Study on Dynamic Voltage Restorer Compensation Strategy

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Abstract: In the research data about power quality, it is shown that voltage sag is the worst power quality problem, which can bring the most losses in various power quality problems. Dynamic voltage restorer (DVR) is the most effective solution to suppress the voltage sag. The compensation effect of DVR can be affected by the compensation strategy. Based on the analysis of existing compensation strategy, the optimized compensation strategy of load voltage is proposed in this paper. The simulation results show that the optimized compensation strategy can give attention to both the capacity of DVR and the compensation effect of the load side voltage.

1. Introduction
Dynamic voltage restorer (DVR) is an effective device for solving voltage sags. DVR can compensate the difference between the fault voltage and normal voltage by the output specific voltage, to maintain the stability of the load side voltage, and ensure the normal operation of critical electrical equipment. In the whole process of compensation, the active power exchange is need between DVR and power system. The exchange process will affect the capacity and structure of the DC energy storage unit and corresponding charging unit, which determines the manufacturing and running costs of DVR. Therefore, to realize the optimization compensation of the voltage sags, we need to have a reasonable DVR compensation strategy[1-3].

2. Compensation strategy analysis
The compensation strategy is a reasonable choice to the amplitude and phase of the injected voltage, so that the DVR can achieve greater voltage compensation and the minimum active power loss under a certain capacity [4-6].
Figure 1. Compensation principle diagram

The notations in Figure 1 can be fixed as follows: \( U_s \) denote the system-side voltage after drop, \( U_L \) denote the load-side voltage after compensation, \( U_{DVR} \) denote output compensation voltage of the DVR, \( U_L^i \) denote the load-side voltage before the drop, \( I \) denote load current, \( \alpha \) denote the phase jump angle after the compensation, \( \theta \) denote the system voltage phase angle after drop, \( \varphi \) denote power factor angle of load.

Firstly, the following three existing compensation strategy is needed to analyze, the analysis reference fig.1 and assumes that the system voltage and load power factor angle is constant in voltage sag.

2.1. Load-voltage fixed compensation

The strategy is considered from the point of the load voltage. Under the compensation, the load will not be affected by the voltage sag. In this kind of compensation strategy, \( U_L = U_L^p \), the phase jump angle \( \alpha = 0 \), that is, the load voltage is exactly the same as before voltage sag. At this time, DVR injection voltage can be given as

\[
U_{DVR} = (U_s^2 + U_L^2 - 2U_L U_s \cos \theta)^{1/2}.
\]

2.2. Same-phase voltage compensation

The strategy is considered from the voltage compensation capability of DVR. In this compensation strategy, there is a phase jump, phase jump angle \( \alpha = \theta \). The same-phase compensation method is only to compensate the magnitude of the drop voltage, which is not to compensate the phase of the drop voltage. Due to the phase deviation of the voltage sag, this result causes that the compensated voltage is discontinuous. The advantage of this strategy is that the injection voltage is the minimum, and can be given as \( U_{DVR} = U_L - U_s \).

2.3. Minimum active power compensation

The strategy is considered from the point of the compensation energy of DVR. Under this strategy, the active power output of the DVR is minimal, which can get a longer compensation time in the case of limited compensation capacity. At this time, the phase jump angle can be calculated from:

\[
P_{DVR} = U_{DVR} I \cos \beta = U_s I \cos \varphi - U_L I \cos (\varphi + \theta - \alpha)
\]

If \( \frac{dP_{DVR}}{d\alpha} = 0 \), \( \alpha = \varphi + \theta \) and \( P_{DVR}^{\text{min}} = U_s I \cos \varphi - U_L I \) can be calculated.

Because the DVR active power output cannot be less than zero, which can avoid power flow backward problem. So if \( U_s > U_L \cos \varphi \), taking \( P_{DVR}^{\text{min}} = 0 \), then can be achieved as follows: \( \alpha = \varphi + \theta - \arccos\left(\frac{U_L \cos \varphi}{U_s}\right) \).

