Research on Selection Method for AVC Control Command of Continuous Variable Equipment

Shangfeng Xiong\textsuperscript{1}, Jingbo Wu\textsuperscript{1,*}, Qinghong Deng\textsuperscript{2}, Tiegang Zhou\textsuperscript{3}, Zhengwen Li\textsuperscript{4}, Xiao He\textsuperscript{3}, Weijun Zhu\textsuperscript{1} and Peiyuan Xie\textsuperscript{4}

\textsuperscript{1}State Grid Hunan Electric Power Co. Ltd. Power Research Institute, Changsha 410007, Hunan Province, China;
\textsuperscript{2}State Grid Hunan Electric Power Co. Ltd. Construction Company, Changsha 410007, Hunan Province, China;
\textsuperscript{3}State Grid Hunan Electric Power Co. Ltd. Shaoyang Power Supply Company, Shaoyang 422000, Hunan Province, China;
\textsuperscript{4}State Grid Hunan Electric Power Co. Ltd., Changsha 410004, Hunan Province, China.

\textsuperscript{*}E-mail: jinbowu1112@qq.com

Abstract. The existing AVC system uses the expected voltage value as the control command value of the continuous adjustable reactive power source. However, the phenomenon of “grabbing reactive power”, which is caused by the difference in the adjustment speeds of various continuous adjustable reactive power sources, is not conducive to safe, economical and high-quality operation of the power grid. To solve this problem, a method of selecting AVC control command is proposed, in which the expected voltage value as control command is delivered to the continuous adjustable voltage source with high sensitivity and fast adjustment speed and the expected reactive power is delivered to the rest. This method, combined with the existing AVC system, forms an AVC control command selection system to effectively solve the problem of “grabbing reactive power” and ensure safe, economical and high-quality operation of the power grid.

1. Introduction

Automatic Voltage Control (AVC) \cite{1} is the main system of modern power grid \cite{2, 3} voltage and reactive power control \cite{4}, which improves power grid voltage quality and reduces the network loss through the automatic and unified regulation of reactive power voltage sources such as grid-connected units, grid dynamic reactive power compensation equipment, parallel capacitors/reactors, transformers, etc. AVC ensures the safe and economical operation of the power grid.

AVC control commands are different in distinct types of reactive voltage sources. For discrete adjustable reactive power sources, remote commands such as capacitors/reactor switching or transformer tap adjustment are generally issued. For continuously adjustable reactive sources, the remote command value which controls the target voltage expected value or which controls the target reactive power output expected value may be issued \cite{5, 6}.

The safety responsibility of the primary station and the reactive source side is relatively clear because of the expected value of the issued voltage. Therefore, the voltage expectation value is generally adopted as the control command value of the continuously adjustable reactive power source. However, due to the difference in the adjustment speeds of various types of continuously adjustable
reactive power sources in reality, the following situations usually occur: power plants with fast adjustment speed are rushing to reactive power and in the state of deep phase or full reactive power for a long time; power plants with slow adjustment speed can’t effectively participate in grid reactive voltage regulation, which cause the idle reactive resources. Even in some cases, power plants with low sensitivity and fast adjustment speed may be rushing to reactive power (“grab power”), resulting the unbalance of power grid reactive power regulation. This becomes more prominent with the increase in the number of new energy power plants with dynamic reactive power compensation equipment such as SVG and power grid dynamic reactive power compensation equipment such as camera, SVC, STATCOM.

In addition, the control precision of the reactive power control command is better than that of the continuously adjustable reactive power resource voltage control command since the adjustable range of the voltage expectation value is much smaller than the expected value of the reactive power output. However, the power grid is a dynamic balanced system and the load current flows in real time. When the power grid reactive load increases or decreases greatly, if all the continuously adjustable reactive power sources execute the reactive power control command, the lacking of dynamic support may cause the grid voltage out of limit.

