A Dynamic Voltage Restorer Based on Matrix Converter with Fuzzy Controller

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Abstract. *In this paper, a Dynamic Voltage Restorer (DVR) without any energy storage devices is proposed to compensate network voltage during disturbances. This DVR utilizes a matrix converter in its topology which eliminates the DC-link capacitor of conventional DVR. The modulation method for matrix converter which is used in this paper is indirect space vector modulation. A fuzzy PI controller is proposed instead of conventional PI controllers. The proposed topology is able to compensate balanced sags/swells as well as unbalanced ones. Moreover it can compensate harmonic pollution of the input source. The simulation results in MATLAB/Simulink environment show that the proposed DVR operates well during different disturbances and it has the ability to control the sensitive load voltage.*

Keywords

Dynamic voltage restorer, fuzzy PI controller, indirect space vector modulation, matrix converter.

1. Introduction

In recent years, modern industrials are mostly based on electronic devices such as programmable logic controllers and power electronic drives. These devices are very sensitive to voltage disturbances and power quality problems. Voltage sags are considered to be one of the most occurring disturbances in power systems [1], [2]. Voltage sag is defined as a decrease in voltage from 10 % to 90 % of rated voltage during half cycle to one minute. Voltage sags are usually caused by system faults, switching of heavy loads or starting of large motors [3].

Voltage support at loads can be achieved by reactive power injection at common coupling point of the system. The usual method for this is to install mechanically switched shunt capacitors in the primary terminal of the distribution transformer. The disadvantage of this procedure is inability of high speed transient compensation. Some sags are not corrected within the limited time frame of mechanical switches. Transformer taps may be used but tap changing under load is costly. Another solution to the voltage regulation is the use of a dynamic voltage restorer (DVR). DVRs are a class of custom power devices for providing reliable distribution power quality. They have been designed to protect critical loads from all supply-side disturbances other than outages [3]. There are four DVR topologies which are compared in [4]. Besides various DVR topologies, different types of power converters have been proposed in literatures. Generally all of them have a DC-link in their topology which has a big capacitor that needs maintenance. One method to solve this problem is to use AC-AC converters. A three phase matrix converter is a direct AC to AC converter with nine bidirectional switches and any output phase can be directly connected to any input phase at any time [6]. Matrix converters provide bi-directional power flow, nearly sinusoidal input and output waveforms, a controllable input power factor, and a compact design due to the lack of dc-link capacitors for energy storage. The complexity of matrix converter topology and control are its main drawbacks [6]. This paper proposes a DVR based on matrix converter with indirect space vector modulation strategy. The advantage of using matrix converter is the elimination of DC-link and its bulky capacitors. Moreover the proposed topology uses the system voltage as an input voltage of the DVR and no energy storage devices are needed.

Different DVR topologies based on matrix converters are presented in literatures. In [8] and [9], a flywheel supported DVR controlled by matrix converter is proposed. In [10] a matrix converter-based DVR is analyzed which utilizes a direct space vector modulation (DSVM) and PI controller. Another solution is studied in [11] and the behavior of a DVR with matrix converter utilizing Alesina-Venturini modulation (AVM) is shown. In this paper a DVR based on the matrix converter which uses indirect space vector modulation (ISVM) is analyzed. Comparing with AVM method, ISVM has a better voltage ratio and the ability to control unbalanced voltages. The advantage of ISVM over DSVM is the simplicity of implementation. One disadvantage of PI controller is using fixed gains which may cause the controller not to provide the suitable performance specially when there are variations in system parameters or operating conditions. To overcome this problem, a PI controller utilizing fuzzy logic algorithm is used instead of the simple PI controller. The fuzzy algorithm can adjust the value of the two gains in the PI controller in order to make a better response to the system operating point variations.

In this paper, the proposed DVR structure is introduced in Section 2. Indirect space vector modulation for matrix converters is reviewed in Section 3, followed by fuzzy control strategy of DVR in Section 4. Typical system simulations and numerical results via MATLAB/Simulink software are presented in Section 5. In Section 6, the conventional PI controller is compared with the proposed fuzzy PI controller. Finally, Section 7 concludes the discussion.

2. 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. 1.

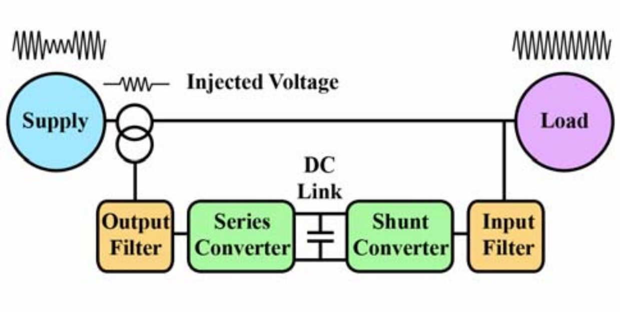


Fig. 1: General Type of DVR with no energy storage and load-side-connected converter.

