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Power Quality Improvement using Series Active Filter for Matrix Converter Controlled Load

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Abstract: This study proposes a new methodology to minimize the power quality impact present in matrix converter's output using a series active filter instead of passive filter. A matrix converter produces significant harmonics and nonstandard frequency components into load. The proposed approach eliminates the total load voltage harmonic distortions efficiently. The smaller THD, the harmonic pollution in the power system will be reduced and the power quality will be increased. The proposed approach 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, series active filter, power quality, voltage harmonics, nominal voltage, resistance

INTRODUCTION

The matrix converter is the three phases to three phase configuration is one of the possible direct AC-AC converter topologies (Bansal *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 and 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 ≅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, variously arranged have to be used for each bi-directional switch. But it will particularly produce higher order harmonics (Sunter and Aydogmus, 2008). The matrix converter consists of 9 bi-directional switches that allow any output phase to be connected to any input phase. The general architecture of matrix converter is shown in Fig. 1. Nine bi-directional switches in the matrix converter can theoretically assume 512 (2^9) different switching states combinations. However, not all of them can be usefully employed. Regardless to the control method used, the choice of the matrix converter switching states combinations (from now on simply matrix converter configurations) to be used must 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 beshort-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 three phase to three phase matrix converter, only 27 switching combinations are permitted.

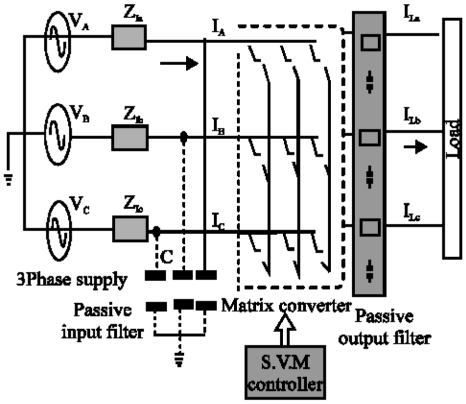

Fig. 1: General architecture of matrix converter

MATERIALS AND METHODS

Power quality: 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

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Corresponding Author: P. Jeno Paul, Electrical and Electronics Engineering, Noorul Islam University, Tamilnadu, India operate at well. There are many possible ways in which electric power can be poor quality. Ideally, voltage is fed by a utility as sinusoidal having a magnitude and frequency given by national, 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 andload.

When the RMS voltage goes beyond the nominal voltage by 10-80% for 0.5 cycles to 1 min, the phenomena is called a swell (Boonchiam and Mithulananthan, 2006). Sag is the opposite action. The RMS voltage goes below the rated voltage by 10-90% for 0.5 cycles to 1 min (Kusko and Marc, 2007). Variations in the wave shape usually known as harmonics (Collins and Jiang, 2009). Overvoltage occurs when the nominal voltage increases above 110% for >1 min (Fuchs and Mosoum, 2008). Under voltage occur when the nominal voltage fall or <90% for >1 min (Heydt, 1995).

Harmonics: Harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency (Emadi *et al*., 2005). Therefore, harmonic is the presence of voltage/current with the frequency of a multiple of fundamental voltage/current in the voltage/current of the system.

For example, a waveform with 60 Hz fundamental frequency and 5th (300 Hz), 7th (420 Hz), 11th (660 Hz) and 13th (780 Hz) harmonics. For the metering and comparison of harmonic contents of waveforms, a parameter defined as a Total Harmonic Distortion (THD), it is defined for both current and voltage as given in Eq. 1and 2:

$$\text{For voltage}: \text{THDv} = 100\sqrt{\frac{v_h^2}{v_1}} \tag{1}$$

$$\text{For current}: \text{THDi} = 100\sqrt{\frac{I_h^2}{I_1}} \tag{2}$$

In Eq. 1 and 2, I_h and v_h are current and voltage harmonics, respectively. There are many nonlinear loads drawing no sinusoidal currents from electrical power systems. These no sinusoidal currents pass through different impedances in the power systems and produce voltage harmonics. These voltage harmonics propagate in power systems and affect all of the power system components. The important harmonic source is AC/DC converters/inverters. Many low-power single-phase converters/inverters and high-power three phase converters/inverters are being used in electrical power systems. If the number of converter/inverter pulses is p then the order of harmonic current in AC side will be np_1 (n_1, 2, 3…).

