

Voltage balance optimisation among subsystems of wind-photovoltaic-ES hybrid generating system

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Abstract: Wind-photovoltaic-energy storage (ES) hybrid generating system has numerous reactive power sources. It is crucially important for coordinated control of these reactive power sources. According to the test results, there are unbalanced control problem in subsystem voltage of the hybrid generating system. The problem caused reactive power circulation and loop current. A subsystem voltage balance optimisation strategy is proposed to solve the problem. The case study shows the efficiency of the proposed strategies.

1 Introduction

Wind-photovoltaic (PV)-ES hybrid generating system contains various and numerous generators including wind generators, PV modules and energy storage batteries. The external characteristics of the hybrid generating system are composed of a large number of individual responses, which are very different from the response of the single unit with the same capacity, resulting in an increased difficulty in automatic voltage control (AVC) of the system.

The reactive power sources include constant voltage control static var generator (SVG), constant reactive power control SVG, wind turbines and PV unit. The constant voltage control SVG works in the constant voltage control mode, while the rest of reactive power sources work in constant reactive power control mode.

The voltage control capacity of the point of common coupling (PCC) is regarded as an important assessment indicator, making the voltage of PCC attract too much attention. A single wind farm or PV power plant (50–100 MW) has a good performance in reactive power control, especially for power plants with SVG. However, when a number of small new energy power plants form a large hybrid generating system, it is difficult to ignore the interactions of these small power plants. According to operating records, there are still two problems in AVC system:

1. i) Large voltage deviation among eight buses of 35 kV.
2. ii) Reactive power circulation among the 220 kV/35 kV transformers.

The problems can be attributed to the existing AVC system has a large number of control points with different control performances in the short electrical distance. It is difficult to maintain the station voltage balance and reactive power balance.

AVC system has become an important part of the new energy power plant monitoring system. For the wind farm AVC system, there have been a lot of literature researches. The reactive power limit of the doubly fed induction generator is given in [1]. The AVC system of the wind farm is gradually forming a three-layer control structure [2, 3]. The concept of secondary distribution of reactive power is proposed [4]. In [5], the reactive power and voltage coordination control strategy of the wind farm is proposed, and the reactive voltage of multiple wind farms is coordinated by the control centre, and the coordinated control of the subsystem voltage is considered. According to the AVC system of PV power station, Chen et al. [6] proposed a three-layer reactive power control strategy for PV power plants. On the basis of the sensitivity nine-zone method, the reactive power control for active and reactive power (PQ) control and PV control type PV power plants strategy are proposed [7].

The control theory of the AVC system of a single wind farm or a PV power plant has attracted wide attention, and the AVC system of the new energy hybrid generating system adopts the similar control structure of the wind farm or PV power plant. A multi-objective AVC algorithm for a variety of renewable energy generating systems is proposed [8]. The reactive power control strategy of wind power and the battery storage hybrid generating system is proposed to improve the PCC voltage control characteristics [9]. The AVC system model of the wind and the solar hybrid generating system is established [10]. However, the above literatures rarely consider the subsystem voltage distribution in the system.

On the basis of the analysis of test results, this paper puts forward the problem of unbalanced subsystem voltage control in the hybrid generating system, and analyses the reasons. Finally, the voltage balance optimisation strategy of the subsystem is proposed to maintain the 35 kV buses voltage balance, and verified by simulation.

2 Unbalanced control of subsystem voltage

Generally, concentrated compensation is used in a wind farm or a PV power plant. Moreover, the main reactive power sources for the 35 kV voltage bus are the capacitor group and SVG/static var compensator (SVC), with a good performance in voltage control. However, the number and type of reactive power sources in the hybrid generating system are significantly increased. With wide distribution of the reactive power sources, changing working conditions of the generators and the different load rates of the main transformers, there are unbalanced reactive power flow and large voltage distribution deviation in the hybrid generating system.
Under the reference of the State Grid Corporation standard, the reactive power and voltage control tests have been done in Zhangjiakou wind-PV-ES hybrid generating system. As shown in Fig. 1, 35 kV bus voltage curves of six SVG distribute between 35.6 and 36.6 kV, and the largest voltage deviation between two SVG is nearly 1 kV. It is obvious of unbalanced subsystem voltage distribution. The unbalance causes reactive power circulation among multiple main transformers. Moreover, reactive power circulation wastes reactive power capacity of SVG and increases the reactive power loop current. The increased current brings more active power loss.

3 Reactive power circulation and unbalanced voltage control

Unbalance subsystem voltage problem will cause reactive power loop current. When the active power of hybrid generating system remains unchanged, and the voltage of PCC is in steady state, the increase of reactive power current must cause the increase of reactive power of the collector system, and the increase of reactive power is only caused by the increase of reactive power current. So, the change of reactive power circulation should be characterised by the change of reactive power.