From the above analysis, it can be seen that the load-voltage fixed compensation achieve a minimum voltage phase jump angle. The maximum voltage compensation were achieved by the
same-phase voltage compensation, and maximum energy compensation were achieved by the minimum active power compensation. Three kinds of compensation can be considered as single-objective optimization problem. Each compensation strategy can obtain a different compensation effect by reasonable solving the objective function.

In three-phase systems, assuming the three-phase load is symmetrical, and the load power and power factor are constant, the DVR output power can be shown as:

$$P_{DVR} = 3U_L I \cos \phi - \sum_{i=1}^{3} U_{is} I \cos(\phi + \theta_i - \alpha)$$  \hspace{1cm} (1)

Obtain the derivative of $P_{DVR}$ to $\alpha$, and make it equal to zero:

$$\frac{dP_{DVR}}{d\alpha} = -\sum_{i=1}^{3} U_{is} I \sin(\phi + \theta_i - \alpha) = 0$$

Can be simplified as:

$$\tan(\alpha - \phi) = \frac{\sum_{i=1}^{3} U_{is} \sin \theta_i}{\sum_{i=1}^{3} U_{is} \cos \theta_i}$$

Can be solved

$$\alpha = \phi + \arctan\left(\frac{\sum_{i=1}^{3} U_{is} \sin \theta_i}{\sum_{i=1}^{3} U_{is} \cos \theta_i}\right)$$  \hspace{1cm} (2)

The same as the previous analysis, DVR power flow backward problem cannot occur, so $P_{DVR}$ can be obtained when $\alpha$ taken the above-mentioned values by solving.

1) when $3U_L \cos \phi < D$, then $P_{DVR}^{\text{min}}=0$;

2) when $3U_L \cos \phi \geq D$, then $\alpha = \phi + \arctan\left(\frac{\sum_{i=1}^{3} U_{is} \sin \theta_i}{\sum_{i=1}^{3} U_{is} \cos \theta_i}\right)$

And $P_{DVR}^{\text{min}} = 3U_L I \cos \phi - ID$

In the formula $D = \sqrt{\left(\sum_{i=1}^{3} U_{is} \sin \theta_i\right)^2 + \left(\sum_{i=1}^{3} U_{is} \cos \theta_i\right)^2}$

The injection voltage of DVR can be represented by:

$$U_{is}^{\text{DVR}} = \sqrt{U_{is}^2 + U_L^2 - 2U_{is} U_L \cos(\alpha - \theta_i)} \hspace{1cm} (i = 1, 2, 3)$$  \hspace{1cm} (3)

Obviously can obtain $U_{is}^{\text{DVR}} = U_L - U_{is}$, when $\alpha = \theta_i$

3. Proposed new compensation strategy

Based on the above analysis, we can get the following compensation strategy. When the system voltage sag occurs, DVR is used to provide energy and compensate for the voltage sag, which can ensure the normal voltage of load. Due to the asymmetry of voltage sags, according to the symmetrical component method of fault voltage decomposition, considering only the positive sequence component, the DVR injected voltage and output energy only is decided by positive sequence component [7]. Assuming the system-side phase is $\theta_1, \theta_2, \theta_3$ after three-phase voltage sag, and the fall of the three-phase voltage are within the scope of compensation, then DVR each phase the optimization compensation strategy is as follows:

1) When the system voltage sag is in the range of DVR compensation, the optimization
compensation strategy can be carried out at this time;

