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Voltage Sag and Swell Mitigation Using Matrix Converter with Reduced Number of Switches

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-----ABSTRACT-----
Dynamic Voltage Restorer (DVR) is used in power distribution system to protect sensitive loads in voltage disturbances. The performance of DVR is related to the adopted configuration and control strategy used for inverters. In this paper, matrix converter with reduced number of switches (RMC) is used to improve operation of DVR to compensate voltage sag/swell. Simulation results using MATLAB/ Simulink are presented to demonstrate the feasibility and the practicality of the proposed novel Dynamic Voltage Restorer topology. Total Harmonic Distortion (THD) is calculated. The simulation results of new DVR presented in this paper, are found quite satisfactory to eliminate voltage sag/swell.

Keywords: DVR, Matrix converter, swell, THD and voltage sag.

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I Introduction

Power quality problems in industrial applications concern a wide range of disturbances such as voltage sags and swells, flicker, interruptions, harmonic distortion. Preventing such phenomena is particularly important because of the increasing heavy automation in almost all the industrial processes. Electronics devices hold substantial promise for making distributed energy applications more efficient and cost effective. There is a need to develop advanced power electronics interfaces for the distributed applications with increased functionality (such as improved power quality,voltage/volt-amperes reactive (VAR) support), compatibility (such as reduced distributed energy fault contributions), and flexibility (such as operation with various distributed energy sources) while reducing overall interconnection costs. The use of voltage source inverters is increasing [1]. They are used both for feeding power from distributed generators to the transmission grid and power to various types of electronic loads. In recent years, the number of different power resources connected to power systems (voltage grids) has increased and there has been a move toward connecting small power resources to the medium and low voltage network [2]. Power quality standards for connection of an inverter to the grid are still under development, since previously there have been a few similar high power applications. In [3] it is that the power quality is determined by the voltage quality, when the voltage is a controlled variable. In order to deliver a good ac power the controlled pulse width modulation (PWM) inverter and L-C output filter have to convert a dc voltage source (e.g. batteries) to a sinusoidal ac voltage with low voltage THD and fast transient response under load disturbances. Another important aspect of power quality is harmonic distortion. General requirements for harmonic distortion can be found in standard [4] and particularly for connection of distributed resources to grid.

PWM control is the most powerful technique that offers a simple method for control of analog systems with the processor's digital output. With the availability of low cost high performance DSP chips characterized by the execution of most instructions in one instruction cycle, complicated control algorithms can be executed with fast speed, making very high sampling rate possible for digitally-controlled inverters.

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A DVR consists of a voltage-source inverter, a series-connected injection transformer, an inverter output filter, and an energy storage device that is connected to the dc link [5]. The voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. This device employs insulated gate bipolar transistors (IGBT) as switches [6]. This converter injects a dynamically controlled voltage in series with the supply voltage through the three single-phase transformers to correct the load voltage. The main functions of the injection transformer include voltage boost and electrical isolation.

The DC side of the converter is connected to a DC energy-storage device. Energy-storage devices, such as batteries or super-conducting magnetic energy-storage systems (SMES) are required to provide active power to the load when voltage sags occur [7]. In this paper, battery is used as a source of the DC voltage for the reduced matrix converter. The output of the inverter (before the transformer) is filtered by Passive filters in order to reject the switching harmonic components from the injected voltage [8].Different control strategies were proposed for DVR. Voltage-Space Vector PWM was implemented in Estimation of symmetrical components of voltage to control DVR is used in [9]. Synchronous reference frame control can be adopted to improve voltage quality of sensitive loads[10].In this paper, a DVR with a new inverter topology is presented to suppress the load harmonics and to compensate the voltage disturbances. This inverter has less voltage harmonics generated on the ac terminal of the inverter compared with conventional technique .