Fig. 2 shows flow calculation equivalent circuit of two electrical branches with SVG, as an example to derive the relationship between the transformer reactive power and voltage distribution deviation. Assuming two SVG control modes are uncertain, and the transformer high- and low-voltage sides have been calculated, the derivation process is as follows:

\[
\begin{align*}
S_1 &= S_{\text{avg}1} + S_{G1} \\
S_2 &= S_{\text{avg}2} + S_{G2} \\
S_{G1} &= P_{G1} + jQ_{G1} \\
S_{G2} &= P_{G2} + jQ_{G2} \\
S_4 &= S_1 + S_2 + S_{\text{avg}} \\
S_{\text{avg}1} &= jQ_{\text{avg}1} \\
S_{\text{avg}2} &= jQ_{\text{avg}2} \\
\end{align*}
\]  

(1)

From (1), it is available as

\[
\begin{align*}
S_i &= P_{G1} + jQ_{G1} + jQ_{\text{avg}} = P_{G1} + jQ_1 \\
Q_1 &= Q_{G1} + Q_{\text{avg}} \\
S_2 &= P_{G2} + jQ_{G2} + jQ_{\text{avg}} = P_{G2} + jQ_2 \\
Q_2 &= Q_{G2} + Q_{\text{avg}} \\
\end{align*}
\]  

(2)

Calculating \(\Delta U_{14}\) and \(\Delta U_{14}\)

\[
\begin{align*}
\Delta U_{14} &= \frac{Q_1 X_{T1}}{U_1} \\
\Delta U_{42} &= -\frac{Q_2 X_{T2}}{U_2} \\
\end{align*}
\]  

(3)

\(\Delta V_{12}\) is calculated from (3) as

\[
\Delta U_{12} = \Delta U_{14} + \Delta U_{42} \approx \Delta U_{14}
\]

Assuming that the two transformers are close to the capacity and \(X_{T1} \approx X_{T2} \approx X_T\), substituting for (4)

\[
\Delta U_{12} = \frac{U_1 Q_1 - U_1 Q_2}{U_1 U_2} X_T
\]  

(5)

Calculate the total reactive power on the two transformers

\[
\begin{align*}
Q_{LT} &= \left[U_1^2 B_{T1} + \left(\frac{S_1}{U_1}\right)^2 X_{T1}\right] + \left[U_1^2 B_{T2} + \left(\frac{S_2}{U_2}\right)^2 X_{T2}\right] \\
&= \left(U_1^2 B_{T1} + U_1^2 B_{T2}\right) + \left[\frac{P_1^2}{U_1^2} + \frac{Q_1^2}{U_1^2}\right] X_{T1} + \left[\frac{P_2^2}{U_2^2} + \frac{Q_2^2}{U_2^2}\right] X_{T2} \\
&= \left(U_1^2 B_{T1} + U_1^2 B_{T2}\right) + \left[\frac{P_1^2}{U_1^2} + \frac{Q_1^2}{U_1^2}\right] X_T + \left[\frac{P_2^2}{U_2^2} + \frac{Q_2^2}{U_2^2}\right] X_T \\
&= Q_{LT0} + \frac{Q_1^2}{U_1^2} + \frac{Q_2^2}{U_2^2} X_T
\end{align*}
\]

Assuming that the active powers of branches 1 and 2 are constant, it is considered that the reactive power required for active power transmission does not change. Assuming that two transformers work near rated capacity, it can be assumed that \(Q_{LT0}\) is constant when
the transformer excitation reactive power is constant. From (6), it is available as
\[
Q_{LT} = Q_{LTT} + \frac{Q_1^2}{U_1^2} + \frac{Q_2^2}{U_2^2} \times X_T
\]
\[
= Q_{LTT} + \frac{U_TQ_1 - U_1Q_2}{U_1^2} \times X_T
\]
\[
= Q_{LTT} + \frac{Q_1^2}{U_1^2} X_T + 2 \frac{U_1U_2Q_1Q_2}{U_1^2} X_T
\]
\[
= Q_{LTT} + \frac{(U_2Q_1 - U_1Q_2/U_1U_2)^2}{X_T} + 2 \frac{U_1Q_2}{U_1^2} X_T
\]
\[
= Q_{LTT} + \frac{(\Delta Q_{12})^2}{X_T} + 2 \frac{U_1Q_2}{U_1^2} X_T
\]
Substituting (4) into (7)
\[
Q_{LT} = Q_{LTT} + \frac{(\Delta U_{12})^2}{X_T} + \frac{2\Delta U_{14}\Delta U_{42}}{X_T}
\]
\[
Q_{LT} = Q_{LTT} + \frac{(\Delta U_{14} + \Delta U_{42})^2}{X_T} - 2\Delta U_{14}\Delta U_{14}
\]
\[
= Q_{LTT} + \frac{(\Delta U_{14})^2 + (\Delta U_{42})^2}{X_T}
\]
(i) If SVG1 and SVG2 are constant reactive power control mode SVGs, then node 1 and node 2 are PQ nodes, from (8) it is available as
\[
Q_{LT} = Q_{LTT} + \frac{(U_1 - U_4)^2 + (U_4 - U_2)^2}{X_T}
\]
Then when \(U_4\) is set, the reactive power of the two branches will change with \(U_1\) and \(U_2\), then the smaller the differences among \(U_1, U_2\) and \(U_4\), the smaller the reactive powers. When \(U_1 = U_2 = U_A\), the two branches operate on the minimum reactive power.