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. 1 two converters are replaced by a matrix converter and the DC-link capacitor is removed. Figure 2 shows the resultant DVR system.

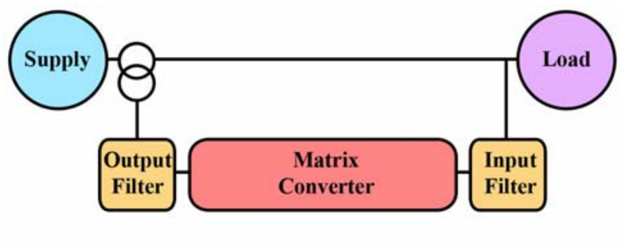


Fig. 2: Matrix converter based DVR.

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

3. Indirect Space Vector Modulation for Matrix Converters

Matrix Converter is made up of nine bi-directional switches arranged in an array of in such a way as to enable any input phase to be connected to any output phase at any time (Fig. 3). The switch duty cycles are modulated to produce desired output voltage from the supply voltage. There are various modulation techniques such as Venturini modulation, Optimum Venturini modulation, and Space Vector modulations (SVM). The last one has two types: direct SVM, and indirect SVM which is utilized in this paper.

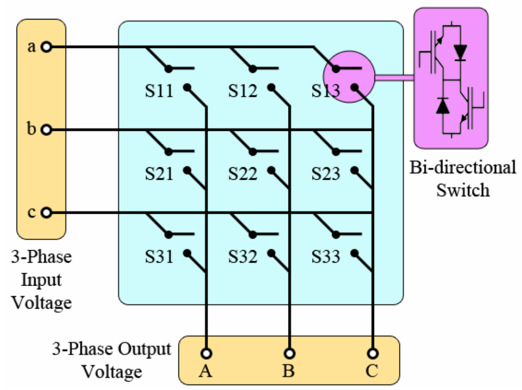


Fig. 3: Matrix converter topology.

In indirect method, matrix converter is modeled as two stage back-to-back converter: a rectification stage to create an imaginary DC link voltage, and an inverter stage to provide the required three-phase output voltage [12]. Figure 4 shows the equivalent model for the indirect space vector modulation.

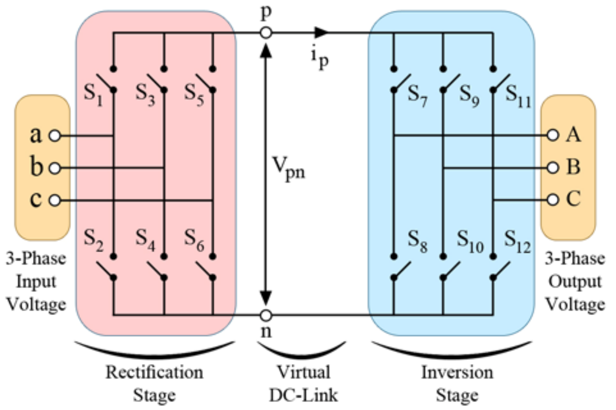


Fig. 4: Equivalent circuit of matrix converter for indirect space vector modulation.

The switching function in a matrix converter is as follows:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}, \tag{2}$$

where:

$$S_{\alpha\beta} = \begin{cases} 1 & S_{\alpha\beta} : Close \\ 0 & S_{\alpha\beta} : Open \end{cases} . \tag{3}$$

$$\alpha \in \{1,2,3\}, \quad \beta \in \{1,2,3\}$$

The control algorithm of indirect matrix converter is based on separating this switching function into the product of a rectifier and an inverter switching function:

$$\begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix}. \tag{4}$$

There are two modulations which should be implemented: a current source rectifier space vector modulation and a voltage source inverter space vector modulation.

3.1. Rectifier stage modulation

The input current space vector may be defined as:

$$I_{in} = \frac{2}{3}\left(i_a + a i_b + a^2 i_c\right) = I_m \angle \theta_i \, . \tag{5}$$
$$a = e^{j\frac{2\pi}{3}}$$