II DVR Topology

The main function of a DVR is voltage injection to compensate the voltage drop due to the voltage sag occurrence. In the other word DVR restores the load voltage to its rated value. To do this, DVR needs to exchange active and reactive power with the system. There are two types of DVR in general: 1) DVR with no energy storage system 2) DVR with energy storage system. Each type has two topologies: 1) supply-side-connected converter and 2) load-side-connected converter. All of the mentioned topologies are compared in [4] and the no energy storage DVR topology with load-side-connected converter has been evaluated as the best one which is shown in Fig. 2.1

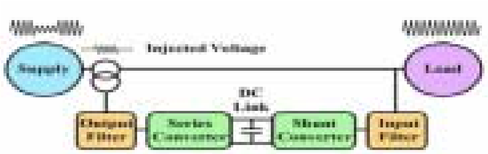

Fig 2.1 General Type of DVR with no energy storage and load-side-connected converter.

As there is no energy storage device in this topology, DVR needs a minimum system voltage to work properly and it may not be able to compensate very deep sags but the lack of energy storage device is a great economical advantage. Furthermore, most usual sags are within the range of DVR limits. The matrix converter based DVR in this paper is established on this topology which means a DVR with no energy storage and load-side connected converter. According to Fig. 2.1 two converters are replaced by a matrix converter and the DC-link capacitor is removed. Figure 2.2 shows the resultant DVR system.

Figure 2.2 Matrix converter based DVR.

The input voltage of matrix converter comes from the load and the output of matrix converter is connected to an

$$m^k{}_j = \frac{\text{the time interval when the circuit is in mode } j \text{, during the kth cycle}}{T_s} = \frac{\Delta^k_j}{T_s}$$

injection transformer. Matrix converter controls the required compensation voltage and injects that voltage through the transformer. To reduce harmonics, both input and output of matrix converter are supplied with filters. There is no energy storage device and the energy is taken from the grid.

III Reduced matrix converter

Reduced matrix converter (RMC) is a convenient topology due to its potential to reduce the size and weight of the converter and to increase the efficiency inherent to less stages of conversion. The reduced matrix converter (RMC) provides direct AC-AC conversion without the need of a bulky DC link capacitor, it is thus a compact solution. Its main advantages are adjustable (including unity) power factor, bi-directional power flow, high quality waveform, and the possibility of a compact design due to the lack of large energy storage components. It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no sub-harmonics; the input power factor can be fully controlled. However, the complexity of its conventional PWM strategy is prone to commutation failure, which is a factor that keeps it from being utilized in industry. The proposed matrix converter has following advantages

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- The proposed method matrix converter consists of only the 4 bi-directional switches.
- Line to line short circuits at the input is overcome by varying the switching pattern and by means of commutation control.
- Open circuits at the output (assuming inductive load) is overcome by varying the switching pattern and by means of commutation control

IV Principle of operation

The Single-Phase Matrix Converter (SPMC) consists of a matrix of input and output lines with four bi-directional switches connecting the single-phase input to the single-phase output at the intersection. The SPMC is presented schematically in Fig 4.1 Its instantaneous input voltage *v*i(t) and its output voltage *v*o(t). It comprises of four ideal switches S1, S2, S3, and S4 capable of blocking forward and reverses voltages (symmetrical devices) and switching between states without any delays.

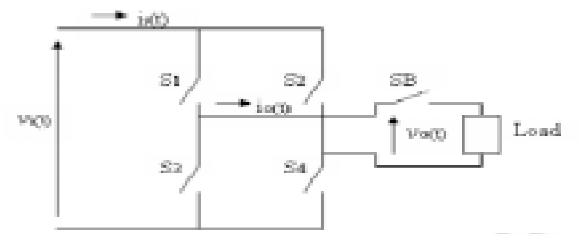

Fig 4.1 Single-phase matrix converter circuit configuration at no load

SPMC operating at no-load: With the SB open the SPMC is unloaded as shown in Fig4.1. This topology converts the input voltage *v*i(t), with constant amplitude and frequency, through the four ideal switches to the output terminals in accordance with pre-calculated switching angles.

