ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

Multifunctional Dynamic Voltage Restorer Using Matrix Converter

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Abstract*— Power Quality (PQ) has become a critical issue in highly automated industries and sensitive load centers. The voltage quality is the most important part of the PQ for customers. The voltage disturbances in the form of voltage sag, swell, flicker and harmonics can cause huge financial losses. In the past few years, power electronic solutions have been proposed to avoid these problems. Custom Power devices also called as power quality compensator employ power electronic or static controllers in medium or low voltage distribution systems for the purpose of supplying a level of power quality that is needed by electric power customers. One such reliable custom power device used to overcome these problems is Dynamic Voltage Restorer (DVR). It is a series connected custom power device, which is considered to be cost effective when compared with other compensation devices. But the use of DC link capacitor in the conventional DVR will increase the size, weight and the cost of the entire system which inhibits widespread use of DVR. This paper presents a new control circuit topology for the mitigation of wide variety of voltage disturbances affecting critical loads such as voltage sag, swell and flicker. The DVR used here is based on a three-phase to single-phase direct ac/ac converter energized from the main grid, known as Matrix Converter, characterized by the elimination of energy storage elements and dc link capacitors. This, in turn, leads to the compensation of long time voltage sag and the reduction of size, weight and cost of the entire system. This method is based on the minimum error between the real and the forecasted output voltages. Simulations are carried out in PSCAD/EMTDC software package.

***Index Terms*—Dynamic Voltage Restorer (DVR), matrix converter, voltage sag, voltage swell.**

I. INTRODUCTION

The electric power system is considered to be composed of three functional blocks - generation, transmission and distribution. For a reliable power system, the generation unit must produce adequate power to meet customers demand, transmission systems must transport bulk power over long distances without overloading system stability and distribution systems must deliver electric power to each customer premises from bulk power systems. Distribution system locates at the end of power system and is connected to the customer directly, so the power quality [1] mainly depends on the distribution system. The reason behind this is that the electrical distribution network failures account for about 90% of the average customer interruptions. In the earlier days, the major focus for power system reliability was on generation and transmission only as these more capital cost is involved in these. In addition their insufficiency can cause widespread consequences for both society and environment

But nowadays distribution systems have begun to receive more attention for reliability assessment.

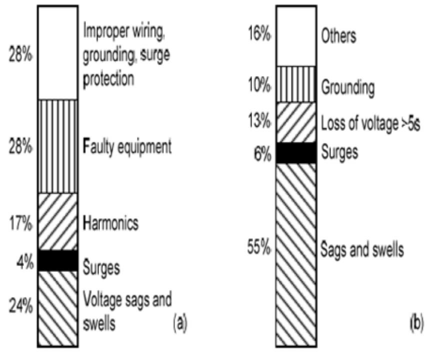

Fig. 1: Basic disturbances (a) at customer side (b) at utility side [1]

Initially for the improvement of power quality or reliability of the system FACTS devices like STATic synchronous COMpensator (STATCOM), Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC), and Unified Power Flow Controller (UPFC) etc are introduced. These FACTS devices are designed for the transmission system. But now a day's more attention is on the distribution system for the improvement of power quality, these devices are modified and known as custom power devices. The main custom power devices which are used in distribution system for power quality improvement are Distribution STATic synchronous COMpensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Active Filter (AF), Unified Power Quality Conditioner (UPQC) etc [2], [3]. From the above custom power devices, here DVR is used for the power quality improvement in the distribution system because of its low cost and reduced size compared to other devices [4]. Traditional DVRs mainly consists of series and shunt converters connected back-to-back and a common dc capacitor used as an energy-storage element [5]. The DVR injects three-phase compensating voltages in series to the power lines through a three-phase series transformer or three single-phase series transformers. The energy required for the compensation of voltage sag is taken from the dc capacitor or another energy-storage element such as a double-layer capacitor, a superconducting magnet, or a lead-acid battery. This type of configuration uses AC/DC/AC conversion. The required dc voltage is provided through a transformer from in the dc link for providing compensation energy. The cost of this dc-link capacitor is high and it results in high cost and limited application of DVRs [6]. To increase the wide range