Figure 5 shows that I_{in} is synthesized using two adjacent vectors I_γ and I_δ with duty cycles d_γ and d_δ, respectively which are defined as:

$$d_\gamma = \frac{T_\gamma}{T_s} = m_c \sin\left(\frac{\pi}{3} - \theta_i\right). \tag{6}$$

$$d_\delta = \frac{T_\delta}{T_s} = m_c \sin\left(\theta_i\right). \tag{7}$$

In these equations, the current modulation index is $m_c = I_m / i_p$ and i_p is the DC link current which is shown in Fig. 4. The zero vector duty cycle is:

$$d_{0c} = 1 - \left(d_\gamma + d_\delta\right). \tag{8}$$

Then I_{in} is as follows:

$$I_{in} = d_\gamma I_\gamma + d_\delta I_\delta + d_{0c} I_0 \, . \tag{9}$$

The average voltage of the DC-link, V_{pn}^{avg}, which is generated by rectification stage, can be determined using the following equation:

$$V_{pn}^{avg} = \frac{3}{2}\left(V_{in}^{Peak}\right)\left(m_c\right)\cos\left(\varphi_i\right). \tag{10}$$

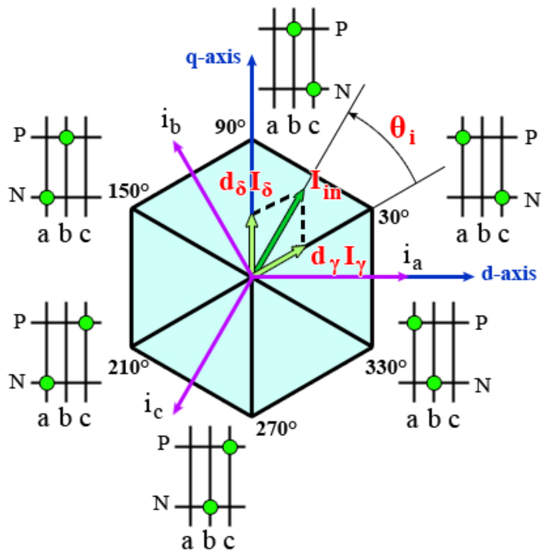


Fig. 5: Input current space vector.

3.2. Inverter stage modulation

The inversion stage space vector, V_{out}, is defined as:

$$V_{out} = \frac{2}{3}\left(V_A + aV_B + a^2V_C\right) = V_m\angle\theta_v \qquad a = e^{j\frac{2\pi}{3}}. \tag{11}$$

Similar approach is taken to synthesize this vector as shown in Fig. 6. Duty cycles in this stage are:

$$d_\alpha = \frac{T_\alpha}{T_s} = m_v \sin\left(\frac{\pi}{3} - \theta_v\right). \tag{12}$$

$$d_\beta = \frac{T_\beta}{T_s} = m_v \sin\left(\theta_v\right). \tag{13}$$

$$d_{0v} = 1 - \left(d_\alpha + d_\beta\right). \tag{14}$$

where $m_v = \sqrt{3}V_m/V_{pn}$ is the voltage modulation index and V_{pn} indicates the DC link voltage which is shown in Fig. 4. So V_{out} can be written as:

$$V_{out} = d_\alpha V_\alpha + d_\beta V_\beta + d_{0v}V_0. \tag{15}$$

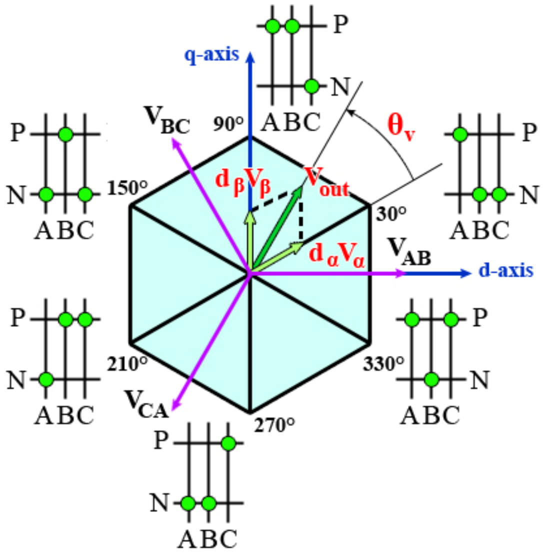


Fig. 6: Output voltage space vector.

3.3. Combination of stages

By combining rectification and inversion modulation stages, the switching pattern for nine switches of matrix converter is generated:

$$d_{\alpha\gamma} = d_\alpha . d_\gamma. \tag{16}$$

$$d_{\beta\gamma} = d_\beta . d_\gamma. \tag{17}$$

$$d_{\alpha\delta} = d_\alpha . d_\delta. \tag{18}$$

$$d_{\beta\delta} = d_\beta . d_\delta. \tag{19}$$

$$d_0 = 1 - \left(d_{\alpha\gamma} + d_{\beta\gamma} + d_{\alpha\delta} + d_{\beta\delta}\right). \tag{20}$$

The symmetrical double-sided switching pattern which is used in this paper is shown in Fig. 7 where:

$$T_{xy} = d_{xy}.T_s; \quad T_s = \frac{1}{f_s}. \qquad x \in \{\alpha, \beta\}, \quad y \in \{\gamma, \delta\} \tag{21}$$

and f_s is switching frequency of the modulation.

