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Matrix Converter Disturbances Compensation Using Shunt Active and Series Active Filters

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Abstract: This study has proposed a series active filter and shunt active filter to minimize the power quality impact present in matrix converter's instead of passive filter. A matrix converter produces significant harmonics and nonstandard frequency components into load. The proposed approach compensates the sag and swells problems efficiently accrued in matrix converter. The proposed approach has been tested and validated on the matrix converter using Matlab/Simulink software. Simulated and experimental results confirm that the active power filters can maintain high performance for matrix converter.

Key words: Matrix converter, series active filter, shunt active filter, power quality, voltage Space Vector Modulation (SVM), Total Harmonic Distortion (THD)

INTRODUCTION

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 well. There are many possible ways in which electric power can be a poor quality and many more causes or effects of such poor quality power (Kusko and Thompson, 2007).

Ideally, voltage is fed by a utility as sinusoidal having a magnitude and frequency given by international standards or system specifications with an impedance of zero ohms at all frequencies. Power quality disturbance is produced by inverters and converters (Yacamini and Oliveira, 1978).

The matrix converter is the 3 phase to 3 phase configuration and is just one of the possible direct AC-AC converter topologies (Casadei *et al*., 1997). 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. Inspite of the advantages the matrix converter has also some disadvantages. It has a maximum input output voltage transfer ratio limited to ≅87% for

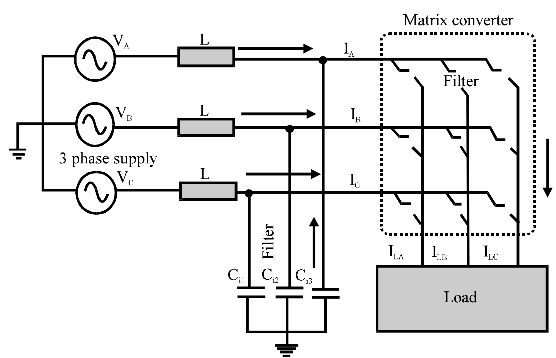

Fig. 1: The general architecture of matrix

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, variously arranged have to be used for each bi-directional switch. The matrix converter consists of 9 bi-directional switches (Sunter and Aydogmus, 2008) that allow any output phase to be connected to any input phase.

Figure 1 shows the block diagram of a matrix converter feeding a standalone load. The three phases AC line voltage is applied to matrix converter after appropriate filtering. The matrix converter converts the fixed voltage to voltage with variable amplitude and frequency. The output can be supplied to any load that requires variable voltage with variable frequencies such as to drive an induction motor and the permanent magnet synchronous

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motor. Matrix converter has several advantages but it may also produces higher order harmonics (Wheeler *et al.*, 1993).

MATERIALS AND METHODS

General structure and compensation technique of matrix converter

General structure: A matrix converter is a variable amplitude and frequency power supply that converts the three phase line voltage directly, i.e., without intermediate DC-voltage or current link into three phase output voltage. It is very simple in structure and has powerful controllability. The converter consists of nine modular H-bridge capacitor-clamped switch cells connected from each input phase to each output phase. The terminal ac voltages of the converter are synthesized from the modulation techniques of Space Vector Modulation (SVM). The space vector modulation approach is a well-known technique for control of three-phase converters (Karpagam *et al.*, 2010).

The switching pulses for the power devices in each bridge are obtained from the modulation techniques. The converter is capable of both increasing and decreasing the voltage magnitude and frequency while operating with arbitrary power factors. Multilevel switching can be used to synthesize the voltage waveforms at both the input and output of the converter.

The switch cells can be connected in series in each branch of the matrix to increase the voltage rating of the converter. The converter is capable of increasing the number of levels of operation by connecting >1 switch cell in series.

Passive filter compensation: The principal method of reducing the harmonics generated by static converters is provided by the input filter using reactive storage elements as shown in Fig 2.

The problem of the input filter design for a matrix converter has been addressed in literature (Zargari *et al.*, 1993; Huber and Borojevic, 1991) and looking at the literature different.

So, many configurations are proposed for the matrix converter input filter (Heldwein and Kolar, 2009; Biela *et al.*, 2009). Such differences are a consequence of different design criteria or at least differently weighted different switching frequencies and different modulation strategies.