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ISO 9001:2008 Certified
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application of DVR, a configuration that is based on direct AC/AC converters are introduced. As a result, there is no need for bulky and costly dc-link and energy storage elements. These converters are directly connected to the grid without a dc link. The compensation voltage in each phase is taken from all three phases of the source so it can compensate outages in any phase [7]. That means, if one phase of the source voltages has lost, the other two phases are supplied by the corresponding phase of the load. Other advantage of this topology in comparison with the conventional DVRs is their ability to overcome the problem of limiting energy stored in a dc-link capacitor during fault occurrence. A converter with the ability of ac-ac conversion with no dc link is required to eliminate the energy storing elements. The converter with this characteristic is called Matrix Converter (MC) [8]. In this paper, the power circuit of the proposed DVR is initially contemplated and its control method is described then. The experimental and simulation results in PSCAD software admit the ability of proposed structure in compensating balanced and unbalanced voltage sag, voltage swell and extreme voltage disturbances.

II. SYSTEM DESCRIPTION

A. DVR with Matrix Converter

Dynamic voltage restorer (DVR) is a power-electronic converter based device capable of protecting sensitive loads from all supply-side disturbances [5]. DVR can be assumed as an external voltage source with controllable amplitude, frequency and phase connected in series with distribution feeder, through a coupling transformer. Conventional DVR uses bulky and costly electrolytic capacitors at dc-link. This results increase in system's size, weight, cost and losses and also large input and output filters are necessary for harmonic reduction. In these DVRs, one-directional power transfer has to be carried out only. To overcome the disadvantages of traditional DVR a new ac/ac converter (Matrix Converter) based DVR is introduced to compensate both voltage sag and swell [9]. This converter has the ability of ac-ac conversion with no dc link to eliminate the energy storing element. The system representation of DVR with matrix converter is depicted in fig. 2. The system is mainly composed of a source, injection transformer, bypass switch, low pass filter, matrix converter and an output load. During normal operating condition, the bypass switch is in closed position and input voltage is transferred to the load. When any abnormal condition arises, matrix converter switches are turned on and provide required compensating voltage at the output. At this time the bypass switch is in off position. The output of the converter is filtered and it is injected in series with the line through a transformer. This injected voltage is added up with the sag voltage and full output is obtained at the load.

$$V_{Lk}(t) = V_{Gk}(t) + V_{injk}(t);\ \text{for } k = 1, 2, 3 \quad (1)$$

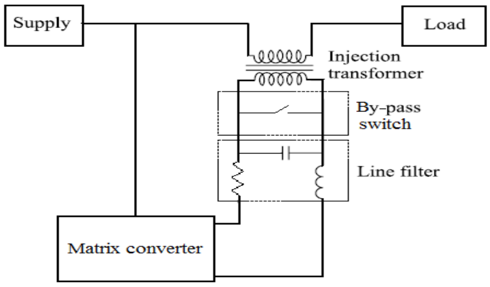

Fig. 1: Schematic diagram of DVR with matrix converter [5]

In equation (1) L, G and inj subscripts are the load, grid, and injected quantities respectively. Also, subscript k refers to the number of phases and its value is 1, 2 and 3. During voltage swell condition, a negative voltage is injected to the line. A Least Mean Square Error method [7], [10], is used to control the switching operation of matrix converter. It can compensate voltage sag, swell and flicker, because it uses bidirectional switches. There are two possible configuration ways of building the bi-directional switch; one consisting of a transistor embedded in a diode bridge arrangement while the alternative configuration consists of two anti-paralleled transistors and anti-parallel diodes. The later configuration can be implemented as either a Common Emitter (CE) or a Common Collector (CC). Here Common Emitter arrangement of switch is used [11].

