A new control method for Dynamic Voltage Restorer with asymmetrical inverter legs based on fuzzy logic controller

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1. Introduction

Due to the advent of a large numbers of sophisticated electrical and electronic equipments, such as computers, program-

A DVR consists of a voltage-source inverter, a series-connected injection transformer, an inverter output filter, and an en-

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 [5]. This

converter injects a dynamically controlled voltage in series with the supply voltage through the three single-phase trans-

formers to correct the load voltage. The main functions of the injection transformer include voltage boost and electrical

isolation [6]. 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

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sags occur [7]. In this paper, battery is used as a source of the DC voltage for the VSC. 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 [5]. A typical DVR connected to the distribution system is shown in Fig. 1.

Different control strategies were proposed for DVR. Voltage-Space Vector PWM was implemented in [8]. Estimation of symmetrical components of voltage to control DVR is used in [9]. Hysteresis voltage control can be adopted to improve voltage quality of sensitive loads [2,10].

In this paper, a DVR with a new inverter topology is presented to suppress the load harmonics and to compensate the voltage disturbances. The adopted voltage-source inverter is based on an asymmetrical inverter leg to achieve five voltage levels in output voltage. This inverter has less voltage harmonics generated on the ac terminal of the inverter compared with two-level PWM operation. In the adopted inverter, on the contrary of conventional inverter, no flying capacitor and clamped diode are used in the circuit configuration. The adopted control scheme is fuzzy logic controller based on hysteresis method.

2. Proposed circuit configuration

Voltage-Source Converter (VSC) is one of the main parts of DVR. Commonly, a symmetrical VSC with two-level output voltage is utilized in DVR. In this paper, a new asymmetrical Voltage-Source Converter is proposed to improve the behavior of DVR. The single-phase configuration of the proposed inverter for DVR is depicted in Fig. 2.

The voltage stress of power switches $S_{a2}$ and $S_{a2}'$ is equal to half of the dc bus voltage and the voltage stress of active switches $S_{a1}$, $S_{a1}'$, $S_{b}$ and $S_{b}'$ is equal to dc bus voltage. In high switching frequency, the power switches placed in arms a and b produce five levels in the output inverter. If the voltage of two capacitors, $V_{c1}$ and $V_{c2}$ are equal, five voltage levels ($V_{dc}$, $V_{dc}/2$, 0, $-V_{dc}$, $-V_{dc}/2$) are produced in the output of inverter [11].

![Fig. 1. Typical DVR circuit topology (single-phase representation).](image1)

![Fig. 2. Adopted single-phase DVR based on asymmetrical inverter legs.](image2)
To produce the mentioned voltage levels in the output, the switches can be defined as follows:

\[ S_{xy} + S_{xy} = 1 \]  

(1)

Therefore, the equivalent circuit of converter can be presented as shown in Fig. 3.

Here \( g_a \) and \( g_b \) represent the switches in leg a and leg b. The ac side to neutral point voltages can be expressed as:

\[ v_{a0} = \frac{g_a(g_a + 1)}{2} v_{c1} - \frac{g_a(g_a - 1)}{2} v_{c1} \]  

(2)

\[ v_{b0} = \frac{g_b(g_b + 1)}{2} v_{c1} - \frac{g_b(g_b - 1)}{2} v_{c1} \]  

(3)

Fig. 3. Equivalent circuit of the adopted DVR.

Fig. 4. Operating states of the adopted inverter: (a) state 1 \((g_a = 1, g_b = -1)\); (b) state 2 \((g_a = 0, g_b = -1)\); (c) state 3 \((g_a = -1, g_b = -1)\); (d) state 4 \((g_a = 1, g_b = 1)\); (e) state 5 \((g_a = 0, g_b = 1)\); (f) state 6 \((g_a = -1, g_b = 1)\).
The ac terminal voltage $V_{ab}$ is expressed as:

$$V_{ab} = V_{a0} - V_{b0} = \frac{g_a - g_b}{2} v_{dc} + \frac{g_a^2 - g_b^2}{2} \Delta v.$$  \hspace{1cm} (4)

If the voltage of capacitors $c_1$ and $c_2$ are equal, therefore, the voltage variation between two capacitor voltages is zero ($\Delta v = 0$). Then, the Eq. (4) can be written as follows:

$$V_{ab} = V_{a0} - V_{b0} = \frac{g_a - g_b}{2} v_{dc}$$  \hspace{1cm} (5)

