Advanced DVR with Elimination Zero-Sequence Voltage Component for Three-Phase Three-Wire Distribution Systems

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Dynamic Voltage Restore (DVR) is a power electronics device to protect sensitive load when voltage sag occurs. The magnitude and phase of compensated voltage in DVR depend on grounding system and type of fault. If the system is floating, the zero sequence components do not appear on the load side. Meanwhile, in a neutral grounded system, voltage sag is extremely affected by zero sequence components. This paper presents new method to mitigate unbalance voltage sag caused by zero sequence components. To avoid the impact of zero sequence components, in this simulation the value of zero axis components is determined by using d-q-0 axis method. From simulation result shows that this method able to compensate voltage sag with compensation error is 0.99%.

Keywords: voltage sag, DVR, zero sequence components

1. Introduction

According to EPRI report (1995), the revenue losses due to poor power quality in U.S. business were $400 billion per year (1). Power quality problems are caused by dynamic or non-linear loads and interaction between the load and network. Two of the main problems in the field of power quality are voltage sag and instantaneous power loss. In addition, voltage sag has two main parameters including magnitude and time duration (2). DVR is one of the best devices mitigating short voltage sag. DVR can provide the most cost effective solution to mitigate voltage sags by establishing the proper voltage quality level that is required by customer. When a fault happens in a distribution network, sudden voltage sag will appear on adjacent loads. DVR installed on a sensitive load restores the line voltage to its nominal value within the response time of a few milliseconds. Most of the DVR design studies are based on the assumption of the balanced three-phase system. And almost all the researches are on the three-phase three-wire systems (3)-(4). Under the foregoing assumption, only the restoration of positive-sequence and the compensation of negative sequence are taken into consideration, while zero-sequence components are ignored. But the real power plant and distribution systems are generally using neutral grounding. Therefore the zero-sequence components will appear due to ground fault in the system. Zero-sequence currents can cause large voltage drops because of the voltages induced by the coupling inductances of the lines. Thus the influence of the zero-sequence components must be considered when a DVR is designed (5). This paper presented DVR uses d-q-0 axis method which concerns zero sequence voltage compensation to compensate voltage sags in distribution system with neutral grounding. The detailed switching DVR is modeled by Matlab and the control scheme to eliminate zero-sequence voltage is proposed.

2. Voltage Sag in Distribution System

According to IEEE Standard, voltage sags can be defined as rms variation with a magnitude between 10 % to 90 % of nominal voltage and duration between 0.5 cycles to one minute. Voltage sags are caused by fault such as short circuits, overload and starting of large motor. Voltage sags are the most common power disturbance which certainly gives the impact especially to the several types of equipment : adjustable speed drives, process control equipment, and computers are notorious for their sensitivity (6). Model of distribution system is depicted in Figure 1. Which is radial and has a power plant with neutral grounded system. In this model, power plant has

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Fig. 1. Model of distribution system
rated capacity of 10 MW, 6.6 kV; both of feeder are equal R = 0.2024 Ohm, L = 2.84 mH; normal load is P = 4 MW, Q = 1 MVAR; Sensitive load is P = 5 MW, Q = 1 MVAR. Most of the faults in power systems are single phase to ground fault. When single fault occurs in normal load bus feeder, sensitive load feeder will suffer voltage sag. Phasor of three voltage vectors diagram for single phase fault is depicted in Fig. 2. Before fault occur, voltage in sensitive load bus can be described using following equation:

\[
\begin{align*}
V_a &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \cr V_b \cr V_c \end{bmatrix} \\
V_b &= \begin{bmatrix} -\frac{1}{2} & -\frac{1}{2} & \frac{j\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \cr V_b \cr V_c \end{bmatrix} \\
V_c &= \begin{bmatrix} -\frac{1}{2} & -\frac{1}{2} & \frac{j\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \cr V_b \cr V_c \end{bmatrix}
\end{align*}
\]  

(1)

During fault, the voltage mentioned in equation 1 can be replaced with

\[
\begin{align*}
\bar{V}_a &= V \cos \delta + jV \sin \delta \\
\bar{V}_b &= -\frac{1}{2} + \frac{1}{2}j\sqrt{3} \\
\bar{V}_c &= -\frac{1}{2} - \frac{1}{2}j\sqrt{3}
\end{align*}
\]  

(2)

Where V is voltage sag magnitude and \( \delta \) is phase angle jump. Zero sequence components during fault can be obtained by

\[
\bar{V}_o = \frac{1}{3}(V_a + V_b + V_c)
\]

\[
\bar{V}_a = \frac{1}{3}(V \cos \delta + jV \sin \delta - 1)
\]  

(3)

In the equation 3, the resultant of three vectors is not zero, it means that zero sequence components are generated during ground fault. Therefore the process of eliminating the zero sequence components is required.