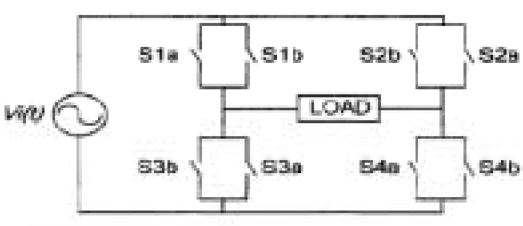

Fig 4.2 Single-phase matrix converter circuit configurations at load

$$V_i(t) = \sqrt{2}V_i(t)\cos\omega_i t \qquad \text{……….(1)}$$

The matrix converter will be designed and controlled in such a manner that the fundamental of the output voltage is

$$V_0(t) = \sqrt{2}V_o(t)\cos \ \omega_o t \qquad \text{……….(2)}$$

The instantaneous value of the output voltage, *v*o(t), has the following characteristics:

1. Its maximum value is identical to the maximum value of the input voltage.
2. It contains fundamental and additional high order harmonics located at well defined sampled frequencies.
3. Its main harmonic has a stepped-up frequency and a stepped–down amplitude.

The four power switching devices are switched at high frequency, fs (fs >>fi and fo where fi = ωi / 2Π and fo = ωo /2Π). The normalized switching time (or duty cycles of every switch) during any switching cycle (Ts = 1/fs), is defined by

Where j = 1, 2 is the operation mode, k= 1, 2… n… is the cycle number.

It is obvious that

$$\sum_{j=1}^{2} \Delta_j = T_s \qquad \text{……. (3)}$$

$$m_1^k + m_2^k = 1 \qquad \text{……..(4)}$$

As a result of high frequency of the converter, the average output voltage during any *k*th switching cycle Ts is given by

$$V_0^k,_{av} = (m_1^k - m_2^k)V_i^k(t) \qquad \text{………..(5)}$$

Where vi(t) is the input voltage during the *K*th cycle and is practically constant. Keeping with equation 6 one can write that the fundamental of output voltage is given by

$$V_o \cos(\omega_o t) = (m_1 - m_2)V_i \cos(\omega_i t) \text{……… (6)}$$

Figure 4.3 shows the input voltage, the instantaneous output voltage, the desired fundamental of the output voltage and the averaged output voltage during one input switching cycle (1ms @ fs = 1KHz). From the figure4.3 , it can be seen that the input voltage is almost constant within one switching cycle (fi << fs)

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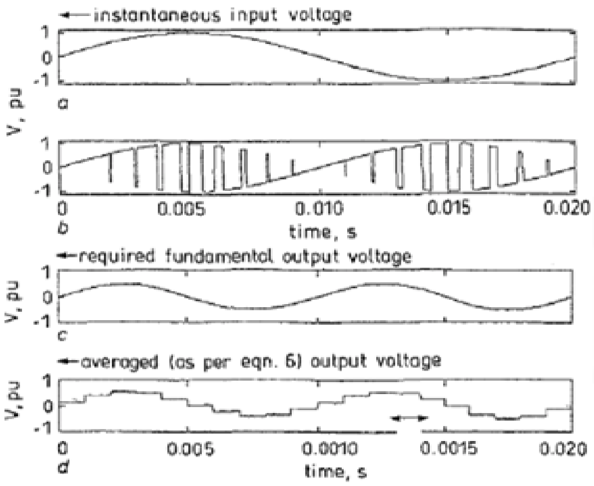

Fig 4.3 Input, Output, required output and averaged output wave forms

From equations (5) and (6), we obtain

$$m_1 = \frac{1 + \frac{V_0 \cos(\omega_0 t)}{V_i \cos(\omega_0 t)}}{2}$$

$$m_2 = \frac{1 - \frac{V_0 \cos(\omega_0 t)}{V \cos(\omega_0 t)}}{2} \quad \text{......... (7)}$$

It is obvious that

$$0 \le mj \le 1 \quad \text{.......... (8)}$$

From equations 4.7 and 4.8 is evident that

$$\left| \frac{V_o \cos(\omega_0 t)}{V_i \cos(\omega_0 t)} \right| \le 1 \quad \text{......... (9)}$$