Effects of harmonics: Except devices such as ovens and furnaces which produce heat, most of theother electrical loads are sensitive to harmonics. In fact, harmonics may lead to their improper operation. Passing harmonic currents through the transmission lines cause interference with the communication circuits near the transmission lines and may cause a malfunction in these circuits. On the other hand, harmonic 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 has higher sensitivity to harmonics and may not work properly in the presence of harmonics. Next issue is the loss in the power transmission lines. It can be expressed as:

$$\text{PLoss} = \text{RI}^2 \tag{3}$$

Where is the AC resistance of the transmission line and I is the RMS value of the line current. If the current includes harmonics then:

$$I_2 = I_1^2 + \sum I_H^2 \tag{4}$$

and then;

$$\text{PLoss} - h = R\sum I_H^2 \tag{5}$$

Although, the harmonic currents cannot apply active power to the loads, they cause higher losses in the transmission lines. Harmonics also cause higher losses in power transformers which are proportional to the square of the harmonic amplitude. Excessive losses and torque fluctuation also appears in electric motors in the presence of harmonics because only the fundamental component yields average torque in motors and harmonics yield core losses and torque fluctuation (Sunter and Altun, 2005).

Another problem is the presence of current harmonics in electrical power a system that increases neutral currents. In this case, the most important part of the neutral current is the third harmonic. Higher neutral currents in four-wire, 3 phase systems in addition to the increasing size of the neutral wire can cause overloaded power feeders, overloaded transformers, voltage distortion and common mode noise.

Another important problem caused by harmonics is resonance in power circuits. Current and voltage harmonics which are produced by nonlinear loads when passing through the power system or other load may cause a resonance problem.

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 beengiven in some researches (Heydt, 1995; Emadi *et al.*, 2005; De La Rosa, 2006) and looking at the literature different. So, many configurations are proposed for the matrix converter input filter (Sunter and Altun, 2005). 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 increase on filter size. Moreover, the input filter output impedance, related to the total filter capacitor value is more difficult to control and leads 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, 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.

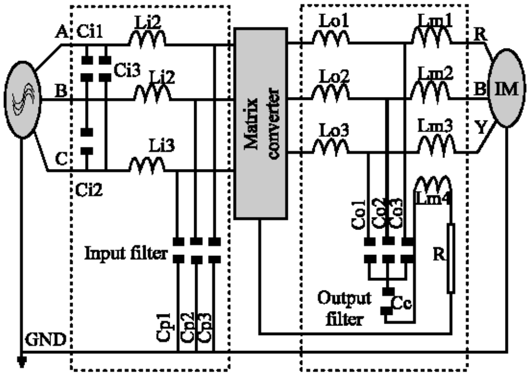

Fig. 2: Existing technique of power quality improvement for the matrix converter

The proposed compensation scheme for matrix converter: The most popular type of active filters is the series active filter. Series active filters can be single-phase or 3 phase, voltage source or current source converter. Figure 3 shows the proposed compensation scheme for matrix converter.

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.

The series converter is capable of suppressing the voltage harmonics of the load. The main disadvantage of matrix converter is if 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

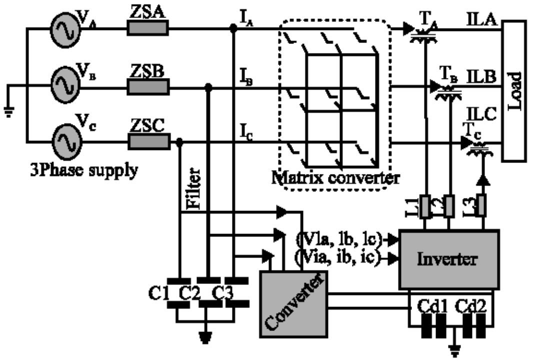

Fig. 3: Proposed compensation for matrix converter

delivers a zero average instantaneous power for voltage harmonic cancelation. The voltage across the series converters:

$$V_{ref} - V_s + \sum V_h = V_s\left(1 - \frac{1}{k} + \sum V_h\right) \qquad (6)$$

In Eq. 6, $k = V_s/V_{ref}$ 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:

$$CS = I_{rms}Vr_{ms} \qquad (7)$$

In Eq. 7, CS is the characteristic power and Irms and Vrms are effective values of current and voltage including harmonics. The value of V_{rms} for the output of the series converter is (Fig. 4):

$$V_{rms} = \left(v_i^2 + \sum_h^2\right)^{1/2} = V_s\left[\left(1 - \frac{1}{(k)^2} + THD_v^2\right)\right]^{1/2}$$

In Eq. 8 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:

$$CSSeries = v_s l_i \cos\theta\sqrt{\left(\left(\frac{1}{k}\right) - [1)\right]^2 + THD_v^2} \qquad (8)$$

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

$$THDv = \frac{\sqrt{\sum v_h^2}}{V_s}$$

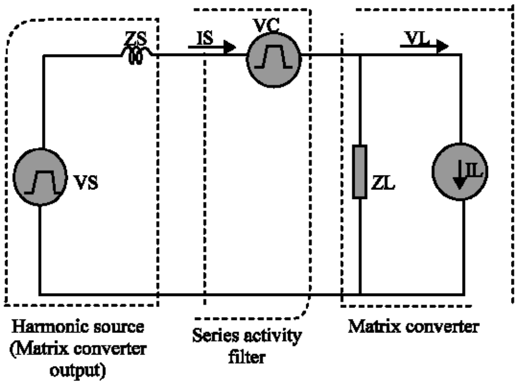

Fig. 4: Principal of series active filter for matrix converter

Cosθ is the power factor of the load and I1 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.