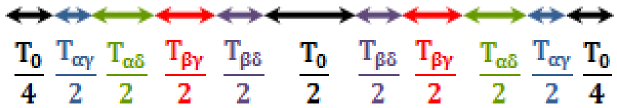


Fig. 7: Symmetrical double-sided switching pattern for indirect space vector modulation.

4. Control Strategy of DVR

PI controllers are widely used in many electrical applications. One reason is its simplicity. The other reason is the ability to control the steady state error of the system. The disadvantage of conventional PI controllers is its fix gains which makes it unable to control the transient response of the system in abnormal conditions [13]. One solution is using an adaptive controller to adopt the PI controller gains in real-time. Figure 8 shows a fuzzy PI controller. One feature of fuzzy algorithm is that it doesn't need a mathematical model of the system.

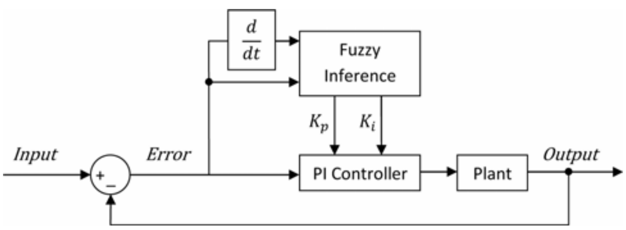
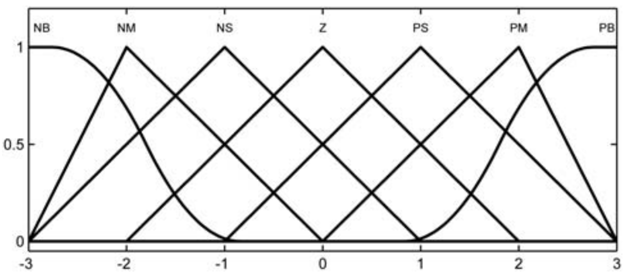
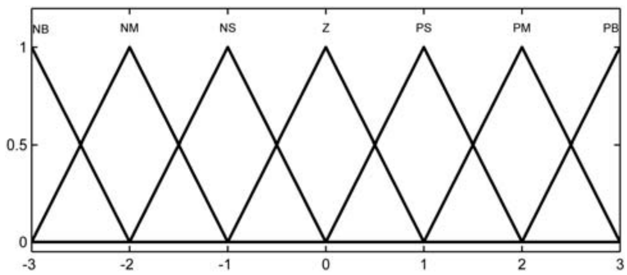


Fig. 8: Fuzzy PI controller structure.



a)



b)

Fig. 9: Membership function curves of: a) e and Δe; b) K_p and K_i.

It only requires some data of experiences of the system. Moreover it is very robust so it is suitable for nonlinear or variable-time systems.

The fuzzy logic system variables could have any value between 0 and 1. Therefore this system is able to address the values of the variables that are between completely true and completely false. These variables are called linguistic variables. Each variable is characterized by a membership function which has a specific degree of membership at a particular instance. According to Fig. 8, error and the rate of error are chosen to be fuzzy variables and the proportional and integral gains of PI controller are its outputs. In this paper, the membership functions of these variables are obtained by trial and error through repetitive simulations. Fig. 9a) and 9b) show the membership function of fuzzy variables, e and Δe, and the membership function of output variables, K_p and K_i, respectively.

The fuzzy logic is an IF-THEN rule inference [13] in the form of:

IF {(Error) and (Rate of Error)} THEN {(K_p) and (K_i)}

These rules are defined by trial-and-error procedure through different simulation running or by using experimental data. The fuzzy subsets of each variable are named as (NB, NM, NS, Z, PS, PM, PB) and the fuzzy control rules of K_p and K_i, are shown in Tab. 1 and Tab. 2, respectively.

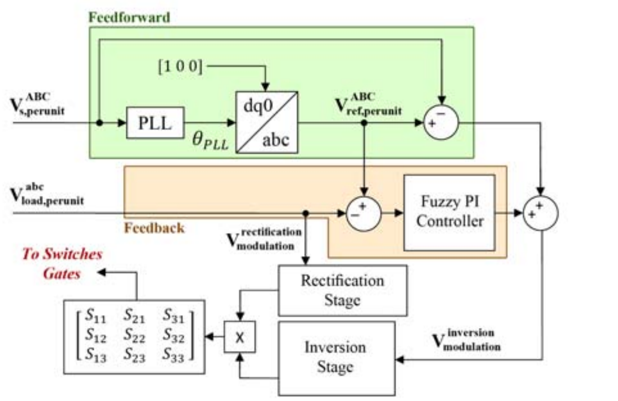
Tab.1: Fuzzy control rules of K_p.