### 3. Dynamic Voltage Restorer

DVR is power electronics device which is installed in series with the distribution line system as can be seen in Figure 3. DVR uses semiconductor device to maintain voltage of sensitive load by injecting voltage whose magnitude and phase can be controlled. The DVR is able to control the voltage across a sensitive load by injecting an appropriate voltage phasor through an injection transformer. Nominal voltage will be compared with voltage sags in order to get a injected voltage by DVR.
Basically, the ideal DVR injection voltage can be obtained as following

\[ V_{inj} = V_{ref} - V_{sag} \]  \( (4) \)

Where \( V_{inj} \) is DVR injection voltage, \( V_{ref} \) is reference pre-fault voltage and \( V_{sag} \) is voltage sags. Basic DVR phasor diagram depicted in Figure 4.

### 4. Conventional Control Scheme

The simple diagram of conventional control scheme of DVR is shown in Figure 5. Transformation of \( a\)-\( b\)-\( c\) to \( d\)-\( q\)-\( 0\) axis makes it easier for the control system to work. Control using the \( d\)-\( q\)-\( 0\) transformation also avoids the processing delay inherent in working with root mean square phasor values. Value of parameters \( V_{d ref} = 1 \) and \( V_{q ref} = 0 \).

Almost all conventional DVR use wye-delta transformer to block zero sequence components. Therefore, control method concern only \( d \) and \( q \) components. Conversion of \( a\)-\( b\)-\( c\) to \( d\)-\( q\)-\( 0\) axis is shown in equation 5.

\[
\begin{bmatrix}
V_d \\
V_q \\
V_0
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & \frac{1}{2} & \frac{1}{2} \\
\sin(\alpha) & \cos(\alpha) & 0 \\
\cos(\beta) & \sin(\beta) & 0
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]  \( (5) \)

On distribution system without zero sequence component (floating or using delta winding), during ground fault \( V_0 \) in \( d\)-\( q\)-\( 0\) axis is 0. But in system distribution with neutral grounding, during ground fault \( V_0 \) in \( d\)-\( q\)-\( 0\) axis is not 0. Zero sequence components in \( d\)-\( q\)-\( 0\) axis during ground fault can be obtained by

\[
V_0 = \frac{1}{3} (V_a + V_b + V_c) \]  \( (6) \)

Because this control method is concerned with only \( d \) and \( q \) components, this scheme cannot compensate for zero sequence components.

### 5. Proposed Control Scheme

Proposed control scheme in simplified block diagram of DVR is shown in Figure 6. Voltage sag restorer method employed is the comparison between real time voltage and voltage in \( a\)-\( b\)-\( c\) axis converted to \( d\)-\( q\)-\( 0\) axis, using \( d\)-\( q\)-\( 0\) reference voltage. Reference voltages are taken of \( V_{d ref} = 1 \), \( V_{q ref} = 0 \) and \( V_{0 ref} = 0 \).

The difference \( V_{ref} \) with measurement is the error signal which shows the value of voltage drop \( \Delta V \). It is clear that not only \( d\)-\( q\) voltage is being compensated as many researches did, but also \( d \), \( q \), and \( 0 \), so that the asymmetrical voltage sag (consisting of zero sequence component) can be restored.

This paper using fuzzy polar application method (7)-(8) to improve the conventional PI compensator 9. Fuzzy polar consists of 3 basic parameters: derivative multiplier \( (As) \), the angle membership function \( (\alpha) \), and radius membership function \( (Dr) \). Operation values of polar coordinate are shown in equations 7 to 9.

\[
p(k) = [Zs(k) As\theta(k)]
\]  \( (7) \)
Given the input signal $Z_s$, the controller need the signal derivative to get $Z_a$. Point $p(k)$ is represented by input $Z_s$ as $x$ axis and $Z_a$ as $y$ axis. To be used for fuzzy polar controller, input form $p(k)$ in rectangular form should be transformed to polar form, $D(k)$ as magnitude and $\theta(k)$ is the angle. The polar form of fuzzy polar is shown in Figure 7.