Aiming at the above problems in existing technology, this paper proposes a continuous variable AVC selecting control command method for unit and power grid dynamic reactive power compensation equipment to support the dynamic reactive power demand of the power grid, which combines with the existing AVC system to form a set of AVC selecting control command system. At the same time, the problem of “grab reactive power” caused by the difference of continuous adjustable reactive power source adjustment speed is solved, which further improves the grid voltage quality, reduces the network loss and ensures the safe and economical operation of the power grid.

2. The existing AVC system

At present, the AVC system mainly adopts a three-level voltage control mode [7]. The control system is divided into three levels. The third-level and second-level voltage control are controlled of the main stations of corresponding power grid control centers in which the control time constant is generally minute. The third-level voltage control calculates the expected value of the central bus voltage of each region according to the state estimation result and the global optimal target [8] which mainly minimizes network loss in the premise of satisfying the voltage quality. The second-level voltage control coordinates the reactive voltage sources in the control region according to the target of the central mother voltage without deviating from the expected value controlled by the three-level voltage and calculates the expected state value of each reactive voltage source as a control command which is issued to first-level. The first-level voltage control, the local control of the reactive voltage source, adjust the reactive power source according to the control command of the main station. The control time constant is generally seconds. The reactive voltage source can be divided into a continuously adjustable reactive voltage source such as grid-connected unit and grid dynamic reactive power compensation device and a discrete adjustable reactive source such as parallel capacitor/reactor and transformer. For different types of reactive voltage sources, the main station control commands are different. For discrete adjustable reactive sources, the remote control commands such as capacitor/reactor switching or transformer tap adjusting are generally issued. For continuous adjustable reactive power source, the remote command that controls the expected value of the target voltage or the remote command that controls the expected value of the target reactive power can be issued.

Coordinated Secondary Voltage Control (CSVC) [9] is currently adopted in the second-level voltage control. The mathematical model is as follows:

\[
\min \quad r \left\| \left( V_p - V^\text{ref}_p \right) \right\|^2 + C_{pq} \Delta Q_g \right\|^2 + h \| \theta \|^2
\]  

(1)
\[
\begin{align*}
Q_e^{\text{min}} & \leq Q_e + \Delta Q_e \leq Q_e^{\text{max}} \\
V_e^{\text{min}} & \leq V_e + C_{\text{v}} \Delta Q_e \leq V_e^{\text{max}} \\
& \text{subject to } \Delta V_{H}^{\text{max}}
\end{align*}
\]  

(2)

\(V_p\) and \(V_p^{\text{ref}}\) are the central bus real-time voltage and target voltage. \(C_{pg}\) is the sensitivity coefficient matrix of the continuously adjustable reactive source to the central bus. \(\Delta Q_e\) is the continuous adjustable reactive source reactive power adjustment expected value. \(r\) and \(h\) are the weight coefficients. \(\theta\) is the reactive power coordination vector (participation factor), which means that the number of generators is greater than the number of central bus bars and has a certain degree of freedom so that the equilibrium distribution of reactive power flows is adjusted. \(Q_e^{\text{g}}, Q_e^{\text{max}}, Q_e^{\text{min}}\) are respectively the current reactive output, upper limit and lower limit of continuously adjustable power source. \(V_e, V_e^{\text{max}}, V_e^{\text{min}}\) are the current voltage, voltage upper and lower limit of the key bus, respectively. \(C_{cg}\) is the sensitivity coefficient matrix of the continuously adjustable reactive power source to the key bus. \(C_{vg}\) is sensitivity coefficients matrix of the continuously adjustable reactive power source to the control bus. \(\Delta V_{H}^{\text{max}}\) is the maximum adjustment amount of the bus voltage for each control.

The coordinated second-level voltage control algorithm can directly calculate the reactive output expected value of each continuously adjustable reactive source and obtain the expected voltage value at the same time. Therefore, no matter whether the reactive power or voltage control command value is issued to the continuously adjustable reactive power source, the coordinated second-level voltage control algorithm does not need to be modified.