There are three possible values for switching function $g_a$ and two possible values for $g_b$. Therefore, five different voltage levels, $V_{dc}, V_{dc}/2, 0, -V_{dc}/2$ and $-V_{dc}$, can be generated on the ac terminal voltage $V_{ab}$ \cite{10}. Fig. 4 gives six valid operating states in the adopted inverter to generate five different voltage levels on the ac side of inverter. During the positive mains voltage, the operating states 1–3 are used to generate three voltage levels, $V_{dc}, V_{dc}/2$ and 0, on the ac side to control the inverter. During the negative mains voltage, the operating states 4–6 are selected to generate another three voltage levels, 0, $-V_{dc}/2$ and $-V_{dc}$, on the ac side of the inverter.

3. Conventional control strategy

The possibility of voltage sag compensation can be limited by a number of factors including finite DVR power rating, different load conditions, and different types of voltage sag. Some loads are very sensitive to phase angle jump and others are tolerant to phase angle jump. Therefore, the control strategy depends on the type of load characteristics. There are three distinguishing methods to inject DVR compensating voltage, that is, pre-sag compensation method, in-phase compensation method, and minimal energy method \cite{12–14}. In this paper, the adopted control strategy is pre-sag compensation to maintain load voltage at pre fault value.

3.1. Pre-sag compensation technique

Most nonlinear loads such as thyristor-controlled loads which use the supply voltage phase angle as a set point are sensitive to phase jumps. To overcome this problem, this technique compensates the difference between the sagged and the pre-sag voltages by restoring the instantaneous voltages to the same phase and magnitude as the nominal pre-sag voltage. The drawback is the capacity limitation of energy-storage device for the injection of real power.

Fig. 5 shows the single-phase vector diagrams of the pre-sag compensation where $V_s$, $V_L$, $V_{DVR}$, and $V_{L_{pre-sag}}$ mean the magnitudes of the voltage vectors that are explained in Fig. 5 and Eq. (3). In this method, the load voltage can be restored ideally. When a fault occurs in other lines, the left hand side voltage of DVR, i.e., $V_s$ drops and the DVR injects a series voltage, $V_{DVR}$ through the injection transformer as:

$$V_{DVR} = V_L - V_s$$  \hspace{1cm} (6)

$$\alpha = \tan^{-1}\left(\frac{V_{pre-sag} \sin(\delta)}{V_{pre-sag} \cos(\delta) - V_{sag}}\right)$$  \hspace{1cm} (7)

3.2. In-phase compensation technique

In in-phase compensation technique shown in Fig. 6, the injected DVR voltage ($V_{DVR}$) is in phase with measured supply voltage ($V_s$) regardless of the load current and the pre-sag voltage.
$I_L$ and $\varphi$ are load current and load power angle, respectively. The magnitude of $V_{DVR}$ is so that the magnitude of $V_L$ is 1 pu.

\[ V_{DVR} = 1 - V_s \]  

(8)

The advantage of this method is that the magnitude of the injected voltage is minimum. Therefore, for a given load current and voltage sag the apparent power of DVR is minimized.

3.3. Minimal energy technique

Another existing control strategy is to use as much reactive power as possible to compensate the sag. Therefore, the DVR voltage is controlled in such a way that the load current is in phase with the grid voltage after the sag. As long as the voltage sag is quite shallow, it is possible to compensate sag with pure reactive power and therefore, the compensation time is not limited. Fig. 7 shows the phasor diagram for the minimal energy control strategy. In this diagram, $\delta$, $\alpha$ are the angles of $V_L$ and $V_{DVR}$, respectively. In this case, $\alpha$ can be obtained as:

\[ \alpha = \frac{\pi}{2} - \varphi + \delta \]  

(9)

and the $\delta$ is calculated by the following equation:

\[ \delta = \varphi - \cos^{-1} \left( \frac{V_L \cdot \cos(\varphi)}{V_s} \right) \]  

(10)

If the supply voltage parameters satisfy the following condition then the value of $\delta$ is feasible.

\[ V_L \cdot \cos(\varphi) \leq V_s \]  

(11)

Inequality (11) means that the level of voltage sag is shallow sag. Therefore, injected active power of DVR is zero and the optimum $\alpha$ is obtained from (9). If inequality (11) is not satisfied then level of voltage sag will be deep sag and injected active power is not zero.
4. Proposed method

The main considerations for the control system of a DVR include: detection of the start and finish of the sag, voltage reference generation, transient and steady-state control of the injected voltage, and protection of the system. The control system presented in Fig. 8 is used to control the DVR.