(ii) If both SVG1 and SVG2 are constant voltage control mode SVGs, then node 1 and node 2 are PV nodes, available from (8)
\[
Q_{LT} = Q_{LTT} + \frac{(\Delta U_{12})^2}{X_T} - 2\Delta U_{14}\Delta U_{42}
\]
\[
= Q_{LTT} + \frac{(\Delta U_{14})^2}{X_T} + 2\Delta U_{14}\Delta U_{14}
\]
\[
= Q_{LTT} + 0.5\frac{(\Delta U_{12})^2}{X_T} + \frac{2(\Delta U_{14} - 0.5 \cdot \Delta U_{12})^2}{X_T}
\]
\[
= Q_{LTT} + 0.5\frac{(\Delta U_{12})^2}{X_T} + \frac{2(U_4 - 0.5(U_1 + U_2))^2}{X_T}
\]
Then \(U_1, U_2\) and \(\Delta U_{12}\) are for the fixed value, and the reactive power of the two branches will change with \(U_4\). Closer \(U_4\) and \(0.5(U_1 + U_2)\), less reactive power. When \(\Delta U_{12}\) tends to 0, \(U_1 \approx U_2 \approx U_A\), the two branches operate on the minimum reactive power.

(iii) If one of node 1 and node 2 is PV node and the other one is PQ node, then (9) can also be concluded that when \(U_4 \approx U_2 \approx U_A\) the two branches operate on the minimum reactive power.

From (i)-(iii), regardless of node 1 and node 2 are PV or PQ nodes (\(U_4\) as the equilibrium node), when the node voltage of each branch is maximally close to \(U_A\), the sum of squares of deviation between the nodes is the smallest, then the circuits operate on the minimum reactive power.

From the above formula to derive and prove available, the unbalanced subsystem voltage problem will produce more reactive power loop current and reactive power requirements. The bigger sum of squares of the voltage deviation between the subsystems, the bigger reactive power demand. The bigger reactive power circulation, the more active power loss. Then, the minimum sum of squares of the voltage deviations among the subsystems can be used as the optimal objective function of the coordination voltage control strategy.

4 Subsystem voltage balance optimisation

In this section, optimisation strategy of AVC is proposed to solve the unbalanced subsystem voltage problem. The optimisation target is to the minimum sum of squares of the voltage deviations between the 35 kV bus lines, to maintain subsystem voltage balance.

The optimisation objective function is
\[
\min \sum_{j=1}^{4} \sum_{i=1}^{4} (U_j - U_{j4})^2
\]
where \(U_{j4}\) is the terminal voltage matrix for multiple constant voltage control mode SVG; \(Q_{j4}\) is the reactive power matrix for multiple constant reactive power control mode SVG; \(Q_{j4}\) is the reactive power matrix of multiple wind turbines; \(Q_{jq}\) is the reactive power matrix of multiple PV cells; \(U_j, U_4\) are any two low-voltage side voltages of main transformers; and Num is the number of low-voltage side nodes.

To simplify the power flow calculation in the optimisation process, only calculating power flow of important nodes including 220 kV bus bar, low-voltage and high-voltage sides of main transformers.

Node 2 is the PV node, and nodes 2 and 3 are the PQ node, and node 4 is the balanced node or PCC. After the AVC system completes the initial reactive power instruction distribution according to the real-time states, the subsystem voltage balance optimisation method is used to optimise the node 1 voltage command \(U_{14}\) and the node 2 reactive power command \(Q_{24}\) issued by the AVC system. The detailed realisation flowchart is shown in Fig. 3.

First, enter the node matrix for the power flow calculation. Then, judge whether the PCC point voltage \(U_4\) is in a steady state. Set \(U_{44}\) as the dead band value of \(U_4\). If in more than five instruction cycles meet \(|U_4 - U_{4}\| < U_{4DB1}\), the PCC point voltage is considered in a steady state, then go into subsystem voltage balance optimisation. Moreover, if not, go into the end.