2) Under $3U_l \cos \varphi \geq D_\varphi$, the power flow backward problem is not presented when compensation occurs. The minimum energy compensation phase jump angle choice the minimum absolute value in the interval $[-\pi, \pi]$, which satisfy the conditions $\alpha = \varphi + \arctan\left(\frac{\sum_{i=1}^{3} U_{is} \sin \theta_i}{\sum_{i=1}^{3} U_{is} \cos \theta_i}\right)$. If the phase angle $\alpha_{opt} = \alpha$, compensation energy is beyond DVR compensation power limit, and $\alpha_{opt} = \theta_j$ compensation voltage value is beyond injected voltage limit, then the DVR cannot compensate for voltage sag. If the phase jump angle meet compensation power limit or injected voltage limit, then the optimal phase jump angle $\alpha_{opt} = \begin{cases} \alpha + \delta & |\alpha| < |\theta_j| \\ \theta_j + \delta & |\alpha| \geq |\theta_j| \end{cases}$ (where $\alpha$ is the minimum energy compensation phase jump angle, $\theta_j$ is the same-phase voltage compensation phase jump angle, and $\delta$ is smaller boundary value to $\alpha_{opt}$ satisfy the compensation power or injected voltage limit of DVR, that the specific numerical can be obtained by formula (1), (3)).

3) When $3U_l \cos \varphi < D_\varphi$, the power flow backward problem should be considered. When DVR output active power is zero, in the interval $[-\pi, \pi]$ generally have two eligible values, select smaller the absolute value $\alpha = \varphi + \theta_j - \arccos\left(\frac{U_l \cos \varphi}{U_s}\right)$. When $|\alpha| \geq |\theta_j|$ and $\alpha$ is within the DVR limit injected voltage, the optimal phase jump angle $\alpha_{opt} = \alpha$ is taken, and the DVR can only provide the reactive power to the load at the same time. When $|\alpha| < |\theta_j|$ and $\alpha$ is within the DVR limit injected voltage, the optimal phase jump angle $\alpha_{opt} = \alpha + \delta$, the value of $\delta$ should make the compensation voltage in the DVR provide voltage range, to reduce injection voltage magnitude.

For three-phase system, firstly, the DVR injected voltage range should considered the obtained intersection interval of three-phase voltage range. The phase jump angle of the minimum active power compensation can be calculated, and then it can be considered as a single-phase voltage range and compensated by above methods.

In the actual operation, the phase jump angle of the load voltage is determined according to the nature of the sensitive load to be protected, and the phase change of the compensation strategy must be within the allowable range of the load. For voltage sag within the scope of DVR rated compensation, in order to ensure the load voltage quality, generally the amplitude of voltage cannot be changed, that only through the load voltage phase change to optimize active power output and injection voltage. When the sag is likely to cause the active power backward, at this point, the load voltage phase angle should be appropriate regulated, to ensure the DVR active power output is zero.

The optimization compensation generally exist phase jump, in order to avoid impacting load due to large phase change, load voltage phase gradually and smoothly transit to the optimal phase jump angle by selecting a proper step size.

4. Simulation studies
The new compensation strategy has been tested by the 7.0/SIMULINK MATLAB simulation. The Fig.2 is the simulation schematic diagram. The parameters are set as follows: the power supply voltage is three-phase symmetrical, the phase voltage is 220V, the load is three-phase symmetrical load, the power factor is 0.6, and the single-phase load power consumption is 454W. DVR maximum compensation energy is 600W, single-phase compensation limited voltage is 105V.
When the three-phase symmetrical transient fault occurs, assuming the grounding resistance is 27Ω, the system-side voltage is shown in Table 1.

|       | A phase | B phase | C phase |
|-------|---------|---------|---------|
| U(V)  | 150     | 150     | 150     |
| \(\theta\) (rad) | 0.0615  | -1.0745 | 0.9579  |

According to the new compensation strategy, if the condition \(3U_L \cos \varphi \geq D\) is satisfy, the minimum active power compensation phase jump angle can be calculated \(\alpha = 0.9368\text{rad}\). The phase jump angle range, satisfying DVR compensation active power, is \([-0.3132, 2.227]\) through the formula (1) to calculate.

The relationship between the three-phase injection voltage and the phase jump angle is shown in the figure 3.

**Figure 2.** Simulation principle diagram

**Figure 3.** Relationship between injection voltage and phase jump angle
power compensation and the same-phase voltage compensation can only compensate the C phase.

5. Conclusion
The proposed optimal compensation strategy can get a reasonable compensation under limited active power capacity, which is useful to reduce active power capacity of DVR and get optimum load voltage.

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