As it is shown in Fig. 8, \( V_s \) is the supply voltage used to detect voltage sag and \( V_L \) is the load voltage which is used as a feedback of the output voltage.

A new hysteresis voltage control using a user defined fuzzy logic controller in Matlab software is implemented to improve the DVR performances in fault and abnormal conditions. The following sections, describe the controller unit of DVR in detailed.

4.1. Voltage sag detection

The essential part for well-performance of controller in DVR is the sag detection circuit. Voltage sag must be detected fast and corrected with a minimum of false operations. The voltage sag detection method is based on Root Means Square (RMS) of the error vector which allows detection of symmetrical and asymmetrical sags, as well as the associated phase jump. The controller system is presented in Fig. 8.

The three-phase supply voltage is transformed from abc to odq frame using park transformation. Phase Locked Loop (PLL) is used to track supply voltage phase. The park transformation matrix is shown as follows:

\[
\begin{bmatrix}
V_d \\
V_q \\
V_o
\end{bmatrix}
= \frac{1}{\sqrt{3}}
\begin{bmatrix}
\cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\
\sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

\( \theta = \theta_0 - \int_0^t \omega dt \)  

\( |V_s| = \sqrt{V_d^2 + V_q^2} \)  

Closed loop load voltage feedback is added, and is implemented in the o-d-q frame in order to minimize any steady-state error in the fundamental component \([2,15,16]\).

When the grid voltage is normal, the DVR system is held in a null state to lower its losses. When voltage sag is detected, the DVR switches into active mode to react as fast as possible to inject the required ac voltage. The injection voltage is also generated according to the difference between the reference load voltage and the supply voltage and it is applied to the VSC to produce the preferred voltage, using the Hysteresis Voltage Control based on fuzzy logic controller.

4.2. Hysteretic voltage control combined with fuzzy logic controller

There are different methods to produce the signals needed for VSC switching. This part presents a new control approach which is based on hysteresis voltage control combined with fuzzy logic control method. Comparing with previous approaches the proposed method is able to extend its control capability even to those operating conditions where linear control techniques fail.
4.2.1. Hysteretic voltage control

The hysteretic voltage control method is one of the several approaches which have been introduced to produce switching signals.

A hysteresis band voltage control scheme composed of a hysteresis band around the reference voltage is shown in Fig. 9. Three-phase reference Voltages are obtained by subtraction of pre-sag voltages from three-phase detected voltages. This method is based on the difference between the voltage produced by the converter and the reference voltage [2,17]. The upper and lower bands are defined by hysteresis band width (HB). As long as the difference between reference voltage and the produced converter voltage remains between the bands, the switching signal will not change. If the difference reaches to the upper or (lower) bands, the signal causes the switch to turn off (turn on) [2,17].

The switching frequency of the hysteresis band voltage control method described above depends on how fast the voltage changes from the upper limit of the hysteresis band to the lower limit of the hysteresis band, or vice versa. Therefore, the switching frequency does not remain constant throughout the switching operation, but varies along with the voltage reference wave form.

Fig. 9. Hysteresis band voltage control.

Fig. 10. Schematic of implemented method.

Fig. 11. Block diagram of fuzzy controller.
The hysteresis band voltage control is characterized by unconditioned stability, very fast response, needless from any information about system parameters and good accuracy. On the other hand, the basic hysteresis technique also exhibits several undesirable features; such as uneven switching frequency that causes acoustic noise and difficulty in designing input filters [2,18].

Table 1
Rule bases of voltage fuzzy controller.

<table>
<thead>
<tr>
<th></th>
<th>NL</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
</tr>
<tr>
<td>Z</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
</tr>
<tr>
<td>P</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
<td>$S_{a1}$, $S_{a2}$, $S_a$</td>
</tr>
</tbody>
</table>

Fig. 12. Input and output membership functions of voltage controller.
4.2.2. Fuzzy logic controller

The switching frequency of hysteresis control method with constant band width is high. This will make the system loss considerable. In order to produce a five level voltage at the converters output, to reduce the switching losses and to improve the behavior of DVR, fuzzy controller method is utilized. Fuzzy logic control (FLC) is based on mamdani's system.

The fuzzy controller has two inputs:

- The difference between the injected voltage and the reference voltage.
- The derivation of the error.