Moreover, then go into the optimisation stage of the node 1 voltage command \(U_{14}\). Set \(U_{4DB1}\) as the dead band value of \(U_4\). If meet \(|U_{14} - U_{1}\| < U_{1DB1}\), the voltage deviation between node 1 and 4 is large, so optimise \(U_{14}\). Moreover, if not, go into next stage.

When \(U_{14}\) still needs to be optimised, set \(C_1\) as the optimisation coefficient of node 1. The value of \(C_1\) is between 0 and 1. Calculate \(U_{14} = C_1(U_{14} - U_{4})\), then calculate the power flow. According to the result of power flow calculation, judge whether \(Q_{24}\) and \(Q_{4}\) are out of limit. If \(Q_{24}\) is out of limit, calculate \(Q_{24}\), the out-of-limit part. Set \(k_2\) as the voltage sensitivity coefficient of node 2, which can be estimated by the sensitivity matrix. Set \(Q_{24} = k_2Q_{24}\). If \(Q_{24}\) is out of limit, the processing method is the same as \(U_4\).

Then repeat the power flow calculation and judgement again, until there is no out-of-limit variable or exceeds the maximum number of iterations.
As the target value of $U_{1_{\text{ref}}}$ is $U_4$, the target value of $Q_{2_{\text{ref}}}$ is $Q_{2_{\text{cos}}}=1$, the reactive power of node 2 when the high-voltage side power factor of the same branch transformer is 1. When the power factor of branch 2 tends to 1, the voltage deviation between node 2 and node 4 will also be minimised. The rest is similar to the $U_{1_{\text{ref}}}$ optimisation process.

Priority order is set as the constant voltage control SVG priority, and the constant reactive power control SVG second. The order of similar SVG set as the direct axis reactance $X_d$ decision, the bigger resistance priority.

5 Simulation

The simulation system of the hybrid generating system is shown in Fig. 4, where the capacities of wind farms 1–3 are, respectively, 48, 48 and 40 MW, and the capacity of PV power plant is 44 MW. SVG1 and SVG3 operate in the constant voltage control mode, and their capacities are 20 and 10 MVar. SVG2 operates in the constant reactive power control mode, and its capacity is 30 MVar. The command cycle is 10 s, and set the hybrid generating system voltage active power step, to make the voltage of PCC step from 220 to 222.2 kV, that is, from 1.00 to 1.01 pu.

The simulation results of unbalanced subsystem voltage control are shown in Fig. 5. It can be observed that the three 35 kV bus voltages have obvious voltage distribution deviations, and the subsystem voltage control is unbalanced. SVG2 and SVG3 operate on $-5$ and $1$ MVar, respectively, with reactive power circulation.

The simulation results of subsystem voltage balance optimisations are shown in Fig. 6. Comparison between before optimisation and optimised simulation results is shown in Table 1.

After the subsystem voltage balance optimisation, the voltage deviations among SVG are obviously reduced, and the sum of the square of the voltage deviations changes from 0.1698 to
The total reactive power of the transformer is positively correlated with the square sum of the voltage difference. Therefore, the total reactive power is reduced. The optimisation strategy can reduce the imbalance of the subsystem voltage under the premise that SVG dynamic reactive power margin is not changed greatly and the total reactive power is decreased.

6 Conclusion

The unbalanced subsystem voltage problem exists in AVC system of wind-PV-ES hybrid generating system, which causes more reactive power loop current and active power loss. To solve it, this paper proposes a subsystem voltage balance optimisation strategy. The optimisation strategy can improve the voltage distribution in the station and reduce the reactive power circulation significantly.

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Table 1 Comparison between before optimisation and optimised simulation results

| Data | Before optimisation | Optimised |
|------|---------------------|-----------|
|      | $U$, kV | $Q$, MVar | $U$, kV | $Q$, MVar |
| SVG 1 | 35.35 | 13.1 | 35.25 | 9.7 |
| SVG 2 | 35.42 | −3.9 | 35.37 | −4.8 |
| SVG 5 | 35.10 | −1.9 | 35.25 | −3.9 |
| $\sum(U_i-U_j)^2$ | 0.1698 (kV)$^2$ | 0.0288 (kV)$^2$ |

0.0288 kV$^2$. The total reactive power of the transformer is positively correlated with the square sum of the voltage difference. Therefore, the total reactive power is reduced. The optimisation strategy can reduce the imbalance of the subsystem voltage under the premise that SVG dynamic reactive power margin is not changed greatly and the total reactive power is decreased.

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