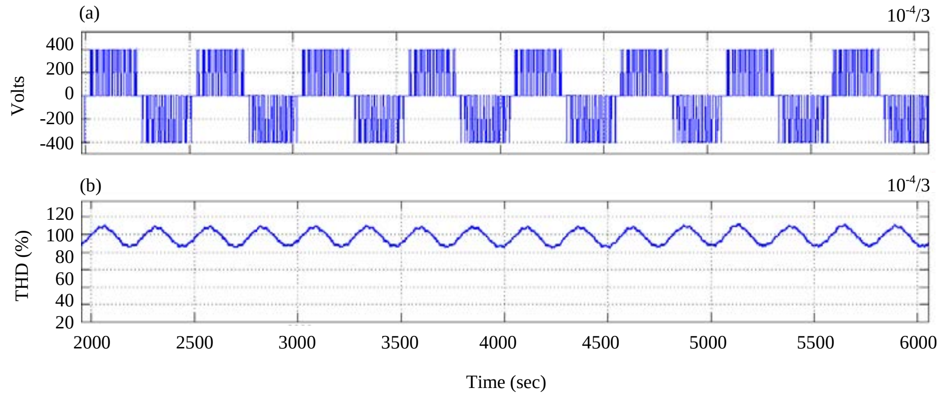

Fig. 7(a, b): Total harmonic distortion of VSC based converter (a) VSC converter output voltage and (b) Total harmonic distortion in %

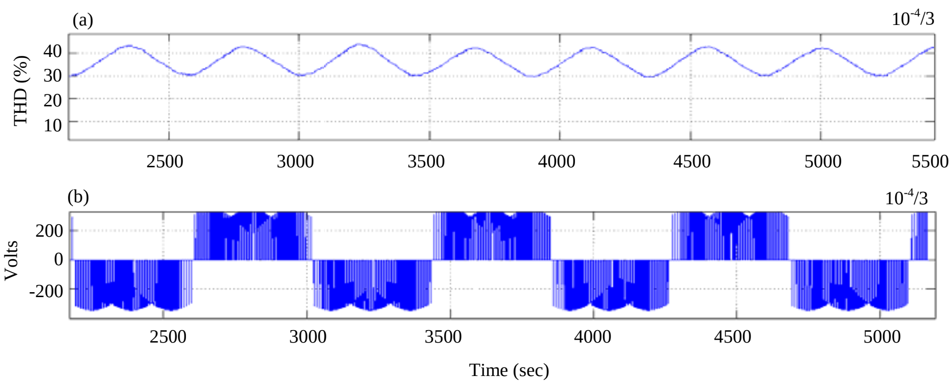

Fig. 8(a, b): Total harmonics distortion of matrix converter (a) Total harmonic distortion in % and (b) Mmatrix converter output voltage

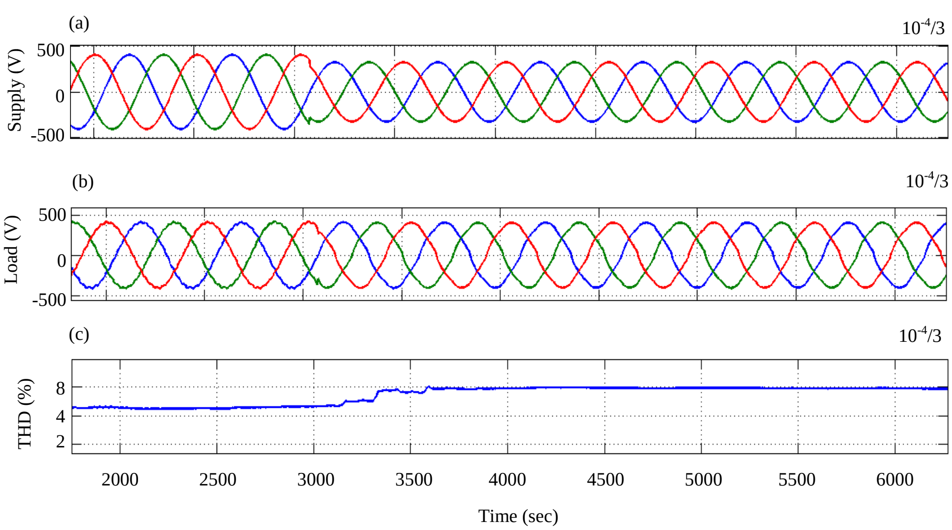

Fig. 9(a-c): (a) Supply voltage (b) Load voltage and (c) Total harmonics distortion of load voltage