3. The selecting method of continuously adjustable AVC

In order to solve the problem that the AVC control is not effective enough and the state of optimized system can not be met which is caused by control command, a continuously adjustable reactive power source AVC control command selecting method is proposed. As shown in Figure 1, the following steps are included:

Step 1): According to the SCADA real-time data and the state estimation result, the main station AVC system is used to obtain the expected values of the continuously adjustable reactive source states in corresponding area.

The state expectation value of each continuously adjustable reactive source includes a control target voltage expected value and a control target reactive power output expected value;

Step 2): According to the dynamic support factor size of the continuously adjustable reactive power source, a part of the continuously adjustable reactive power source as the dynamic reactive power support point of the power grid is selected and a remote adjustment command of target voltage is issued to the dynamic reactive power support point of the power grid. A remote adjustment command of target reactive power output expected value is issued from the remaining continuously adjustable reactive power source.

Step 3): Each continuously adjustable reactive power source AVC primary controller controls the reactive power output of the reactive power source according to the received voltage or reactive power remote command.

The continuously adjustable reactive power source includes the continuously adjustable device device of reactive power such as dynamic reactive compensation device, a grid-connected new energy power plant, a grid-connected conventional water and thermal power unit. The power grid dynamic reactive power compensation device includes the equivalent value of the reactive power capacity branch and the fixed reactive capacity branch which is regarded as a continuously adjustable reactive power source. The grid-connected new energy power plant including the supporting dynamic power compensation equipment such as SVG is regarded as a continuous Adjusting reactive power source and the equivalent value of conventional water and thermal power units with the same outlet point is regarded as a continuously adjustable reactive power source.
The dynamic support factor $\zeta_i$ of the continuously adjustable reactive source mentioned in step 2) is calculated according to the following formula:

$$\zeta_i = k_1 \frac{\sum C_{pgi}}{n} + k_2 \Delta Q_{\Delta t}$$

(3)

Where $\zeta_i$ represents the dynamic support factor of the i-th continuously adjustable reactive source in corresponding region. $C_{pgi}$ represents the sensitivity coefficient (standard value) of each central bus affected by the i-th continuously adjustable reactive source. $\Delta Q_{\Delta t}$ is the maximum reactive power variant (standard value) of the i-th continuously adjustable reactive power source in unit time. $k_1$ and $k_2$, which is influenced by the unit of $C_{pgi}$ and $\Delta Q_{\Delta t}$, represent the sensitivity weight and the weight of the reactive power adjustment speed respectively. The range of $k_1$ and $k_2$ is relative. $k_1$ ranges from 5 to 10 and $k_2$ generally takes 1. $n$ represents the number of central bus bars.

All the dynamic support factors of continuously adjustable reactive sources are arranged in the descending order and one or first N continuously adjustable reactive sources with the largest dynamic support factor $\zeta$ is chosen as the supporting points of the power grid. The value of N is ten percent of the number of all continuously adjustable sources.

From the continuously adjustable reactive power source with the top ranked dynamic support factor, the dynamic reactive power compensation with high sensitivity and fast reactive power regulation is used as the preferred dynamic reactive power support point of the power grid and the grid-connected generator units with high sensitivity are adopted as secondary power grid dynamic reactive support points. Grid-connected generators includes new energy power plants, hydropower units and thermal power units.

The AVC system of main station obtains the expected state value of each reactive voltage source and the method of third-level and second-level voltage control optimizing calculation in the three-level voltage control mode is adopted. The specific process is as follows.

1.1) The AVC main station three-level controller obtains the expected value of the central bus voltage of each region according to the state estimation result and the global optimal power flow method;

1.2) The secondary controller of the AVC main station calculates the expected value of each reactive voltage source state in the region according to the target of the voltage of the central mother system without deviating from the expected value through the coordinated secondary voltage control method. The expected state value of each continuously adjustable reactive power sources includes a control target voltage expectation value and a control target reactive power output expectation value.