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 representedas. The venin's equivalent circuit as shown in Fig. 4. A pure voltage source type of harmonic source is a special case of Thevenin's equivalent with $Z_L{\to}0$. Figure 4 shows the basic principle of series active filter compensating for a harmonic voltage source. If the series active filter is controlled as:

$$V_c = KGI_s \qquad (9)$$

The source current is :

$$I_s = \frac{V_s - V_L}{Z_s + Z_L + KG} \qquad (10)$$

K>>1 pure quirese operating condition for the series active filter to compensate for a harmonic source 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 5 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 andq axis is compared with the

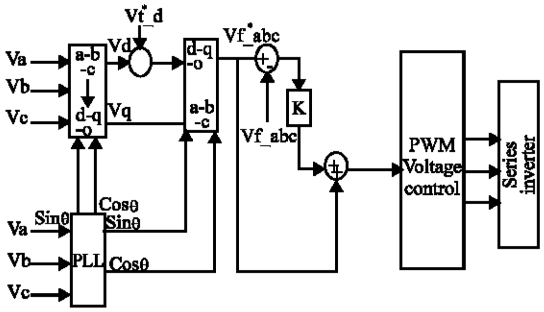

Fig. 5: Control system design of series active power filter for matrix converter

load voltage and the result is considered as the reference signal. The supply voltage detected (V_{abc}) is detected and transformed into the synchronous dqo reference frame using:

$$v_{t_{dqo}} = T_{abc}^{dqo} v_{t_{abc}} \quad (11)$$

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

$$V_{sf_{dqo}}^{ref} = v_{t_{dqo}} - v_{i_{dqo}}^{exp} \quad (12)$$

The compensating reference voltage in Eq. 12 is then transformed back into the (a_{b_c}) reference frame. Resulted reference voltage ($v_{fa}^*, vi_{fb}^*, v_{fc}^*$) and the output current of shunt inverter (v_{fa}, v_{fb}, v_{fc}) are fed to the hysteresis band controller. The required controlling pulses are generated and the required compensation voltage is generated.

RESULTS AND DISCUSSION

The simulation is carried out on a Matlab/Simulink software and the use of the shunt active filter for matrix converter is evaluated The simulated SAPF system parameters are given in Table 1. In the simulation studies, the result are specified before and after serried active filter (SAPF) system is operated. In Fig. 6, 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 contains harmonics.

In the Fig. 7, the simulation output is taken in between the points of matrix converter output and series active filter input points is shown. The series active filter value is mentioned in the Table 1. The input current waveform is also non sinusoidal. Figure 8 shows the proposed series 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. In this simulation, the current waveform is almost sinusoidal. Here, load frequency is 60 Hz.

Table 1: SAPF experimental and simulation parameters

Analysis	Parameters	Values
Source	Voltage (V_{Sabc})	440 V_{rms}
	Frequency (F)	60 Hz
Load	3 phase load resistance (R_L)	2Ω
DC link	Voltage (V_{dc})	700 V
	Capacitor ($C_{1,c2}$)	2200 μF
Series active power filter	Ac line inductance (L_{Cabc})	0.5 mH
	Filter resistance (R_{Cabc})	2 Ω
	Filter capacitor (C_{Cabc})	100 μF
	Switching frequency (F_{pwm})	20 KHz

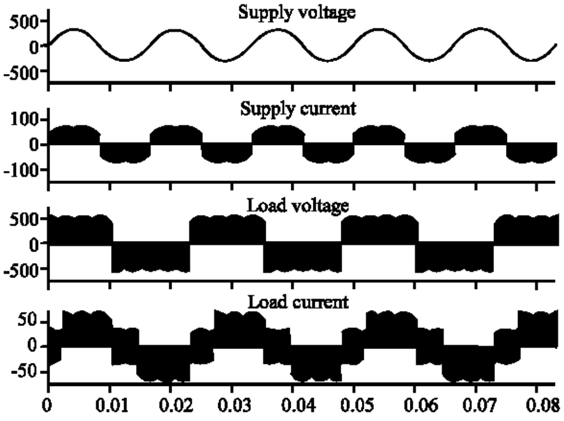

Fig. 6: Supply voltate (v_s), sourrce current (I_s) load voltage (V_L) and load current (I_L) without filter