In order to meet the required attenuation requirement, there is a overall increases on filter size. Moreover, the input filter output impedance related to the total filter capacitor value is more difficult to control and leads

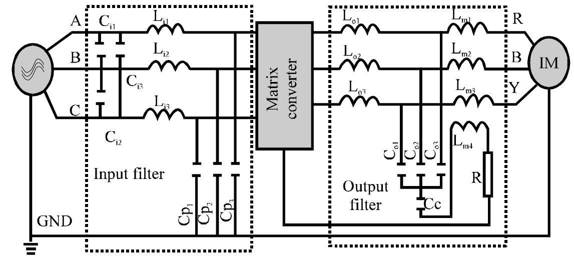

Fig. 2: Existing technique of power quality improvement for the matrix converter

converter instability. As far as the matrix converter is concerned, a high displacement angle of the input line current due to the input filter capacitance component might be compensated by the matrix converter setting as reference for the input current a lagging displacement angle.

But in this way, the maximum voltage transfer ratio for the converter would be significantly reduced. Therefore even for the matrix converter, the upper limit of the input filter capacitance is set by the minimum acceptable AC main power factor.

Similarly, the control of the impedance interaction between the input filter and the voltage converter is necessary. In general, the filters output impedance should be as low when compared to the converter input impedance.

The filter output impedance can be reduced by the filter capacitor size may increase practically the impedance interaction constraint determines the lower constraint on the filter capacitor value. In addition to the above, proper filter pole damping is extremely important for achieving low filter output impedance for all frequencies and thus, overall system stability may be improved. In general, an optimized design of the matrix converter input filter is a quite difficult task since, it relies on a system level approach and in the light of the new coming harmonic and EMI reduction standards it can be considered as an outstanding issue.

The proposed compensation scheme for matrix converter: The proposed technique includes two parts, the first part compensates matrix converter's input power quality problems and the second part compensates matrix converter's output power quality problems. The matrix converter is considered as two types of load, i.e., current-source type of harmonic sources, voltage-source type of harmonic sources. The enhanced control system is proposed to further eliminate harmonics with higher accuracy. Figure 3 shows the proposed compensation for

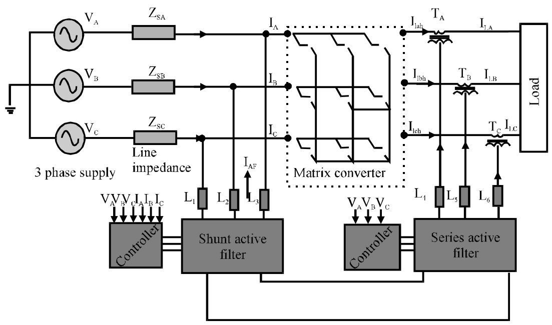

Fig. 3: The proposed configuration for matrix converter

matrix converter with a shunt active filter, source and load when the filter is used to compensate the current harmonics produced by the matrix converter. In Fig. 3, $Z_{sA\text{-}sC}$ is impedances of the source and shunt passive filter, respectively. $I_{lh(a\text{-}c)}$, $V_{Lh(a\text{-}c)}$ and $V_{sh(a\text{-}c)}$ are the current harmonic of the load and voltage harmonic of the load and source harmonics, respectively. I_{AF} is the current of the shunt active filter.

The control system design of the shunt active power filter for matrix converter cancel the harmonic in the supply current is shown in Fig. 3. Shunt active filters are used to compensate current harmonics of nonlinear loads to perform reactive power compensation and to balance imbalance currents. A shunt active filter senses the load current and injects a current into the system to compensate current harmonics or reactive load. In this study, a shunt filter was used to compensate the current harmonics of matrix converter here the shunt active filter acts as a current source. The sum of its current and load current is the total current that flows through the source. Therefore, controlling the output current of the active filter can control the source current.

A series active filter is used to eliminate the voltage harmonics produced by the matrix converter. When the load is sensitive and critical, a series converter is used to regulate line voltage for the load. It cancels out any line voltage distortions such as voltage harmonics, sag, swell and voltage unbalance. It is capable of eliminating any voltage harmonics with a frequency within the bandwidth of the control scheme. For voltage sag (swell) compensation, active power must be delivered to (received from) the system.