4. The selecting system of AVC control commands

According to the proposed AVC control command selecting method of continuously adjustable reactive power source combined with the existing AVC system architecture, a AVC control command selecting system of continuously adjustable reactive power source is formed, as shown in figure 1.
The main station AVC system acquires the expected values of the reactive power sources in the area. Dynamic support factor for each continuously adjustable reactive source in the calculation region $\zeta$. Select one or several continuously adjustable reactive sources as the dynamic reactive support point of the grid. For the remaining continuously adjustable reactive power source, the control target reactive power output expectation value remote adjustment command is issued to the dynamic reactive power support point of the power grid. The control target reactive power output expectation value remote command is issued to the rest continuously adjustable reactive power sources.

**Figure 1.** The selecting system of AVC control commands

In this figure, 1 is the acquisition unit of expected state value of a continuously adjustable reactive source, which is used to acquire the expected value of each continuously adjustable reactive power source state in the region according to the SCADA real-time data and the state estimation result; 2 is the calculation unit of dynamic support factor which is used to calculate the dynamic support factor according to a sensitivity coefficient of the continuously adjustable reactive power source to each of the central bus bars and a maximum reactive power variant per unit time; the dynamic power reactive support point selection unit of the power grid is used to select the continuously adjustable reactive power source as the dynamic reactive support point of power grid according to the dynamic support factor of continuously adjustable reactive power sources. 3 is the command issuing unit, which is used for issuing the control target voltage expectation value remote command to the dynamic reactive power support point of the power grid. The control target reactive power output expectation value remote command is issued to the rest continuously adjustable reactive power sources.

**5. Simulation Examples**

In order to verify the effect of the selection method for AVC control command, both the selection method for AVC control command and the existing control command are simulated in a typical second-level voltage control area (as shown in figure 2). There are two continuous adjustable reactive power sources in the region. G1 is the equivalent unit of grid-connected power plant and G2 is the grid reactive compensation equipment. The central bus is BUS3, and BUS1 and BUS2 are the Interconnection buses of G1 and G2 respectively. The sensitivity of G1 and G2 to BUS3 is 0.1. The sensitivity of G1 to BUS1 and BUS2 is 0.12 and 0.05 respectively, while the sensitivity of G2 to BUS1 and BUS2 is 0.05 and 0.12 respectively. The reactive regulation speed of G1 and G2 is 0.198 p.u. and 0.3 p.u. respectively. The typical CSVC control is used in the secondary voltage control with the
minimum voltage deviation of BUS3 as the control target. The expected voltage value of BUS3 is provided by three-level voltage controller, which is 1.1 p.u.. The current voltage of BUS1, BUS2 and BUS3 is 1.02 p.u., 1.02 p.u. and 1.0 p.u. respectively. The control dead zone of the bus voltage is 0.01 p.u., while the upper and lower limit is [0.85 p.u., 1.25 p.u.]. The current reactive power of G1 and G2 is 0.3 p.u.

![Schematic diagram of the typical secondary voltage control area](image)

**Figure 2.** Schematic diagram of the typical secondary voltage control area

The continuous adjustable reactive power sources in this region are simulated according to the method of selecting AVC control command which is proposed, and the steps are as follow:

1) The typical three-level voltage control mode is adopted, and the expected voltage of BUS3 is provided by the three-level voltage controller. The secondary voltage control adopts the typical CSVC control method, which takes the minimum voltage deviation of BUS3 as the control target and obtains the expected reactive power output of G1 and G2 as well as the expected voltage of BUS1 and BUS2. The expected reactive power output of G1 and G2 is 0.7975 p.u., while the expected voltage of BUS1 and BUS2 is 1.1046 p.u..