		e						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
Δe	**NB**	PB	PB	PM	PM	PS	PS	Z
	NM	PB	PB	PM	PM	PS	Z	NS
	NS	PM	PM	PM	PS	Z	NS	NM
	Z	PM	PS	PS	Z	NS	NM	NM
	PS	PS	PS	Z	NS	NS	NM	NB
	PM	PS	Z	NS	NM	NM	NM	NB
	PB	Z	NS	NS	NM	NM	NB	NB

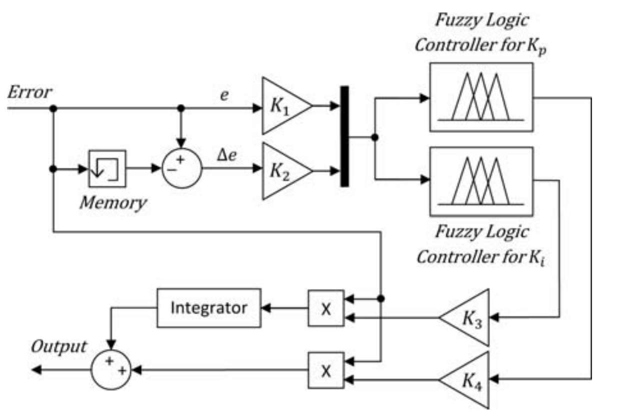
Tab.2: Fuzzy control rules of K_i.

		e						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
Δe	**NB**	NB	NB	NB	NM	NM	NS	Z
	NM	NB	NB	NM	NM	NS	Z	PS
	NS	NM	NM	NS	NS	Z	PS	PS
	Z	NM	NS	NS	Z	PS	PS	PM
	PS	NS	NS	Z	PS	PS	PM	PM
	PM	NS	Z	PS	PM	PM	PB	PB
	PB	Z	PS	PS	PM	PB	PB	PB

The whole control diagram of the DVR is shown in Fig. 10. The proposed controller for DVR consists of a feedforward path and a feedback loop. The feedforward path produces the required voltage that should be injected by DVR to overcome the power quality issue. This is done by comparing the instantaneous source voltage with a reference voltage that is produced by a Phase-Locked Loop (PLL). There are different voltage drop in the system such as voltage drop on the injection transformer impedance, voltage drop on the input and output filters, and voltage drop on the matrix converter switches. These voltage drops cannot be compensated with a feedforward controller. Therefore a feedback loop is added as shown in Fig. 10a).



a)



b)

Fig. 10: a) Proposed control diagram; b) Fuzzy PI controller of each phase.

The load voltage is compared with the reference voltage and produces an error which is the fuzzy controller input. This fuzzy PI controller is shown in Fig. 10b) and finally the calculated compensation voltage by fuzzy logic system is added to the feedforward voltage. The resultant voltage is inserted to the matrix converter controller to produce the signals for its IGBTs. As it is mentioned before, the output value of fuzzy logic systems are between 0 and 1. Therefore it needs to be multiplied before applying to PI controller and in Fig. 10b), K_i $,i=\{1,2,3,4\}$ are scaling factors which are defined through trial-and-error by repetitive simulations to achieve the best response from the controller.

5. Simulations

The proposed matrix converter based DVR is simulated using MATLAB/Simulink software with discrete solution and the time step is set to $2\ \mu sec$. The simulated system parameters are given in Tab. 3. A Discrete 3-phase PLL block with $K_p=180$, $K_i=3200$ and $K_d=1$ is used to create a reference signal that is mention in section 4. There are 18 IGBT/Diode blocks with $R_{on}=1\ m\Omega$ and $R_s=100\ k\Omega$ to simulate a three phase matrix converter. The fuzzy logic controller is simulated using Fuzzy Logic Controller block in Fuzzy Logic Toolbox of MATLAB/Simulink and the appropriate membership functions are inserted to these blocks according to Fig. 9. In this paper, the behaviors of proposed DVR under balanced sag/swell as well as unbalanced disturbances and harmonic pollution have been studied.

Tab.3: Test case system parameters.

Parameter	Value
Grid Phase Voltage (RMS)	220 V
Source Resistance	1 mΩ
Source Inductance	2 µH
Input Filter Resistance	0,8 Ω
Input Filter Capacitance	43 µF
Output Filter Inductance	300 µH
Output Filter Capacitance	7,2 µF
Load Resistance	50 Ω
Load Inductance	200 mH

In the first test, a 30 % three-phase balanced sag is applied to the system during 5 cycles. Figure 11 shows the input voltage, the injected voltage by DVR, and the load voltage. It can be observed that DVR is able to keep the load voltage at its nominal value during the sag period.