Moreover it has six outputs, the driving signals of switches. Considering the difference between converter output voltage and reference voltage and its derivation, the controller determines the voltage condition and directly commands the switches to turn on or off. In conventional hysteresis voltage control, switching signals are determined when the error reaches to upper or lower hysteresis band but as it is shown in Fig. 9, in this new proposed method, switching commands are determined according to the error and derivation of the error. The schematic of implemented method is shown in Fig. 10.

The fuzzy logic controller consists of three stages: the fuzzification, rule execution, and defuzzification. In the first stage, the crisp variables \( e(k) \) and \( de(k) \) are converted into fuzzy variables \( E(k) \) and \( dE(k) \) using the triangular membership functions shown in Fig. 11. Triangular membership functions are chosen to have smooth and constant region in the main points. \( E(k) \) is divided into five fuzzy sets: NL (negative large), NS (negative small), ZE (zero), PS (positive small) and PL (positive large); and \( dE(k) \) is divided into three fuzzy sets: N (negative), ZE (zero), P (positive).

In the second stage of the FLC, the fuzzy variables \( E \) and \( dE \) are processed by an inference engine that executes a set of control rules contained in (10) rule bases. The control rules are formulated using the knowledge of the DVR behavior. The rules are expressed in Table 1:

Different inference algorithms can be used to produce the fuzzy set values for the output fuzzy variables \( S_{a1}, S_{a2}, S_{b1}, S_{b2}, S_b, S_p \). In this paper, the max–min inference algorithm is used, in which the membership degree is equal to the maximum of the product of \( E \) and \( dE \) membership degree.

The inference engine output variables are converted into the crisp values in the defuzzification stage. Various defuzzification algorithms have been proposed in the literature. In this paper, the centroid defuzzification algorithm is used, in which the crisp value is calculated as the centre of gravity of the membership function. Fig. 12 shows inputs and output membership functions.

The definition of the spread of each partition, or conversely the width and symmetry of the membership functions, is generally a compromise between dynamic and steady-state accuracy.

5. Simulation results

To prove the capabilities of the above-mentioned control methods, the test system is modeled with MATLAB/Simulink (ver. 7) and SimPower-System block set. Total Harmonic Distortion (THD) is also calculated to verify the efficiency and well-performance of the proposed control method. The supply network is modeled as an ideal voltage source; the injection transformer has been modeled as a linear element. The transformer winding’s resistances and core saturation effect were neglected. The inverter is modeled as a typical two-pulse inverter with transistors assumed to be ideal switches. Losses in the inverter were modeled as a resistance connected to the DC side capacitor. The rest of the components have been assumed to be ideal ones, and standard SimPower System block set elements were used. The parameters of the case study are presented in Tables 2 and 3. In the simulated model, the following abnormal conditions are considered:

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Case study parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Supply voltage (( V_{L-L} ))</td>
<td>400 V</td>
</tr>
<tr>
<td>( V_{dc}, C_p, R_f )</td>
<td>200 V, 500 μF, 1 Ω</td>
</tr>
<tr>
<td>Series transformer (( V_{ph-ph} ))</td>
<td>96/240 V</td>
</tr>
<tr>
<td>( Z_{trans} )</td>
<td>0.004 + j 0.008</td>
</tr>
<tr>
<td>( R_{load}, L_{load} )</td>
<td>31.84 Ω, 0.139 H</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Parameters of induction motor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>380 V</td>
</tr>
<tr>
<td>Nominal supply frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rated output power</td>
<td>3 kW</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.82</td>
</tr>
<tr>
<td>Nominal speed, no. of poles</td>
<td>1430 rpm, 4</td>
</tr>
</tbody>
</table>
5.1. Resistive load and balanced voltage sag

The first simulation is carried out for a balanced voltage sag and linear resistive load (85 $\Omega$). The PCC voltage drops to 70% of its nominal value from 0.1 to 1.8 s as shown in Fig. 13.

The DVR injected voltages and load voltages are shown in Fig. 13a and b.

Fig. 13. Simulation result of DVR response for a balanced voltage sag and linear resistive load.

5.1. Resistive load and balanced voltage sag

The first simulation is carried out for a balanced voltage sag and linear resistive load (85 $\Omega$). The PCC voltage drops to 70% of its nominal value from 0.1 to 1.8 s as shown in Fig. 13.