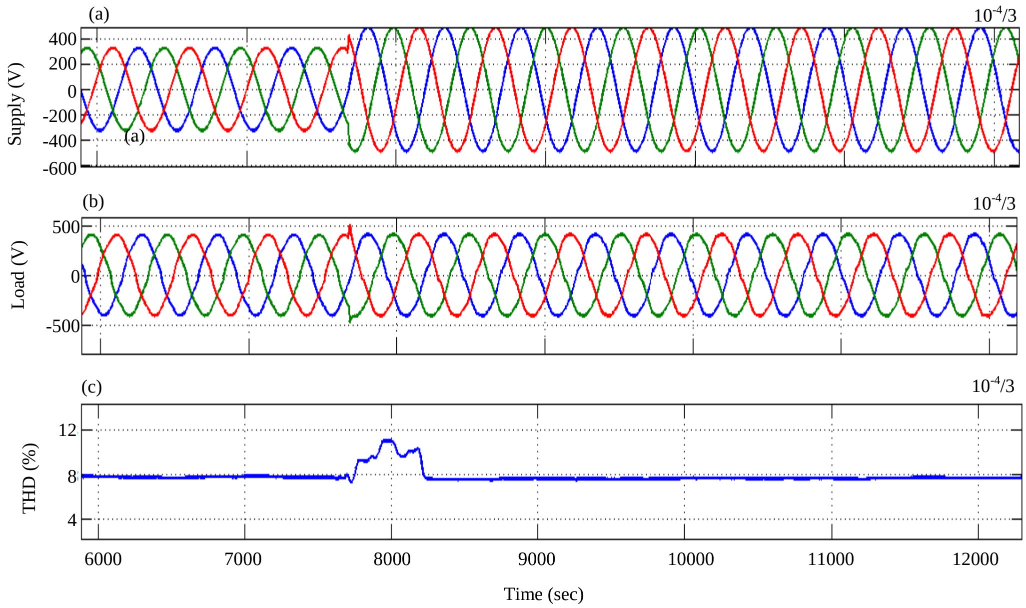

Fig. 10(a-c): (a) Supply voltage, (b) Load voltage and (c) Total harmonics distortion

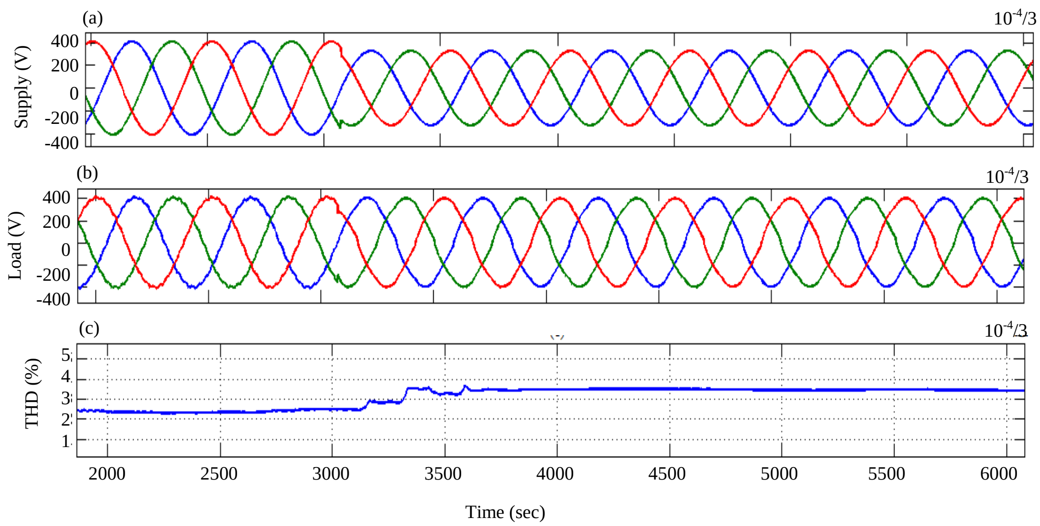

Fig. 11(a-c): Proposed matrix converter controlled series active filter based compensation

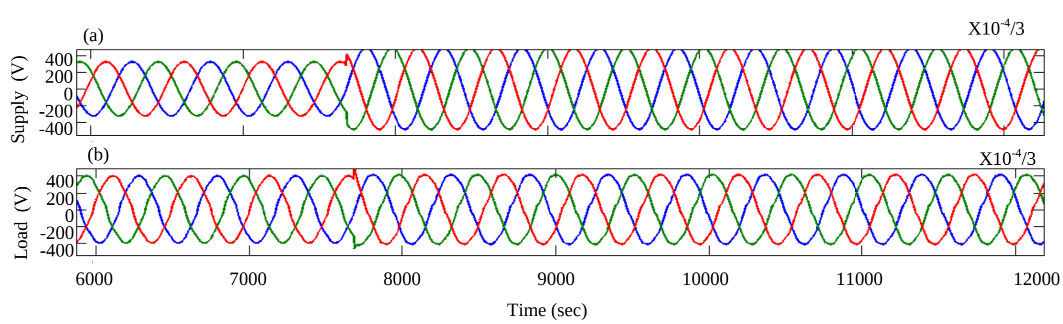

Fig. 12(a-c): Continue

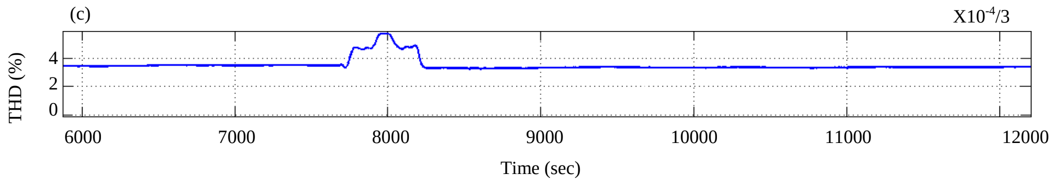

Fig. 12(a-c): (a) Supply voltage, (b) load voltage and (c) total harmonics distortion of supply voltage

CONCLUSION

In this study was investigated the use of matrix converter based series active filtering to mitigate the voltage sag/swell. This study analyzed the matrix converter and conventional voltage source converter based series active filter and found that matrix converter produces less harmonics compared to voltage source converter. The series active filter handles both balanced and unbalanced Situations without any difficulties and injects he appropriate voltage component to correct any abnormally in the supply voltage to keep the load voltage balanced and constant at the nominal value. In the case of voltage sag which is a condition of a temporary reduction in supply voltage, the matrix converter based series active filter injects an equal positive voltage component in all three phases which are in phase with the supply voltage to correct it. On the other hand, for a voltage swell case which is a condition of a temporary increase in supply voltage, the matrix converter based series active filter injects an equal negative voltage in all three phases which are anti-phase with the supply voltage. Based on the simulation results the matrix converter based series active filter mitigates the voltage 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, performance of a matrix converter based series active filter for mitigating voltage sags/swells is demonstrated with the help of MATLAB.

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