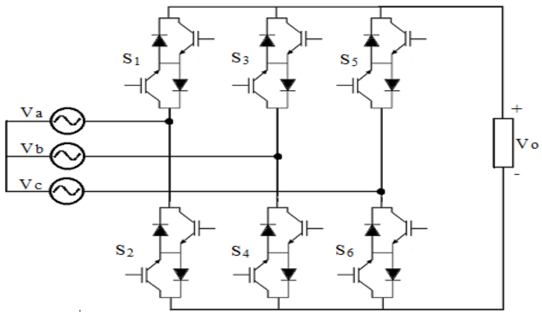

Fig. 2: Switching Arrangement in Matrix Converter [8]

Here a three-phase to single-phase matrix converter is used in each phase. In this converter topology, Least Mean Square Error method is used. A matrix converter with 6 bi-directional power switches is shown in fig. 3. This converter can produce 64 different switching modes and it is reduced to 7 modes by Considering the following two facts [7].

- Avoid short circuit on input side
- Prevent open circuit on load side

Table I: Different permissible switching modes of converter [8]

Mode	ON switches	V_0,mode
1	S_1 & S_4	$V_a - V_b$
2	S_3 & S_6	$V_b – V_c$
3	S_2 & S_5	$V_c – V_a$
4	S_2 & S_3	$V_b – V_a$
5	S_4 & S_5	$V_c - V_b$
6	S_1 & S_6	$V_a – V_c$
7	(S_1 & S_2) or (S_3 & S_4) or (S_5 & S_6)	0

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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III. CONTROL STRATEGY

This control method is based on the minimum error between the desired output voltage and the produced voltage. Fig. 4 shows the block diagram of the control circuit of the matrix converters used in the DVR structure. In this strategy, the error exists between the desired output voltage and produced voltage for different operation modes of MCs are given as follows:

$$E_i(t) = V_{o,Desired}(t) - V_{o,Mode,i}(t) \qquad i = 1, 2, \ldots \quad (2)$$

Where $E_i(t)$ is the error obtained at i^{th} mode, $V_{o,\,Desired}$ and $V_{o,Mode,i}$ is the desired voltage and mode voltage respectively.

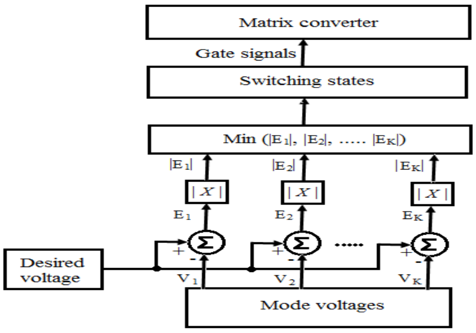


Fig. 3: Control strategy of switching pulse generation [8]

Here, the output voltage in different modes is compared with the desired output, and the error is calculated for each operation mode. After calculating the absolute values of these errors, the minimum error is recognized using "min" block. The switching states in different modes are saved in the look-up table. So according to the mode chosen by "min" block, switch turn on and turn off signals are chosen from the look-up table and are sent to matrix converter through driver circuits [7]. This control strategy results in reduction of switching numbers and consequently considerable reduction in converter losses and increase in its efficiency. By this strategy dv/dt stresses over power switches in MCs are significantly reduced. Also, it is possible to operate with low speed semiconductors [12].

IV. SIMULATION RESULTS

The matrix converter topology uses a load of 220V, 1.2kW for simulation. Table 2 summarizes the circuit parameters. In this configuration the matrix converter is connected to the source side of the system. The active power required for the compensation should be taken from the supply side. So it can compensate long time sag and no need of energy storage elements. Simulation results shown below for the case of both balanced and unbalanced fault.

Table 1: Parameters for modeling of DVR with matrix converter

Parameter	Notation	Value
Nominal Line –Line voltage	V_s	220 V
Frequency	f	50 Hz
Load Power Rating	P_L	1.2 kW
Ripple filter	L_F	1 mH
	C_F	80 µF
	R_F	1 Ω

This type of DVR can compensate voltage sag and swell. Simulation results, shown in figures represent two cases namely balanced voltage sag and swell. In the test system, three phase balanced sag is obtained by reducing the voltages in three phases during the period 0.2s to 0.3s. At this time, switches in the matrix converter will be turned on according to the look-up table and compensation voltage is generated at the output. This injecting voltage is added up with the sag voltage and compensation takes place. Here also voltage sag is applied at t = 0.2s and the duration is 0.1s. When balanced fault occurs, consider the input voltage is reduced to 155V from 220V. Then DVR injects 65V for the compensation. That means it injects full voltage for the compensation. From the simulation results, it is clear that DVR can inject compensating voltage during the fault time. Simulation results are shown in fig. 5.