This active power is supplied (received) by the DC capacitor and creates a voltage ripple on the DC bus voltage. The second function of the series converter of UPQC which is mostly considered in very high-power applications is defined to protect the power system against the voltage distortions originating from the load. Some nonlinear loads which usually have a capacitor bank after a bridge rectifier appear to be voltage harmonic generators. The voltage harmonics at the Point of Common Coupling (PCC) affect the other sensitive loads connected to this point.

Current-source type of harmonic sources in matrix converter: Power electronics converters are a common and typical source of harmonic currents. The distortion of the current waveform, i.e., the generation of harmonics, results from the switching operation. Because the harmonic current contents and characteristic are less dependent upon the AC side, this type of harmonic source behaves like a current source. Therefore, they are called current-source type of harmonic source (or harmonic current source) and represented as a current source. A shunt active filter is to be placed in parallel with a load (matrix converter) to detect the harmonic current of the load and to inject a harmonic current with the same amplitude of that of the load into the AC system. In order not to lose generality, the harmonic current source is represented as Norton's equivalent circuit. A pure current-source type of harmonic source is a special case of the Norton's equivalent with $Z_L \to \infty$.

Figure 4 shows the basic principle of a shunt active filter compensating for a harmonic current source where the harmonic source is represented as Norton's equivalent, Z_s is the source (line) impedance I_L is the equivalent harmonic current source Z_L is the 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. In the following analysis, all equations are represented in per unit. From Fig. 4, the following equations are obtained:

$$I_c = GI_L \tag{1}$$

$$I_s = \frac{Z_L}{Z_s + \frac{Z_L}{1-G}}.I_{Lo} + \frac{V_s}{Z_s + \frac{Z_L}{1-G}} \tag{2}$$

$$I_L = \frac{\frac{Z_L}{1-G}}{Z_s + \frac{Z_L}{1-G}}.I_{Lo} + \frac{1}{1-G}.\frac{V_s}{Z_s + \frac{Z_L}{1-G}} \tag{3}$$

Focusing on harmonic:

$$\left|\frac{Z_L}{1-G}\right|_h > |Z_s|_h \tag{4}$$

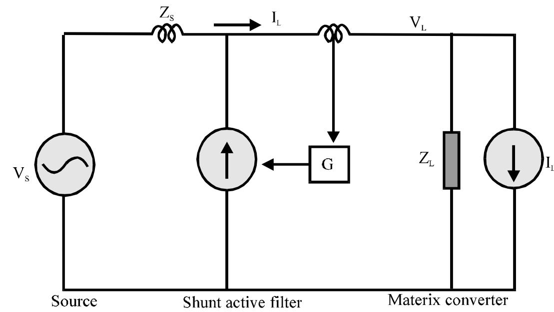

Fig. 4: Principle of shunt active filter for matrix converter

$$I_C = I_{Lh} \tag{5}$$

$$I_{Lh} = I_{Loh} + \frac{V_{sh}}{Z_L} \tag{6}$$

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 most popular type of shunt active filter control system is proposed in the elimination of harmonics in active filter for matrix converter. Shunt active filters can be single or three phases, voltage source or current source.

Active filter compensates the harmonic current of a matrix converter which produces harmonic current. The shunt active power filter control algorithm is shown in Fig. 5. Instantaneous reactive power (p-q) theory is used to control of shunt active power filter in real time. In this theory, instantaneous 3 phase voltages and current are transformed to α-β-0 from a-c coordinates as shown in Eq. 7 and 8:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & \frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & \frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{8}$$

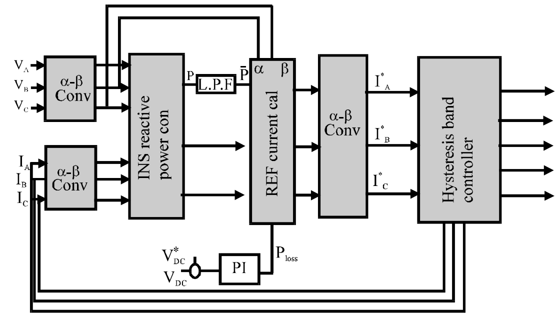

Fig. 5: Control system of shunt active filter for matrix converter

Load side instantaneous real and imaginary power components are calculated by using source currents and phase-neutral voltages as shown in Eq. 9:

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\alpha & v_\beta \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{9}$$

Instantaneous real and imaginary powers include both AC and DC components as shown in Eq. 9. DC components of p and q are obtained from positive sequence components (p and q) of load current. AC components $(\tilde{p} \text{ and } \tilde{q})$ of p and q include harmonic and negative sequence components of load currents. In order to reduce neutral current p_0 was calculated by using DC and AC components of imaginary power and the AC component of real power as shown in Eq. 10 if both harmonic and reactive power compensation is required:

$$p_0 = v_0 . i_0 ; p = \bar{p} + \tilde{p} ; q = \bar{q} + \tilde{q} \tag{10}$$

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} & p_0 & \tilde{p}_{loss} \\ & 0 & \end{bmatrix} \tag{11}$$

$i^*_{s\alpha}$ and $i^*_{s\beta}$ are reference currents of shunt active power filter in α-β-0 coordinates. To compensate neutral current $i^*\ s_0 = -i_0$. These currents are transformed to 3 phase system as shown in Eq. 12:

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{s0} \\ i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} \tag{12}$$

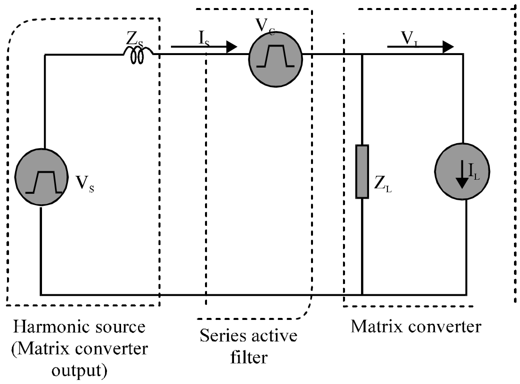

Fig. 6: Principle of series active filter for matrix converter

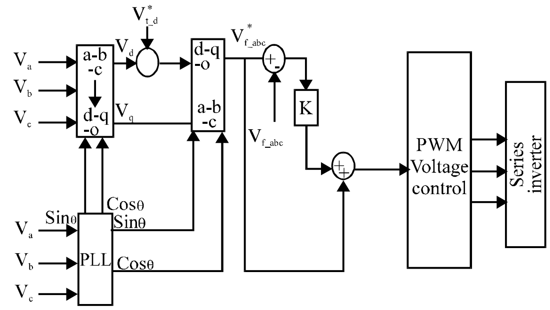

Fig. 7: Control system of series active filter for matrix converter

the reference currents in 3 phase system ($i^*_{sa\text{-}sc}$ are calculated in order to compensate neutral, harmonic and reactive currents in the load. The switching signals used in shunt active power filter control algorithm are generated by comparing reference currents and actual line currents using hysteresis band current control algorithm.

Voltage-source type of harmonic sources in matrix converter: Another type of common harmonic sources is matrix converter output which produces harmonic voltage and current waveforms. Although, the current is highly distorted, its harmonic amplitude is greatly affected by the impedance of the AC side. Therefore, the matrix converter output behaves like a voltage source harmonic. The harmonic voltage source is represented as Thevenin's equivalent circuit as shown in Fig. 6. A pure voltage-source type of harmonic source is a special case of Thevenin's equivalent with $Z_L \rightarrow 0$. Figure 6 shows the basic principle of series active filter compensating for a harmonic voltage source. If the series active filter is controlled as:

$$V_c = KGI_s \tag{13}$$

the source current is:

$$I_s = \frac{v_s - v_L}{z_s + z_L + KG} \tag{14}$$

K>>1 purequirese operating condition for the series active filter to compensate for a harmonic source series active filters control system for voltage type harmonic source compensation is proposed in this matrix converter. Figure 7 shows the proposed compensation scheme for matrix converter. The series converter is capable of suppressing the voltage harmonics of the load. The matrix converter has some disadvantage at the input voltage distortions directly affect the output voltage.