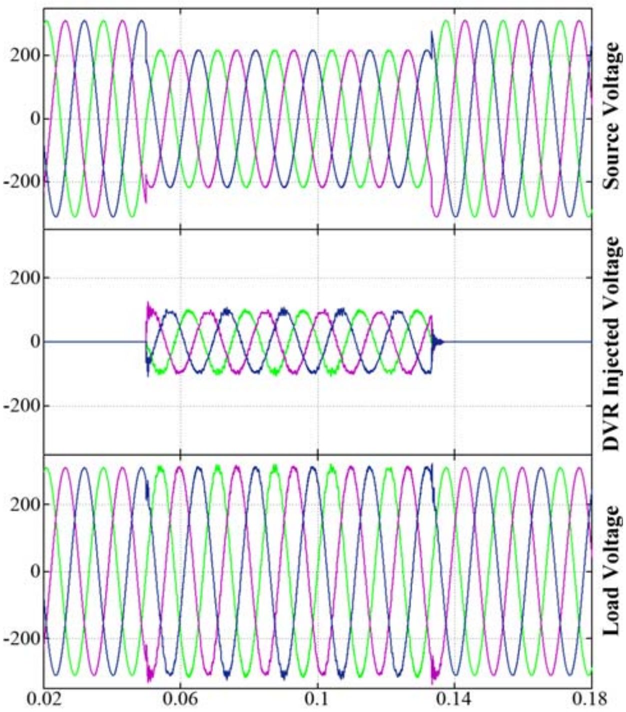


Fig. 11: Test case 1: Balanced sag.

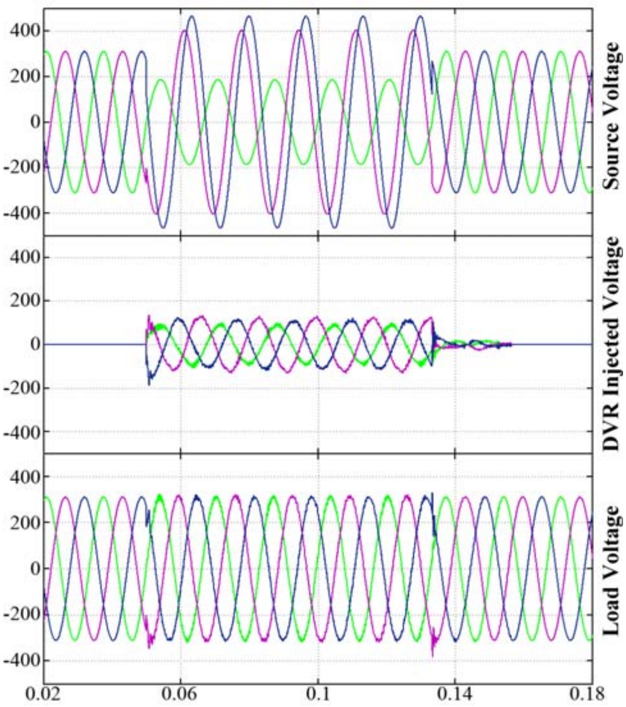


Fig. 12: Test case 2: Unbalanced sag/swell.

In the next test, an unbalance voltage source is analyzed. There is a 40 % sag on phase a. Furthermore there is a 30 % swell with -30 degree phase shift and a 50 % swell with +45 degree phase shift on phase b and c, respectively. The results are plotted in Fig. 12 and it is obvious that DVR has injected an appropriate voltage to maintain the load voltage at a proper level.

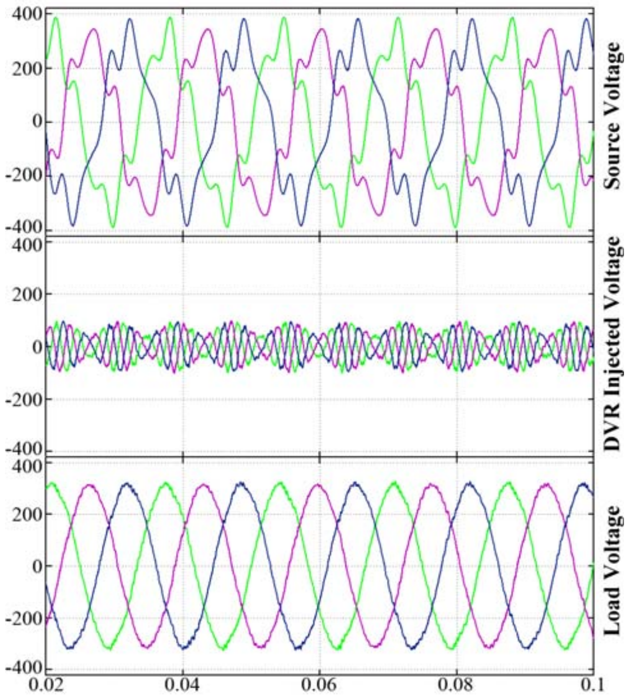


Fig. 13: Test case 3: Harmonic pollution.