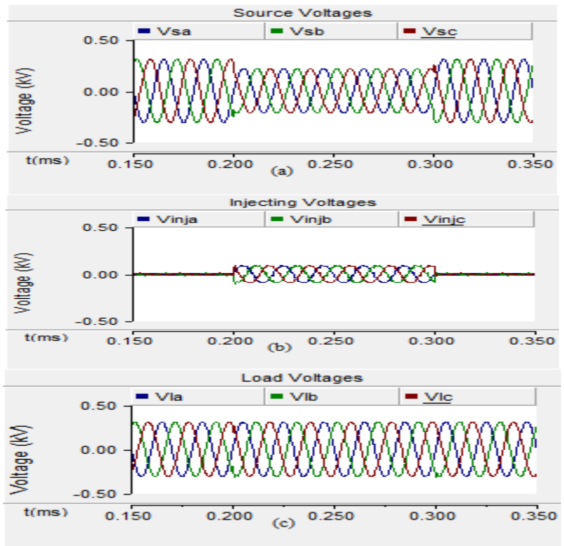
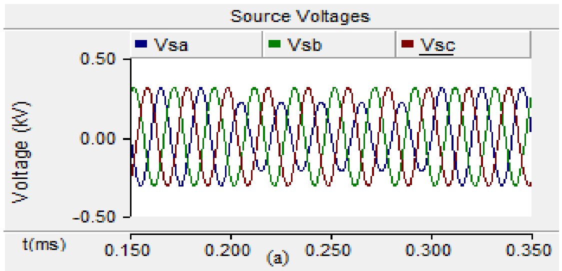


Fig. 5: Simulation results of DVR with matrix converter under balanced sag (a) Source voltages (b) Injecting voltages and (c) Load voltages

In the case of unbalanced voltage sag, a sag is applied in phase 'a' at t = 0.2s and the duration of fault is 0.1s. At this time, the input voltage is reduced to 155V from 220V. The DVR injects 65V through the series transformer to the faulted line for compensation. This compensation voltage is added up with sag voltage and full load voltage is obtained at the output. Simulation results are shown in fig. 6.



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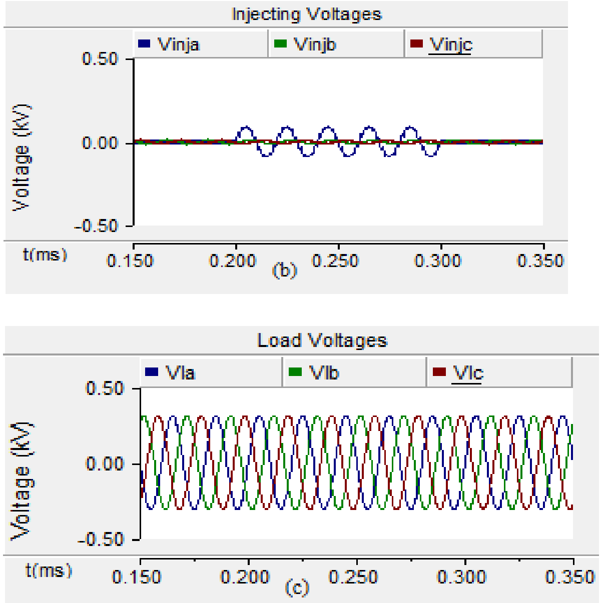
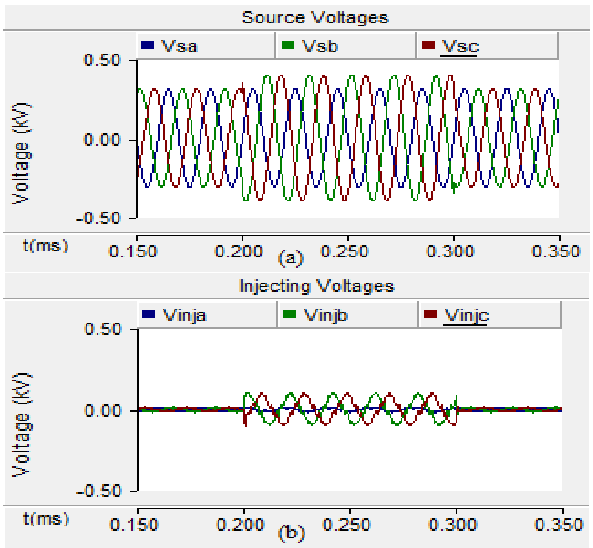


