Study on Influence Factors of Series-Parallel Compensation Device Voltage Control

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Abstract. Aiming at the power quality problem of voltage sag in distribution network, the control factors and effects of dynamic voltage restorer (DVR) and distribution static synchronous compensator (DSTATCOM) are studied to flexibly configure DFACTS devices and improve the voltage quality of distribution network. Firstly, the basic principle and compensation strategy of DVR and DSTATCOM are elaborated. Then, the performance influencing factors of two compensation devices are deduced. The influence of voltage sag amplitude, system capacity and load capacity is discussed. It is concluded that the voltage compensation performance of DVR is directly related to load capacity and voltage sag amplitude, while DSTATCOM is directly related to system capacity and voltage sag amplitude. Finally, the effectiveness of the proposed method is validated by comparing the control effects of the two compensation devices on voltage sag under different voltage sag magnitude, system capacity and load capacity, which provides a theoretical basis for the reasonable access of DVR and DSTATCOM in distribution network.

1. Introduction

As voltage sensitive load increases win the modern industry, voltage sag has become one of the most important electric power quality problems in current power system. DSTATCOM and DVR configured in power distribution network are the most effective measures to restrict voltage sags at present [3,4]. Due to different grid connection methods and topological structure, the performance affecting factors of the two compensation devices in voltage sag treatment are different. The core of active power distribution network is active management [5], i.e., to reasonably configure electric power quality compensation device and other elements when the power distribution system operating status is effectively monitored, and accurately control performance influence factors of each electric power quality compensation devices for the convenience of flexible configuration. Therefore, the research on performance influence factors of different electric power quality compensation devices plays an important role in improving voltage quality of power distribution network.

In case of voltage sags in power distribution network, the series and parallel compensation devices could input power to the system to maintain stable voltage on the grid-connection point. Documents [6-7] expounded operating principle of DSTATCOM, simulated dynamic reactive compensation in power distribution network, and proved outstanding performance of DSTATCOM in improvement of electric energy quality in power distribution network. Document [8] studied basic
principles of DVR device, and pointed out that DVR is one of the most economical solutions to handle voltage-related electric energy quality problems. In order to effectively improve voltage quality of power distribution network, some scholars strive to study optimal configuration of voltage sag compensation device. Documents [9-10] adopted simple radiation network for performance test, studied the optimal configuration of DVR and also pointed out that DVR is only installed to the position of sensitive load in usual case. Documents [11, 12] comprehensively considered the investment cost and income of planning scheme, established mathematical model of DSTATCOM and DVR in voltage sag treatment, and proposed comprehensive treatment scheme of voltage sag. Few documents considered performance influence factors for different devices to treat voltage sags in optimal configuration, and studied performance influence factors for series and parallel compensation devices to treat voltage sags so as to better bring their advantages into full play and improve voltage quality of the power distribution network.

This paper, aiming at the prominent electric power quality problem of voltage sags in power distribution network, studied performance influence factors of DVR and DSTATCOM voltage sag compensation devices. It compared the compensation effects of the two compensation devices for voltage sags under different voltage sag amplitudes, system short-circuit capacities and load capacities. The comparative analysis shows DVR voltage compensation performance is affected seriously by load capacity and voltage sag amplitude, while DSTATCOM is affected seriously by system short-circuit capacity and voltage sag amplitude.

2. Basic principles of compensation devices

2.1 Basic principles of DSTATCOM

The main circuit structure of DSTATCOM can be seen in Fig.1. The figure shows the main circuits of typical DSTATCOM device contain voltage source converter (VSC), voltage capacitance, shunt transformer and filter. The basic principle of DSTATCOM is to install the three-phase bridge converter circuit in parallel to the grid-connection point, appropriately adjust amplitude and phase of output voltage on AC side in case of system voltage deviation, or directly adjust AC side current so that the circuit could send or absorb reactive current required and dynamic reactive compensation purpose will be reached.

![Fig. 1 DSTATCOM parallel equivalent circuit](image)

As shown in Fig. 1, \( U_{th} \) is power grid voltage; \( Z_{th} = R_{th} + jX_{th} \) is short-circuit impedance of power distribution network; \( S = P + jQ \) is the apparent power transmitted by power distribution bus toward load direction; \( S_{th} = P_{th} + jQ_{th} \) is the apparent power injected by parallel compensation device to grid connection point; \( U_L \) is load voltage; and \( S_L = P_L + jQ_L \) is load power.