Equation (9) must exist for any time, t, and this imply that when cos(ωi(t)) vanishes (this function => 0) also cos(ωo(t)) must vanish (=> 0). Therefore, input and the output waveforms must be synchronized and the fundamental of output voltage must cross zero more frequently than the input voltage. Hence, the single-phase matrix converter is a frequency step-up circuit capable of converting an input waveform with an angular frequency given by

$$\omega_o = r * \omega_i \quad \text{.......(10)}$$

Where r = 1, 2, 3…When cos (w(t)) = 0, the m1 and m2 are calculated in accordance with equation 3.8 and L Hospital rule. The result is

$$m_1 = \frac{1 + \frac{V_0 \cos(\omega_0 t)}{V_i \cos(\omega_0 t)}}{2}$$

$$m_2 = \frac{1 - \frac{V_0 \cos(\omega_0 t)}{V \cos(\omega_0 t)}}{2} \quad \text{.........(11)}$$

Keeping with equation (11) we obtain

$$V_0 \le \frac{\omega_i}{\omega_0} V_i \quad \text{.......(12)}$$

The above equation means that single-phase matrix converter is stepping down the output voltage fundamental. Based on the equations (7) - (12), we can conclude that the switching pattern, the Ms might be calculated. The four switching power devices S1, S2, S3, and S4 will be controlled according to the switching pattern. The above discussed matrix converter topics can be summarizes as:

1. The matrix converter will be controlled according to a switching pattern and t the purpose is to obtain an output main harmonics as per equation (2).
2. Its input, *vi*(t) is a sinusoidal waveform and its output, *vo*(t) comprises a number of high order harmonics.
3. Both waveforms have identical maximum values and total RMS values.
4. The matrix converter is a frequency step-up and fundamental voltage step-down converter. Up to this point the SPMC is unloaded.

V Modes of operation

The circuit diagram for the proposed converter and modes of operation is shown in figure5.1, 5.1 (a),(b),(c)&(d).

The conventional matrix converter has 8 switches. But proposed matrix converter consists of 4 switching devices. There are four modes of operation.

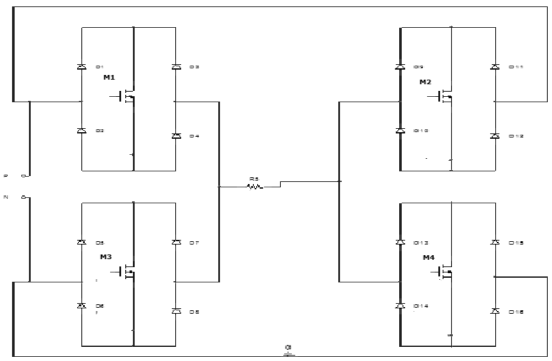

Fig 5.1 Circuit diagram for the proposed converter

Mode 1:

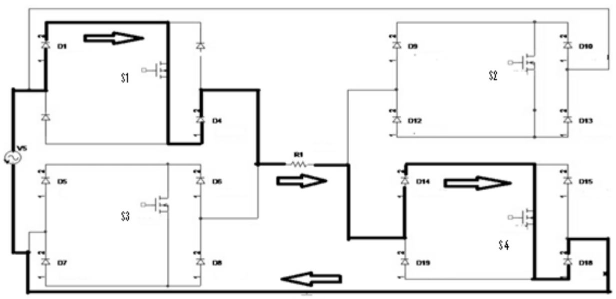

Fig 5.1(a)

In mode 1 switch S_1 and S_4 is 'ON'. The Diode D_1,D_4,D_{14} & D_{18} will conduct. The output voltage is positive

Mode2:

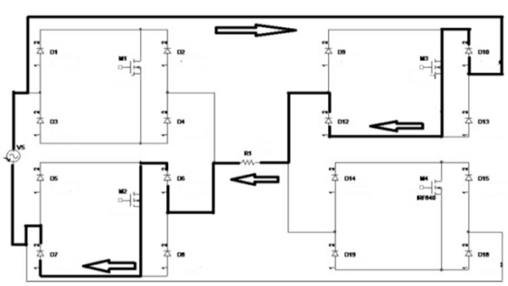

Fig 5.1(b)

In mode 2 switch S_2 and S_3 is 'ON'. The diode D_{10},D_{12},D_6 &D_7 will conduct. The output voltage is negative**.**