The other factors which is also needed in this control system is maximum control signal $U_{max}$. Defuzzification rule as fuzzy polar output ($U$) for the control system is shown in equation 10 (10).

$$U(k) = G(D(k)) [N(\theta(k)) + P(\theta(k))] U_{max} \tag{10}$$

Where $U_{max}$ is the maximum allowable control signal, $G(D(k))$ is the membership value of magnitude $D(k)$, while $N(\theta(k))$ and $P(\theta(k))$ are membership value of the angle $\theta(k)$. Membership function of fuzzy polar is shown in Figure 8.

Error signal $\Delta V_d$, $\Delta V_d'$, $\Delta V_q$, $\Delta V_q'$, $\Delta V_0$, and $\Delta V_0'$ are then transformed to polar $d$-$q$-$0$ form using equations, 7, 8, and 9. The result becomes the input of fuzzy polar control. Figure 9 is the simple model of fuzzy polar with 1 input and 1 output. In reality, there is only one input, $Z_s$. But it needs derivative signal $Z_a$ so that it can be converted to polar coordinate by equations 7, 8, 9.

Result of error compensation from fuzzy polar control is control signal which shows the value of the voltage will be injected to the system by the inverter.

6. Result

Simulation was done using Matlab SimPower System. Simulation duration is 4 cycles. Parameters of fuzzy polar are shown in table 1. It is simulated that a short circuit fault occurs in normal load bus (Fig. 1) for 2 cycles, which causes voltage sag in sensitive load bus. DVR installation in sensitive load bus is intended to restore the voltage which is distorted by sag. To see the proposed control scheme performance, sags of 30%, 50%, and 70% in sensitive load bus will be simulated. Voltage sag caused by two phase to ground fault and the compensated voltage are shown in Fig. 10 and Fig. 11. Fuzzy polar DVR can restore the voltage up to 99.08 % as seen in Fig. 11. Fig. 12 shows the value of zero sequence voltage in sensitive load bus using conventional DVR control scheme. Fig. 13 shows the value of zero sequence voltage at sensitive load bus using proposed control scheme. From Fig. 12 and Fig. 13 can be seen that the value of zero sequence voltage
7. Conclusion

DVR with the technique of elimination zero sequence at distribution system 3 phase 3 wire use neutral grounding was modeled by Matlab SimPower System and fault caused by zero sequence in distribution system was simulated and analyzed. Also, the effects of zero-sequence components were simulated and discussed. This method can reduce zero-sequence components very well. Simulation results show that DVR using this method can restore both symmetrical and asymmetrical voltage sags very well.

Table 2. Voltage sag and harmonics restoration.

<table>
<thead>
<tr>
<th>Voltage Sag</th>
<th>Restoration (%)</th>
<th>Error (%)</th>
</tr>
</thead>
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<tr>
<td>30 % GF</td>
<td>99.02</td>
<td>0.98</td>
</tr>
<tr>
<td>50 % GF</td>
<td>98.95</td>
<td>1.05</td>
</tr>
<tr>
<td>70 % GF</td>
<td>98.94</td>
<td>1.06</td>
</tr>
<tr>
<td>30 % 2F</td>
<td>98.81</td>
<td>1.19</td>
</tr>
<tr>
<td>50 % 2F</td>
<td>98.85</td>
<td>1.15</td>
</tr>
<tr>
<td>70 % 2F</td>
<td>98.91</td>
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<td>99.08</td>
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</tr>
<tr>
<td>70 % 2FG</td>
<td>99.05</td>
<td>0.95</td>
</tr>
<tr>
<td>30 % 3F</td>
<td>99.24</td>
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</tr>
<tr>
<td>50 % 3F</td>
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<td>0.98</td>
</tr>
<tr>
<td>70 % 3F</td>
<td>98.96</td>
<td>1.04</td>
</tr>
</tbody>
</table>


Appendix

GF : ground fault.
2F : phase-phase fault
2FG : phase-phase-ground fault
3F : 3-phase-fault

Bibliography

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