After voltage sags, DSTATCOM may maintain constant system voltage through reactive power exchange with the system; the output voltage \( U_{th} \) and output current \( I_{th} \) decide the reactive power \( Q_L \) injected by the device; in case of voltage sags, the vector diagram of reactive power exchange between DSTATCOM and the power distribution system can be seen in Fig.2. The reactive power exchange between device and power distribution system is controlled by changing amplitude of DSTATCOM output voltage.
In Fig. 2, when the amplitude of voltage outputted by DSTATCOM is higher than that in power distribution system, the reactive current will flow to the system from DSTATCOM device; when current is 90° ahead of DSTATCOM output voltage, DSTATCOM will inject inductive reactive power to the system, equaling to a controllable capacitive load. At that time, the reactive power flowing from the system side to DSTATCOM grid-connection point is partly undertaken by the compensation device to reduce voltage sags on the lines so as to improve voltage level on operation point.

2.2 Basic principles of DVR

The main circuit structure of DVR can be seen in Fig. 3. The figure shows the main circuits of typical DVR device contain VSC, energy storage unit, series transformer and filter. In case of system voltage deviation, DVR and the system shall carry out energy exchange. After small voltage sags, it is only necessary to inject reactive power; in case of large voltage sags, the energy storage device provides necessary active power required for voltage sag compensation to DVR.

As shown in Fig. 3, $U_{DVR}$ is the compensation voltage injected by DVR series circuit; $S_{DVR} = P_{DVR} + jQ_{DVR}$ is power injected by DVR; Other parameters are consistent to the meanings of parameters shown in Fig. 1.

In case of voltage sags on the power side, DVR injects compensation voltage to lines in series till the voltage amplitude of power distribution network is recovered to normal level. During compensation, DVR may adopt different compensation strategies, such as same phase compensation strategy [13], pre-sag voltage compensation strategy [14] and other improvement compensation strategy [15]. The same phase compensation is known as the minimum voltage compensation strategy, and could make effective compensation when voltage sag is deep. The pre-sag voltage compensation is known as full compensation or defect compensation. It is necessary to detect the voltage phase in power grid before sags all the time, and it is the optimal compensation strategy for loads. When energy optimal compensation strategy is used to treat voltage sags, the active power injected is the minimum compared to that of other two strategies. It could effectively improve the time of voltage sag compensation.

This paper adopted same phase compensation strategy for comparative analysis on DVR. At that time, the amplitude of compensation voltage is the balance between load reference voltage and power grid voltage, and the amplitude of compensation current is that of load current before sags. Since the series voltage injected is the minimum when adopting the same phase compensation strategy, the capacity of device required at that time is the minimum. The diagram of compensation can be seen in Fig. 4, in which, $U_{L,pre}$ is the load voltage before sags and $I_L$ is the load current.
3. Influence factors of voltage sag compensation

3.1 Performance influence factors of parallel compensation device

When the parallel compensation device is not accessed, and voltage sags occurred in power distribution network, the voltage amplitude of sensitive load $U_L$ shown in Fig.1 shall be:

$$U'_L = U_{th} - \Delta U$$

$$= U_{th} - \left(\frac{P_L R_{th} + Q_L X_{th}}{U_{th}} + j \frac{P_L X_{th} - Q_L R_{th}}{U_{th}}\right)$$

(1)

The load voltage amplitude $U'_L$ after compensation device is accessed shall be:

$$U'_L = U_{th} - \Delta U$$

$$= U_{th} - \left(\frac{(P_L - P_{sh}) R_{th} + (Q_L - Q_{sh}) X_{th}}{U_{th}} + j \frac{(P_L - P_{sh}) X_{th} - (Q_L - Q_{sh}) R_{th}}{U_{th}}\right)$$

(2)

Take the balance between voltage amplitudes before and after compensation device assess $\Delta V$, then,

$$\Delta V = U'_L - U_L = \frac{P_{sh} + j Q_{sh}}{U_{th}} (R_{sh} + j X_{sh})$$

(3)

In combination with formula of system short circuit capacity and formula (3),

$$\frac{S_{Sh}}{U_{th}} = \frac{\Delta V^*}{S_{th}}$$

(4)

In the formula, $\Delta V^*$ is the per-unit value of voltage sags, and the basic value is $U_{th}$, $\Delta V^* \in [0,1]$.