The series converter deals with the input voltage distortions. It injects or receives active power for voltage sag or swell compensation. It also delivers a zero average instantaneous power for voltage harmonic cancelation. The voltage across the series converters:

$$V_f = V_{ref} - V_s + \sum V_h = V_s(1 - 1/k) + \Sigma V_h \tag{15}$$

In Eq. 15, $k = V_s/V_{ref}$ and V_h is the voltage harmonic of the source. All the voltages are instantaneous values. To indicate the effect of harmonics on the power rating of the converters, we define characteristic power instead of the apparent power. This term is defined as:

$$CS = I_{rms} V_{rms} \tag{16}$$

In Eq. 16, C_S is the characteristic power I_{rms} and V_{rms} are effective values of current and voltage including harmonics. The value of V_{rms} for the output of the series converter is:

$$V_{rms} = \left(v_1^2 + \sum {}_h^2\right)^{1/2} = V_s\left[(1 - 1/k)^2 + THD_v^2\right]^{1/2} \tag{17}$$

In Eq. 17 where, $V_1 = V_{ref}\_V_s$. Considering only active current through the line, the characteristic power of each phase of the series converter is:

$$CS_{series} = v_s I_1 \cos\theta \sqrt{\left(\frac{1}{k} - 1\right)^2 + THD_v^2} \tag{18}$$

Where, THD_v is the Total Harmonic Distortion (THD) of the source voltage and defined as:

$$THD_v = \sqrt{\sum v_h^2} / V_S$$

$\cos\theta$ is the power factor of the load and I_L is the fundamental component of the load current. A series active filter senses the load voltage and injects the compensated voltages into the system to compensate voltage harmonics. In this study, a series active filter used to compensate the voltage harmonics of matrix converter. Matrix converter is sensitive to the disturbances of the input voltage. So, the series active filter also compensates the imbalance voltage present in the output voltage is compensated.

Figure 6 shows the series active filter controlling block diagram using synchronous reference frame theory. In this method, the desired value of load phase voltages in d axis and q axis is compared with the load voltage and the result is considered as the reference signal. The supply voltage detected (V_{abc}) is detected and transformed into the synchronous d_{qo} reference frame using:

$$v_{t\_dqo} = T_{abc}^{dqo}\, v_{t\_abc} \tag{19}$$

The compensating reference voltage in the synchronous d_{qo} reference frame is defined as:

$$v_{sf\_dqo}^{ref} = v_{t\_dqo} - v_{i\_dqo}^{exp} \tag{20}$$

The compensating reference voltage in Eq. 20 is then transformed back into the (a_c) reference frame. Resulted reference voltage (v^*_{fa}, vi^*_{fb}, v^*_{fc}) and the output current of shunt inverter ($v_{fa\text{-}fc}$) are fed to the hysteresis band controller. The required controlling pulses are generated and the required compensation voltage is generated.

RESULTS AND DISCUSSION

In this study, the simulation results of the proposed active filters are discussed using the Matlab/Simulink software computer simulation was carried out for the resistive load. In theprevious study (Fig. 8), the simulation of the matrix converter operated with passive input capacitor is shown. Here, the input current waveform is non sinusoidal. The harmonics are not effectively eliminated by the fixed capacitor bank and the input current wave farm obtained is non sinusoidal. Consider the simulation time 0.025-0.08 sec, the current waveform is non sinusoidal and it contain harmonics during the specified time.

Figure 9 shows the proposed shunt active power filter scheme that compensates the line current wave shape effectively when compared to the existing system effectively as shown in the simulation results. The total simulation time is 0.02-0.085 sec. In this simulation the current waveform is almost sinusoidal. Figure 10 shows the supply current harmonics are 60.05%. After the proposed shunt active filter is implemented to the supply current harmonics is reduced 30% as shown in Fig. 11. So, the power quality is maintained by using the shunt active filter. The proposed control strategy the system was