Mode3:

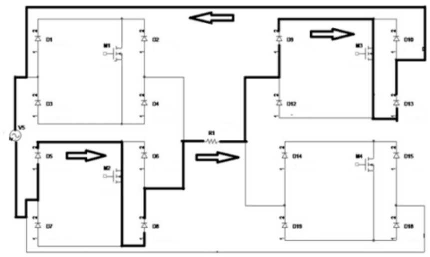

Fig 5.1(c)

In mode3 switch S_2 and S_3 is 'ON'. The Diode D_5, D_8,D_9 & D_{13} the diode will conduct. The output voltage is positive**.**

Mode4:

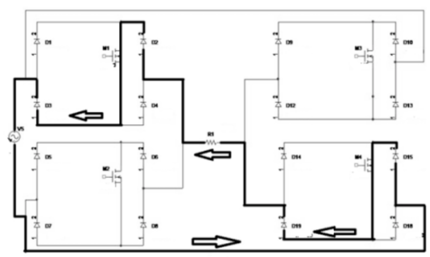

Fig 5.1(d)

In mode 4 switch S1 and S4 is 'ON' the diode D15, D9,D2 & D3 will be conduct. The output voltage is negative.

VI Simulation Results

A typical closed loop controlled DVR with the RMC in a simple power system to protect a sensitive load in a distribution system is presented in Figure 6.1

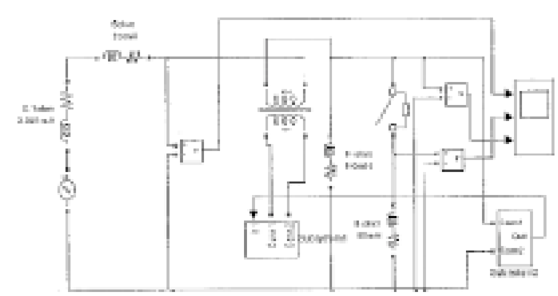

Fig 6.1 Closed loop controlled DVR with a matrix converter

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Subsystem1 contains the rectifier and the inverter as shown in Figure 6.2. The pulse width modulation technique was used to control the RMC. Subsystem2 consists of PWM pulse generation blocks as shown in Figure 6.3 The simulation is done using MATLAB and the results are presented.

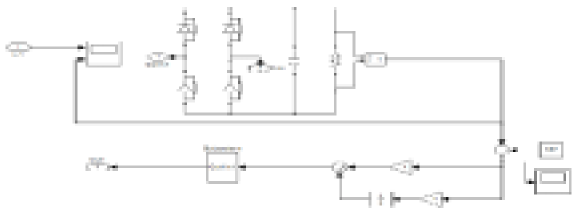

Figure 6.2 Subsystem 1 of the closed loop DVR with a matrix converter

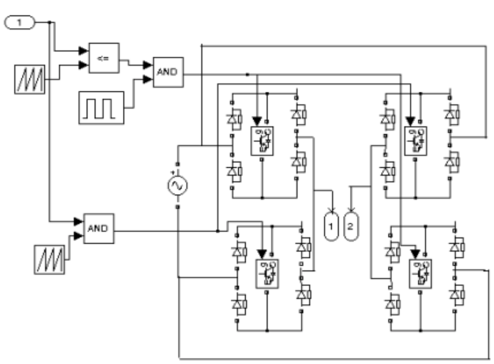

Figure 6.3 Subsystem 2 of the Closed loop DVR with a matrix converter

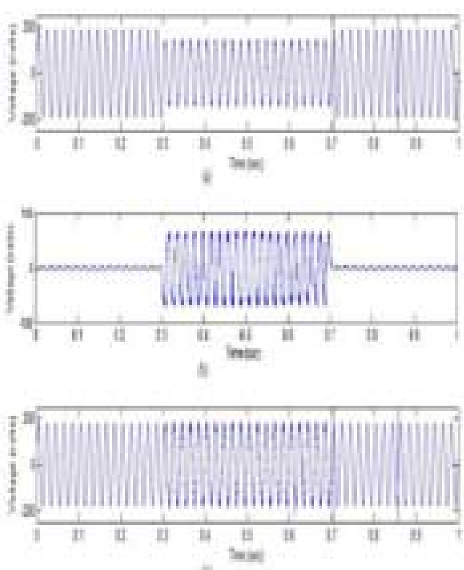

Figure 6.4 Response of RMC based DVR to voltage sag
a. Uncompensated voltage (v)
b. Injected voltage (v)
c. Compensated voltage (v)