According to Formula (4), when compensating power distribution voltage sags, and system short-circuit capacity on grid connection point of DSTATCOM is confirmed, the compensation of reactive power required is only of linear relevance with sag amplitude; when the voltage sag amplitude on DSTATCOM grid connection point is certain, the compensation of reactive power required is only related to system short-circuit capacity, but irrelevant to load capacity.

3.2 Performance influence factors of series compensation device

Take DVR as an example. When DVR is not accessed, and voltage sag occurred on power distribution network, the following formula can be acquired according to Kirchhoff KVL law,

$$U'_L = U_{th} - I_L (R_{th} + j X_{th})$$

(5)

In the formula, $U'_L$ and $I_L$ are respectively the voltage and current on sensitive load side after voltage sags when DVR is not accessed.
The load voltage amplitude $U_L'$ after DVR is accessed in series shall be:

$$U_L = U_{th} + U_{DVR} - I_L (R_{th} + jX_{th})$$  \hspace{1cm} (6)

In the formula, $U_L$ and $I_L$ are respectively the voltage and current on sensitive load side after DVR is accessed. $U_{DVR}$ is the voltage injected by DVR series circuit.

After DVR is accessed, if $U_L$ is equivalent to the voltage amplitude before sags, then,

$$\Delta V = U_L - U_L' = U_{DVR} + (R_{th} + jX_{th})(I_L - I_L')$$  \hspace{1cm} (7)

According to formula (7), the voltage difference on the grid connection point before and after DVR access is comprised of two parts. One is the voltage $U_{DVR}$ injected by DVR series current, and the amplitude is consistent with the compensation voltage of DVR when the same phase compensation strategy is adopted. Before and after DVR access, the difference of voltage sags on both ends of line is smaller; when it is approaching the estimated value, the system impedance partial pressure $(R_{th} + jX_{th})(I_L - I_L')$ may be neglected, i.e., $\Delta V \approx U_{DVR}$.

According to operating principle of DVR,

$$S_{DVR} = U_{DVR} \cdot I_L$$

$$I_L = \left( \frac{S_L}{U_L} \right)$$  \hspace{1cm} (8)

To sum up,

$$S_{DVR} = U_{DVR} \cdot \left( \frac{S_L}{U_L} \right) = \frac{\Delta V}{U_L} S_L = \Delta V^* S_L$$  \hspace{1cm} (9)

In the formula, $S_L$ is sensitive load capacity, $\Delta V^*$ is the per-unit value of voltage sags, and the basic value is $U_L$, $\Delta V^* \in [0,1]$. According to Formula (9), when load capacity is confirmed, the compensation of apparent power required is only of linear relevance with sag amplitude; when the voltage sag amplitude on load bus side is certain, the compensation of apparent power required is only related to load capacity, but irrelevant to system short-circuit capacity.

4. Example analysis

4.1 Introduction to examples

Referring to Fig.1 and Fig.3, this paper established the simulation model of DSTATCOM and DVR in radial power distribution network to carry out example analysis, and verify correctness of the theory by changing system short circuit capacity, load capacity and voltage sag amplitude in the simulation model. DSTATCOM adopted double-loop control mode with voltage as external loop and current as internal loop. For AC voltage loop, the voltage reference value shall be 1. In order to rapidly detect and calculate voltage signal to be compensated, DVR adopts feed forward control mode. Other data of examples can be seen in Table 1.

| Device       | Example | $U_{th}$/kV | $S_{th}$/kVA | $S_L$/kVA | $\Delta V^*$/p.u. |
|--------------|---------|-------------|--------------|-----------|-------------------|
| DVR          | 1       | 10kV        | $2 \times 10^3$ | 2+j1       | 0.12              |
|              | 2       |             | $2 \times 10^3$ | 2+j1       | 0.08              |
|              | 3       |             | $2 \times 10^3$ | 5+j3       | 0.08              |
|              | 4       |             | $3 \times 10^3$ | 2+j1       | 0.08              |
| DSTATCOM     | 5       | 10kV        | $2 \times 10^3$ | 2+j1       | 0.12              |
|              | 6       |             | $2 \times 10^3$ | 2+j1       | 0.08              |
|              | 7       |             | $2 \times 10^3$ | 5+j3       | 0.08              |
|              | 8       |             | $3 \times 10^3$ | 2+j1       | 0.08              |
4.2 Simulation results

To verify the correctness of theories stated in Section 3, the examples are simulated. In Example 1, the voltage of power distribution network is normal when 0~0.1s; voltage sags occur in superior power grid when 0.1~0.2s; the sag amplitude of each example is consistent with data in Table 1. In Example 1, the oscillogram of system side voltage $V_{abc}$, voltage on grid connection point $V_L$ and voltage amplitude on grid connection point $V_{Lrms}$ can be seen in Fig.5.