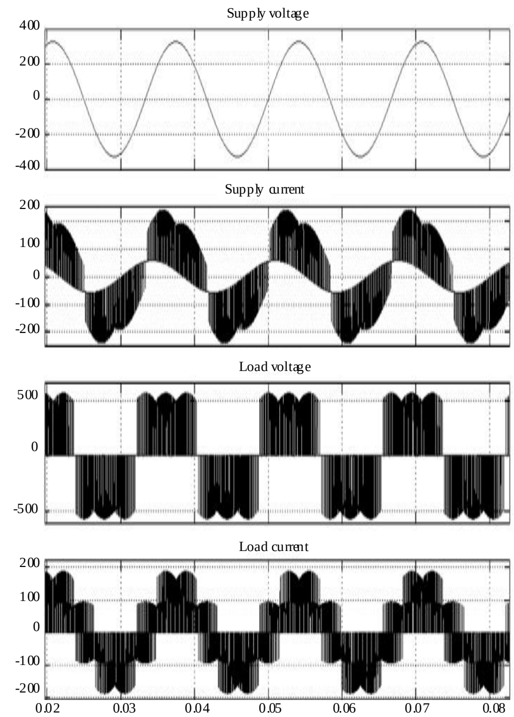

Fig. 8: System voltage (V_s), source current (i_s) load voltage (V_L) and load current (I_L) with passive filter

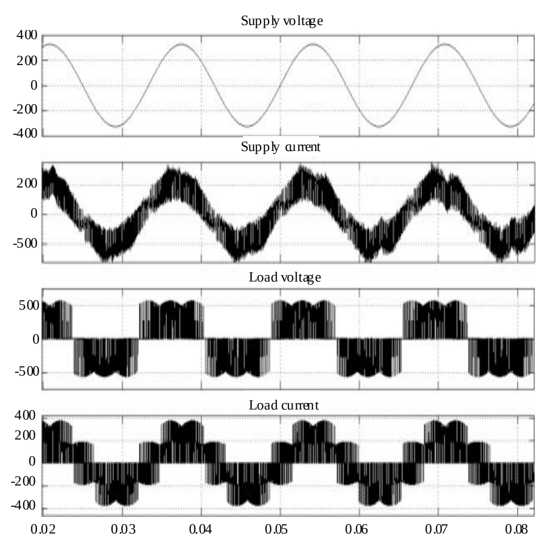

Fig. 9: System voltage (V_s), source current (i_s) load voltage (V_L) and load current (I_L) when the shunt active filter is turned on

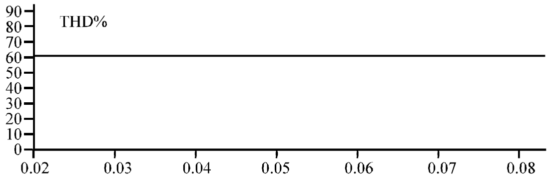

Fig. 10: Total harmonic distortion with capacitor

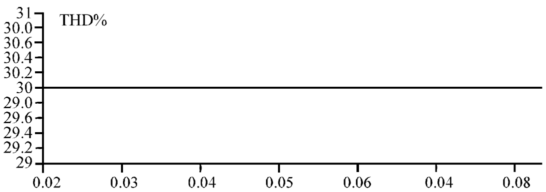

Fig. 11: Total harmonic distortion proposed system

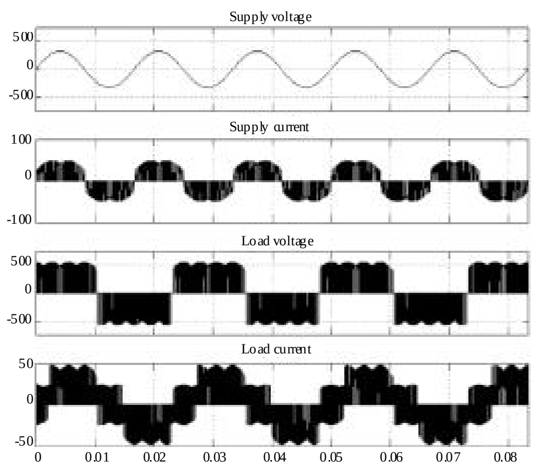

Fig. 12: Supply voltage (V_s), Source current (i_s) Load voltage (V_L) and Load current (I_L) without filter

connected to the 60 Hz utility and transferred power to a resistive load. The input line-to-line voltages are sensed. In the previous simulation studies, the result are specified before and after Series Active Filter (SAPF) system is operated. In Fig. 12, the simulations of the matrix converter operates without input capacitor is shown. Here, the line voltage is 440 v. The supply current is 200 amperes. In this simulation, the input current wave shape is non-sinusoidal and it contains harmonics. The simulation time start from 0.02-0.085. Consider the simulation time 0.025-0.045 sec is the one cycle of the current wave form. Here, the wave shape of this current is non-sinusoidal and it contain harmonics.