Figure 6.5 shows the response of the closed loop DVR system to the voltage sag. Initially, the system was subjected to sag of 30% magnitude and 0.4sec duration. Simulation is done and the transient performance at the sag front and recovery was observed. Figure 6.5(a) shows the sag in voltage. Figure 6.5(b) indicates the injected voltage and the Figure 6.5(c) shows the compensated load voltage after voltage injection

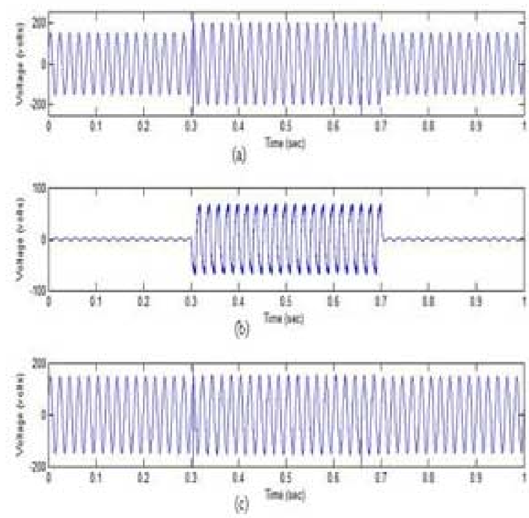

Figure 6.5 Response of RMC based DVR to a voltage swell
a. Uncompensated voltage (v)
b. Injected voltage (v)
c. Compensated voltage (v)

Figure 6.5 shows the response of the closed loop DVR system to the voltage swell. The system was subjected to a swell of 130% magnitude and 0.4sec duration. Simulation is done and the transient performance at the swell front and recovery was observed. Figure 6.5(a) shows the swell in voltage. Figure 6.5(b) indicates the injected voltage and the Figure 6.5(c) shows the compensated load voltage after voltage injection. It is seen that the DVR has successfully compensated the swell.

Figure 6.6 shows the FFT analysis of the closed loop DVR system with a matrix converter. The total harmonic distortion (THD) value is 0.81%. The THD of the load voltage is within the limits (IEEE std.519). The THD is very low in the case of the RMC when compared with conventional matrix converter

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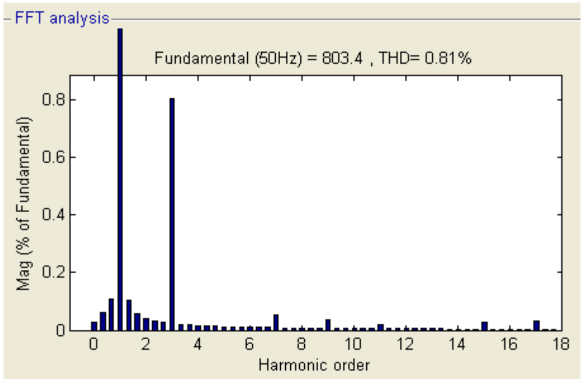

Fig 6.6 FFT Analysis of RMC

VII Conclusion

This paper has presented a novel DVR system topology employing a RMC without energy storage. In this topology, the matrix converter input terminals are connected on the load-side, characteristic that makes it able to generate the voltages for deep voltage sags compensation. The overall system encompassing the voltage injection controller and the plant have been simulated via detailed Matlab/simulink. The proposed converter is more reliable, compact and efficient than the existing converter state of the art for research with indirect-drive, back to back converter and low frequency transformer. The conversion from AC to AC is performed direct by the reduced matrix converter, thus the bulky capacitor which has the highest failure rate of the power electronics equipment can be omitted.

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