Fig.5 Simulation results of Example 1

In case of voltage sags on the system side, DVR injects compensation voltage in series to guarantee stable voltage on grid connection point. According to Fig.5, the system side voltage $V_{abc}$ sags after 0.1s, while the voltage amplitude $V_{Lrms}$ on grid connection point within 0.02s is stabilized at 1p.u., guaranteeing effectiveness of subsequent power data. The simulation results of other examples can be seen in the following diagram:

a) Simulation results of Case 2

b) Simulation results of Case 3

c) Simulation results of Case 4

d) Simulation results of Case 5

e) Simulation results of Case 6

f) Simulation results of Case 7
The simulation results of each example and comparison situations of theoretical data can be seen in Table 2.

| device | Example | Actual injection power/kVA | Theoretical injection power/kVA | D-value/kVA |
|--------|---------|----------------------------|--------------------------------|-------------|
| DVR    | 1       | 0.2397+j0.1196             | 0.24+j0.12                     | 0.0003+j0.0004 |
|        | 2       | 0.1596+j0.0789             | 0.16+j0.08                     | 0.0004+j0.0011 |
|        | 3       | 0.3982+j0.2391             | 0.40+j2.4                      | 0.0018+j0.0009 |
|        | 4       | 0.1598+j0.0791             | 0.16+j0.08                     | 0.0002+j0.0009 |
| DSTAT-COM | 5 | j2.433x10\(^3\)       | j2.4x10\(^3\)                 | j0.033x10\(^3\) |
| M      | 6       | j1.623x10\(^3\)           | j1.6x10\(^3\)                | j0.023x10\(^3\) |
|        | 7       | j1.606x10\(^3\)           | j1.6x10\(^3\)               | j0.006x10\(^3\) |
|        | 8       | j2.441x10\(^3\)           | j2.4x10\(^3\)                | j0.041x10\(^3\) |

For DVR, by comparing data of Example 1 and Example 2, when the system voltage sag amplitudes are different, the injected power of DVR will be changed; by comparing data of Example 2 and Example 3, the injected power of DVR will similarly be affected by load capacity; comparing data of Example 2 and Example 4, when the system short circuit capacities are different, the impact on injected power of DVR is little.

For DSTATCOM, by comparing data of Example 5 and Example 6, when the system voltage sag amplitudes are different, the injected reactive power of DSTATCOM for voltage sag compensation will be changed; by comparing data of Example 6 and Example 7, the injected reactive power of DSTATCOM will be affected little by changes in load capacity; comparing data of Example 6 and Example 8, when the system short circuit capacities are different, the injected power of DSTATCOM will be changed as well.

According to Table 2, the difference between simulation data and theoretical data of each example is small, verifying correctness of the theory.

5. Conclusions

This paper, through theoretical analysis and simulation verification, compared and analyzed performance influence factors of DSTATCOM and DVR in power distribution system for compensating voltage sags. The following conclusions are acquired:

1) The compensation effect of series compensation device for voltage sags is greatly affected by load capacity and voltage sag amplitude, and little by system short circuit capacity, such as DVR device. While the parallel compensation device is greatly affected by system short circuit capacity and voltage sag amplitude, and little by load capacity. Particularly when compensating voltage sags, DSTATCOM mainly injects reactive power, and is mainly affected seriously by reactive power capacity and voltage sag amplitude.
2) The system short circuit capacity on any node of the power distribution network is necessarily larger than or equaling to load capacity. Therefore, when DVR and DSTATCOM are used to compensate voltage sags, the capacity required by DSTATCOM is always larger than capacity of DVR. During actual use, it is necessary to consider influence of economical factors such as unit capacity price, installation and maintenance fee of the device.

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