The simulation output is taken in between the points of matrix converter output and series active filter input points shown in Fig. 13. The input current waveform is also non sinusoidal. Figure 14 shows the proposed series

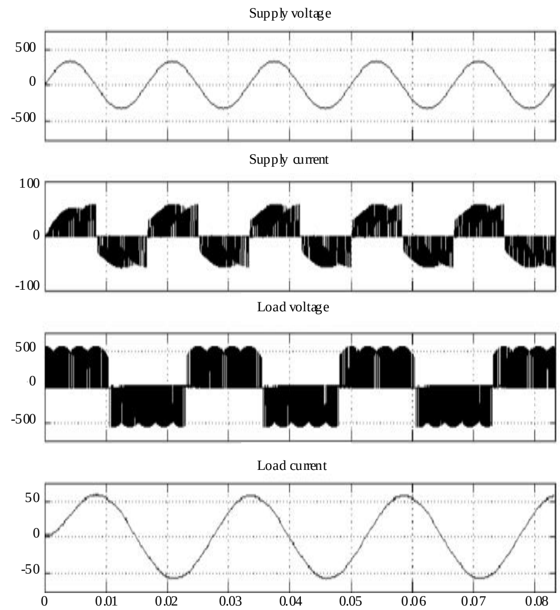

Fig 13: Supply voltage (V_s), source current (i_s) matrix output voltage (V_L) and load current (I_L) with series filter

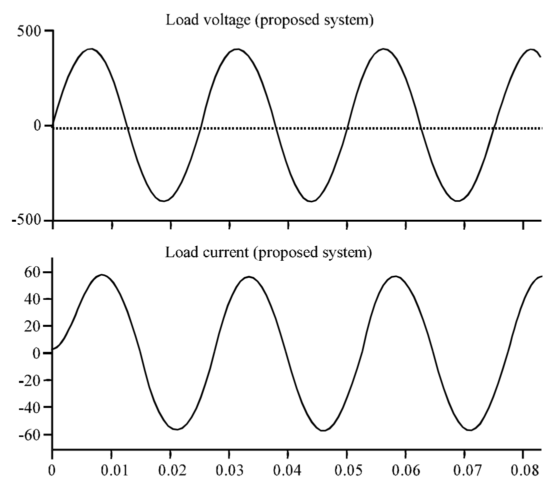

Fig. 14: load voltage (VL)and load current(IL)when the series active filter is turned on

active power filter scheme that compensates the load voltage wave shape effectively when compared to the existing system effectively as shown in the simulation results. The total simulation time is 0.02-0.085 sec. Figure 15 shows the matrix converter output harmonics are 60%. After the proposed series active filter is implemented the matrix converter output voltage harmonics reduced at 3%. Figure 16 shows the input harmonics are 55% after shunt active filter implemented harmonies reduced 3%. Figure 17-18 shows when the matrix converter is affected

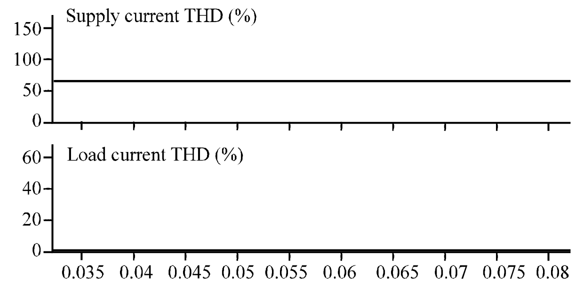

Fig. 15: Total harmonic distortion in matrix converter output voltage without and with compensation

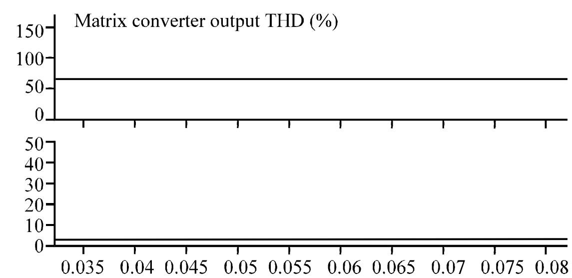

Fig. 16: Total harmonic distortion in matrix converter output current without and with compensation