Fig. 6: Simulation results of DVR with matrix converter under unbalanced sag (a) Source voltages (b) Injecting voltages and (c) Load voltages

Fig. 7 shows the simulation results of source voltage, injecting voltage and load voltage obtained when a balanced voltage swell is at t = 0.2s and sustained for 0.1s. Then the input votage is increased to 350V from 220V during the period t = 0.2s to 0.3s. In the case of voltage swell, DVR injects voltage with 180 degree phase difference to the grid. This voltage conduction is done through the bidirectional switches in the matrix converter. When voltage swell occured, DVR injects 135V to the grid.

Simulation results of source voltage, injecting voltage and load voltage obtained during unbalanced voltage swell is given in fig. 8. The unbalanced swell is occurred in two phases 'b' and 'c'. In these two phases, the voltages are increased up to 350V during the period 0.2s to 0.3s. Then DVR injects voltage of 135V in the negative direction for the compensation.



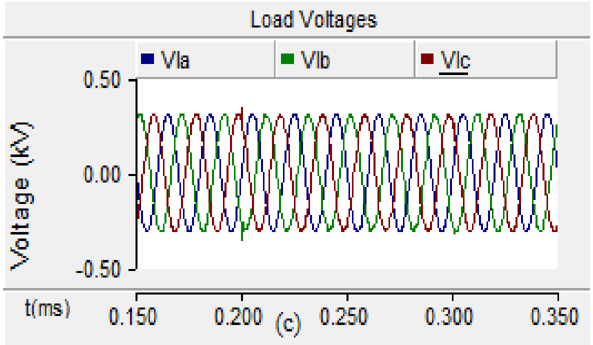


Fig. 8: Simulation results of DVR with matrix converter under unbalanced swell (a) Source voltages (b) Injecting voltages and (c) Load voltages

In this paper THD of the given topology is analyzed by connecting a full bridge rectifier with R and RL load. The value of R = 40Ω and L = 0.055H. In matrix converter topology THDv is about 0.368% in both load conditions because it does not allow entering higher order harmonics. FFT analysis is shown in fig. 9.

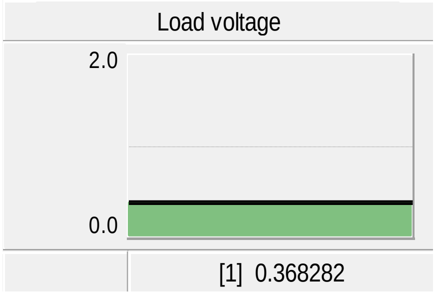


Fig. 9: THD analysis of load voltages

V. CONCLUSION

Voltage sag and current harmonics are the most important power quality problem faced by the utilities and customers. These power quality problems cause tripping of sensitive electronic equipments and tremendous economic losses. Custom Power devices are able to improve the reliability and quality of power delivered to electric power customers. DVR is especially used for compensating the voltage sag. It is connected in series with a distribution feeder. To improve the system efficiency, reduce the cost of Dynamic Voltage Restorer (DVR) and for the mitigation of voltage sag, swell a new control strategy is developed. The performance of the DVR can be increased by using a new converter topology called Matrix Converter. As a result, there is no need for bulky and costly dc-link and energy storage elements. The converters are directly connected to the grid without a dc link. Least Mean Square Error control strategy is used for generating the switching pulses. The voltage sag has been generated by performing faults in the grid. From the simulation results, it is clear that the performance and voltage restoration capability of DVR with matrix converter is better. THD of the topology is analyzed and from the analysis, it is clear that the system generates less THD. The simulation results show that the DVR with matrix converter topology has successfully mitigated the long duration voltage sag.

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ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

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