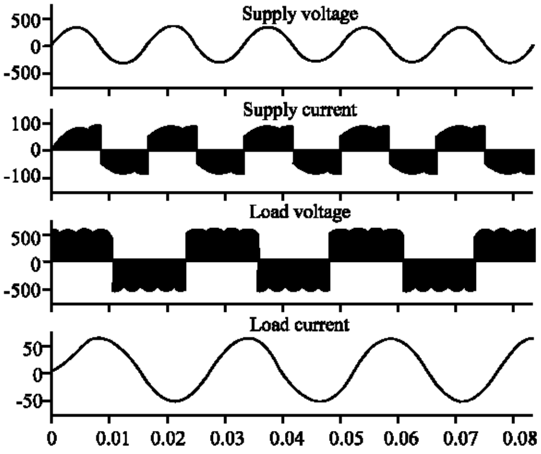

Fig. 7: Supply voltate (v_s), sourrce current (I_s) load voltage (V_L) and load current (I_L) witht filter

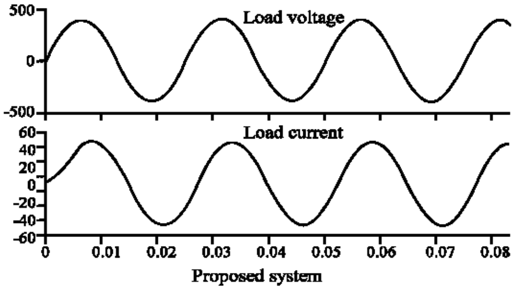

Fig. 8: Load voltage (V_L) and load current (I_L) when the series active filter is turned on

In Fig. 9, the matrix converter output harmonics are 60%. After the proposed series active filter is implemented the matrix converter output voltage harmonics reduced at 3%. So, the power quality is maintained by using the shunt active filter. Figure 10 shows when the matrix converter is affected by swell. The voltage swell present at 0.03-0.05 sec. After the proposed compensation series active filter eliminates the swell problem and maintain the power quality in the matrix converter output as shown in Fig. 11.

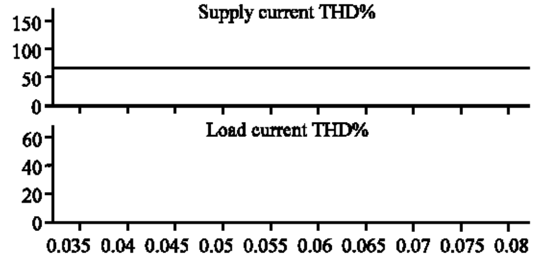

Fig. 9: Total harmonic distortion in matrix converter output voltage without and with compensation

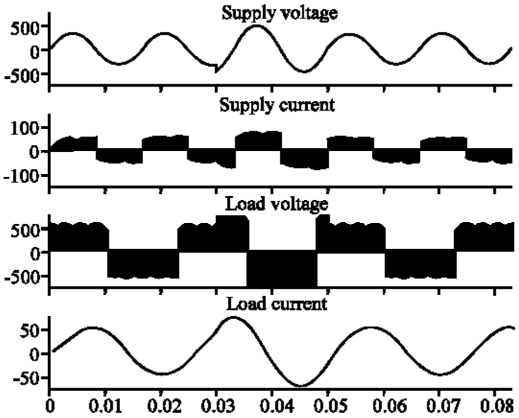

Fig. 10: Voltage swell accord in matrix converter output current voltage without compensation

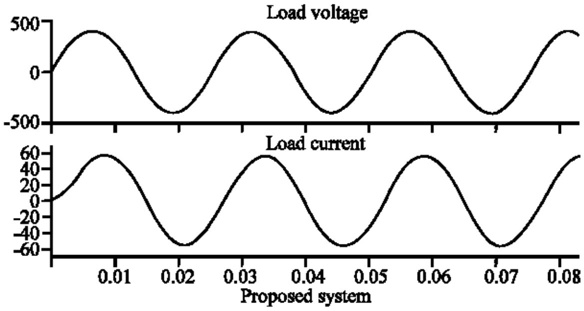

Fig. 11: Voltage swell accord in matrix converter output current voltage witht compensation

CONCLUSION

In this study, Series Active Power Filter (SAPF) compensation is implemented in the matrix converter output for power quality improvement and it is evaluated. In simulation studies, the results are specified for the system before the operation of series active filter and after with the inclusion of series active filter in the matrix converter. The proposed strategy can eliminate up to 90% harmonic components.

When SAPF system is operated in matrix converter, the load harmonics are removed effectively. The modification of this proposed methodology has given considerably good simulation results as compared to the conventional harmonic control method. The proposed method is validated and simulation results are obtained through Matlab/simulink software.

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