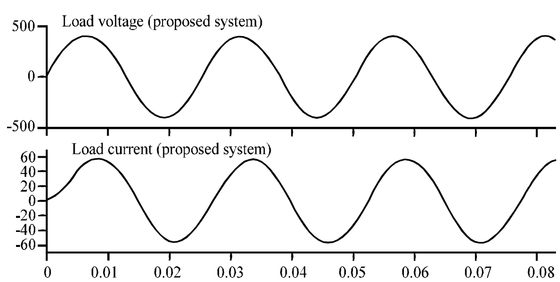

Fig. 17: Voltage swell accord in matrix converter output current, voltage with compensation

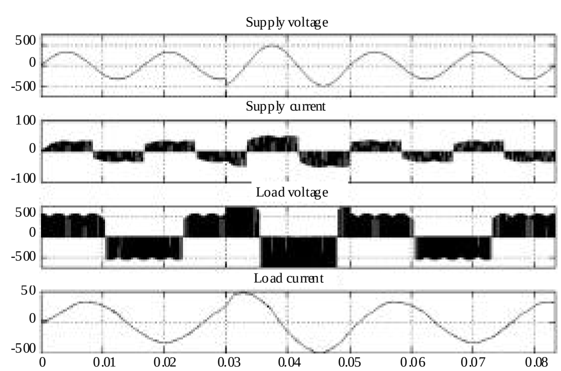

Fig. 18: Voltage swell accord in matrix converter output current, voltage without compensation

by swell. The voltage swell present at 0.03-0.05 sec. After the proposed compensation, series active filter eliminate the swell problem and maintain the power quality in the matrix converter output as shown in the Fig. 17-18.

CONCLUSION

In this study, series active and shunt active filter method compensation is implemented in the matrix converter output for power quality improvement. When active power filter system is operated in matrix converter, the supply harmonics are removed effectively compared to the fixed capacitors in simulation studies, the result are specified before and after active power filter system is operated. In the proposed new strategy which can eliminate 80% harmonic components. When active power filter system is operated in matrix converter, the load harmonics removed effectively. The modification of this proposed methodology has considerably good simulation results as compared the conventional harmonic control method. The proposed method is validated and the simulation results are obtained through Matlab/ Simulink software.

REFERENCES

Biela, J., A. Wirthmueller, R. Waespe, M.L. Heldwein, K. Raggl and J.W. Kolar, 2009. Passive and active hybrid integrated EMI filters. IEEE Trans. Power Electr., 24: 1340-1349.

Casadei, D., G. Serra, A. Tani and P. Nielsen, 1997. Theoretical and experimental analysis of SVM controlled matrix converters under unbalanced supply conditions. Electromotion J., 4: 28-37.

Heldwein, M.L. and J.W. Kolar, 2009. Impact of EMC filters on the power density of modern three-phase PWM converters. IEEE Trans. Power Electr., 24: 1527-1588.

Huber, L. and D. Borojevic, 1991. Input filter design of forced commutated cycloconverters. Proceedings of the 6th Mediterranean Electrotechnical Technical Conference, May 22-24, Ljubljana, Slovenia, pp: 1356-1359.

Karpagam, J., A.N. Kumar and V.K. Chinnaiyan, 2010. Comparison of modulation techniques for matrix converter technology. IACSIT Int. J. Eng. Technol., 2: 189-195.

Kusko, A. and M.T. Thompson, 2007. Power Quality in Electrical System. Chapter 1, McGraw Hill, New York, pp: 225.

Sunter, S. and O. Aydogmus, 2008. Implementation of a single-phase matrix converter induction motor drive. Electr. Eng., 90: 425-433.

Wheeler, P.W., H. Zhang and D.A. Grant, 1993. A theoretical and practical investigation of switching frequency harmonics in a matrix converter. Proceedings of the Universities Power Electronics Conference, September 1993, Stafforf, UK., pp: 502-505.

Yacamini, R. and J.C. Oliveira, 1978. Harmonics produced by direct current converter transformers. Proc. Inst. Elect. Eng., 25: 873-878.

Zargari, N.R., G. Joos and P.D. Ziogas, 1993. Input filter design for pwm current-source rectifiers. Proceedings of the Applied Power Electronics Conference and Exposition, March 7-11, San Diego, CA. USA., pp: 824-830.