The DVR injected voltages and load voltages are shown in Fig. 13a and b.
As it can be seen from the results, the DVR is able to produce the required voltage components for different phases rapidly and help to maintain a balanced and constant load voltage at the nominal value (400 V) during fault condition.

Fig. 14. Simulation result of DVR response for a balanced voltage sag and induction motor load.
5.2. Induction motor load and balanced voltage sag

The parameters of the induction motor are listed in Table 3. Similar to the previous case, PCC voltage drops to 30% of its voltage nominal value from 0.1 s and it is kept until 0.18 s. The PCC sag and DVR injected voltages are shown in Fig. 14. It can be observed that with starting of induction motors load voltage drops to 30% of its voltage nominal value. The DVR would inject the compensating voltage immediately after PCC voltage sag is detected; to maintain load voltages at desired level.

**Fig. 15.** Simulation result of DVR response for a balanced voltage sag and nonlinear load.

5.2. Induction motor load and balanced voltage sag

The parameters of the induction motor are listed in Table 3. Similar to the previous case, PCC voltage drops to 30% of its voltage nominal value from 0.1 s and it is kept until 0.18 s. The PCC sag and DVR injected voltages are shown in Fig. 14. It can be observed that with starting of induction motors load voltage drops to 30% of its voltage nominal value. The DVR would inject the compensating voltage immediately after PCC voltage sag is detected; to maintain load voltages at desired level.
5.3. Nonlinear load and balanced voltage sag

In this case, the nonlinear load is a diode rectifier bridge with a capacitor bank (200 μF) and resistive load (80 Ω) connected in parallel. Again, the PCC voltage drops to 70% of its nominal value from 0.1 s and lasts for four cycles. The PCC voltages and DVR injected voltages are shown in Fig. 15. It can be observed that with nonlinear load connected at downstream, the PCC voltages, DVR injected voltages, and load voltages become slightly distorted.

Fig. 16. Simulation result of DVR response for a unbalanced voltage sag and linear load.

5.3. Nonlinear load and balanced voltage sag

In this case, the nonlinear load is a diode rectifier bridge with a capacitor bank (200 μF) and resistive load (80 Ω) connected in parallel. Again, the PCC voltage drops to 70% of its nominal value from 0.1 s and lasts for four cycles. The PCC voltages and DVR injected voltages are shown in Fig. 15. It can be observed that with nonlinear load connected at downstream, the PCC voltages, DVR injected voltages, and load voltages become slightly distorted.
As it can be observed from simulation results, DVR is capable to detect the voltage sag quickly and compensate the load voltage satisfactorily.

5.4. Unbalanced voltage sag

In this case, there is a 30\% three-phase voltage sag with +30° phase jump in phase-a. Voltage is started at \( t = 0.1 \) s and it is kept until 0.18 s. Fig. 16 shows the result of voltage sag compensation using hysteresis voltage control based on fuzzy controller. As it can be seen from the results, DVR is able to produce the required voltage for different phases rapidly and a balanced and constant load voltage at the nominal value (400 V) is provided.

The calculated THD in all simulation case studies are described in Table 4. According to IEEE standard, the THD in distribution networks should be under 5\% and as it can be seen in Table 4, the calculated THD satisfy the IEEE standard range.

6. Conclusion

This paper investigates a new control approach which is based on hysteresis voltage control combined with fuzzy logic control method. All parameters and structures such as study system, and control unit are described in details. The validity of proposed method is approved by results of the simulation in MATLAB/Simulink for different voltage sag condition. As it can be seen, the new model of DVR with the presented control method is capable to compensate networks faults and mitigate their effects on sensitive loads in distribution power systems.

THD is also calculated to evaluate the quality of the load voltage during the operation of DVR. The simulation results show that the calculated THD in sag conditions fulfill IEEE 519 std. range. The effectiveness of the proposed DVR controller in rejecting load voltage disturbance is proved by the good performance of the DVR under different loading conditions.

References


Table 4
THD for load voltage in all simulation case studies.

<table>
<thead>
<tr>
<th>Simulation case studies</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive load and balanced voltage sag</td>
<td>0.12</td>
</tr>
<tr>
<td>Induction motor load and balanced voltage sag</td>
<td>0.2</td>
</tr>
<tr>
<td>Nonlinear load and balanced voltage sag</td>
<td>0.17</td>
</tr>
<tr>
<td>Unbalanced voltage sag</td>
<td>0.16</td>
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