In the last test, a 20 % of 5th harmonic and 8 % of 7th harmonic are added to the input voltage. Fig. 13 shows that the proposed DVR can effectively control the load voltage and immune it from harmonic pollution of the source voltage. Fig. 14 shows the source voltage, DVR injected voltage and the load voltage in per-unit complex plain during these disturbances.

Table 4 shows Total Harmonic Distortion (THD) of three phases of load voltage during tested disturbances. As it can be considered, THD is in a suitable range.

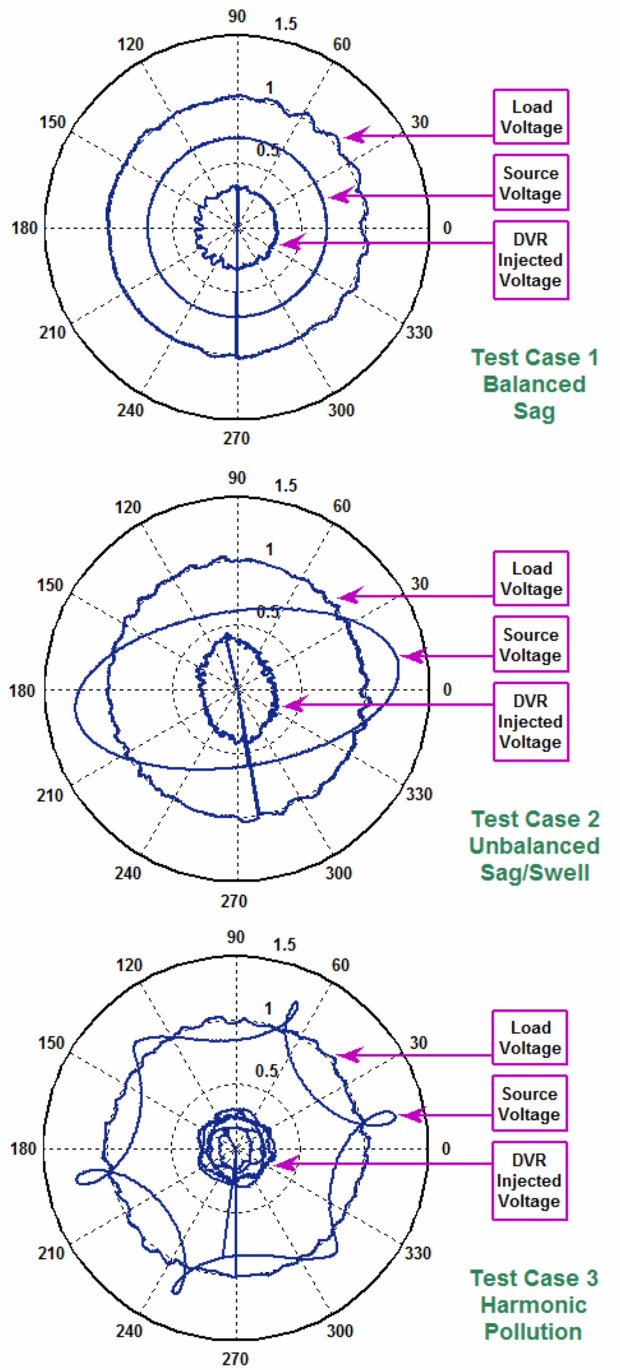


Fig. 14: Source voltage, injected voltage, and load voltage in per-unit complex plain during disturbances.

Tab.4: THD of load voltage during disturbance.

Test Case	V_A	V_B	V_C
Balanced Sag	1,24 %	1,30 %	1,31 %
Unbalanced Sag/Swell	1,55 %	1,82 %	1,52 %
Harmonic Pollution	2,35 %	2,20 %	2,31 %

6. Comparison between Proposed and Conventional Controller

Conventional PI controller is used in many system controllers because of its simplicity. It is designed for a unique system operating point to compensate it in the best way. Therefore its main disadvantage is the inability to operate well under a wider range of operating conditions such as different types of sags and swells with different amplitude or phase shift. In the other word the proportional and integral gains of conventional PI controller should be changed to obtain a proper response from the system. However conventional PI controllers have fixed gains that cannot be controlled. To solve this problem, a fuzzy PI controller is proposed in this paper instead of conventional one. In this section the advantage of using this type of controller is discussed.

At first, a conventional PI controller is used instead of the fuzzy PI controller which is shown in Fig. 10a). The gains of this controller are designed by trial-and-error such that the load voltage has the best waveform in the presence of 30 % balanced sag as shown in Fig. 15. In Fig. 16 and Fig. 17, the operation of this controller and the proposed fuzzy PI controller are analyzed side by side in various disturbances. As it can be considered, the fuzzy one has better response with less overshoot and also a better damping ratio. This behaviour is expected as the fuzzy controller changes the PI gains in each disturbance to have a better response, but the conventional PI controller has fixed gains which create large overshoot in different operating conditions.

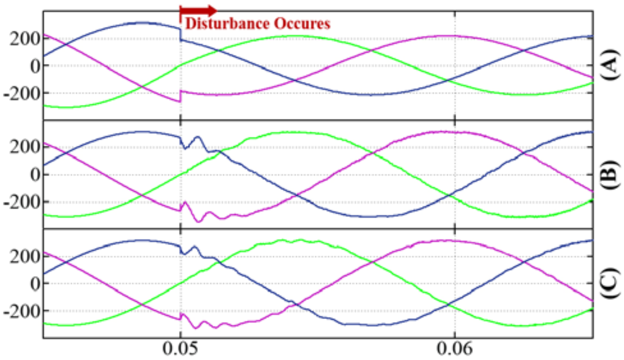


Fig. 15: Comparison of conventional and fuzzy PI controller: 30 % balanced sag: (A) Source voltage, (B) Load voltage with conventional PI controller, (C) Load voltage with fuzzy PI controller.

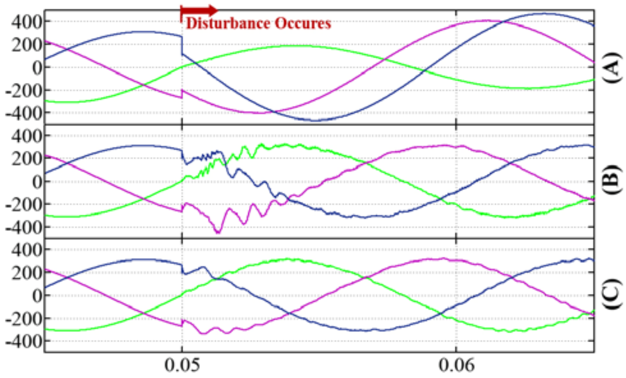


Fig. 16: Comparison of conventional and fuzzy PI controller - unbalanced sag/swell (Phase A: 40 % sag with 0 ° phase shift; phase B: 30 % swell with -30 ° phase shift; phase C: 50 % swell with +45 ° phase shift): (A) Source voltage, (B) Load voltage with conventional PI controller, (C) Load voltage with fuzzy PI controller.

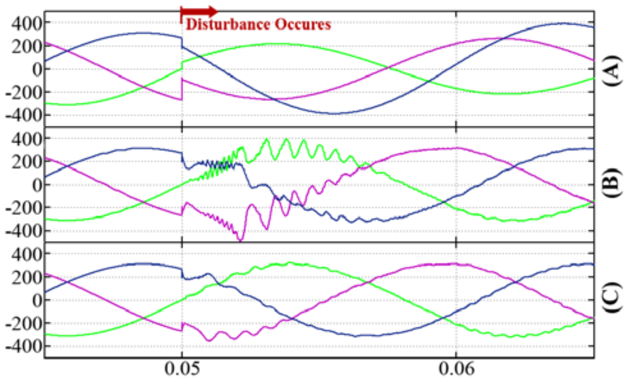


Fig. 17: Comparison of conventional and fuzzy PI controller - unbalanced sag/swell (phase A: 30 % sag with +15 ° phase shift; phase B: 15 % sag with -40 ° phase shift; phase C: 25 % swell with +30 ° phase shift): (A) Source voltage, (B) Load voltage with conventional PI controller, (C) Load voltage with fuzzy PI controller.

7. Conclusion

A DVR topology based on matrix converter utilizing indirect space vector modulation has been analyzed in this paper. The proposed DVR topology is able to compensate balanced sags/swells as well as unbalanced ones and harmonic pollution with acceptable THD for load voltage. The simulation is done in MATLAB/Simulink software. The topology has some advantages such as fast response to voltage disturbances and low cost. Furthermore there is no DC-link and bulky capacitor in the structure so DVR has a compact design; however the number of switches in this topology has increased in comparison with conventional DVR. The controller utilizes a fuzzy PI controller to make an appropriate response during different disturbances with less overshoot and a better damping ratio. That behavior is obtained because the fuzzy PI controller can change its PI gains according to disturbances.

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