2) The dynamic support factors ($\zeta_1$ and $\zeta_2$) of G1 and G2 are calculated by:

$$\begin{align*}
\zeta_1 &= k_1 C_{pg1} + k_2 \Delta Q_{\Delta v1} \\
\zeta_2 &= k_1 C_{pg2} + k_2 \Delta Q_{\Delta v2}
\end{align*}$$

(4)

$C_{pg1}$ and $C_{pg2}$ are sensitivity coefficients of G1 and G2 to BUS3 (per-unit value). $\Delta Q_{\Delta v1}$ and $\Delta Q_{\Delta v2}$ are reactive power adjustment speeds (per-unit value). $k_1$ is the weight of sensitivity and $k_2$ is the weight of Reactive power adjustment speed. $k_1=100, k_2=10$, $\zeta_1=10+0.96=10.96$, $\zeta_2=10+3=13$, $\zeta_1<\zeta_2$.

G2 with the maximum regional dynamic support factor $\zeta$ is selected as the dynamic reactive power support point of power grid in this example. Deliver the remote adjustment command of the expected voltage with control target (1.1046 p.u. that the expected voltage of BUS2), and the remote adjustment command of the expected reactive power is delivered to G1 (0.7975 p.u. that the expected reactive power of G1).

3) The AVC first-level controller of each continuous adjustable reactive source controls the reactive power output according to the received voltage or the command of reactive.

The expected reactive power of G1 (0.7975 p.u.) is sent to G1, and the expected voltage of BUS2 (1.1046 p.u.) is sent to G2 according to the proposed selection method for AVC control command. The expected voltage of BUS1 and BUS2 (1.1046 p.u.) is delivered to G1 and G2 by using the existing command method. The results of these two methods are shown in Table 1.
Table 1. Results of two control methods

|       | the optimal operating condition(p.u.) | The proposed method(p.u.) | The existing method(p.u.) |
|-------|----------------------------------------|---------------------------|---------------------------|
| BUS1  | 1.1046                                 | 1.1066                    | 1.1006                    |
| BUS2  | 1.1046                                 | 1.1037                    | 1.1118                    |
| BUS3  | 1.1                                    | 1.1004                    | 1.1005                    |
| G1    | 0.7975                                 | 0.7978                    | 0.698                     |
| G2    | 0.7975                                 | 0.7975                    | 0.9                       |

The results of AVC control command selection method are consistent with the expected results in Table 1, which ensures the power grid operates under the best condition with safe, economical and high-quality operation of the power grid. The adjustment speed of reactive compensation equipment G2 is fast by using the existing AVC control command method. When the reactive power output of G2 is 0.9 p.u., the reactive power output of G1 which adjust slowly is 0.698 p.u. in actual control situation. The voltage of BUS3 is up to standard with 1.1005 p.u., but there is an imbalance of reactive power regulation that G2 grabs 0.1025 p.u. reactive power over expected, which makes the operating state of power grid deviate from the best operating condition.

6. Conclusion

Aiming at the problem that AVC control command leads to grabbing reactive power, this paper proposes a selection method of continuous adjustable AVC control command. The conclusion is as follows:

1) The proposed method is implemented specifically: Some of continuous adjustable reactive power sources are selected as the dynamic reactive power support of the power grid. The remote adjustment command of the expected voltage with control target is delivered as the power network dynamic reactive power support point, and the remote adjustment command of the expected voltage with control target is delivered for the other continuous adjustable reactive power sources.

2) The dynamic support factor \( \zeta \), the sensitivity of continuous adjustable reactive power source to central bus and the weight of self-regulation speed are selected as the standard of dynamic reactive power support point in power grid, which ensures that continuous adjustable reactive power source with high sensitivity and high speed is selected as the dynamic reactive power support point so that meets the dynamic reactive power support need.

3) The proposed method can be combined with the existing AVC system to form a set of AVC control command selection system, which avoids to change AVC control mode and core control algorithm and add hardware and software equipment.

4) The simulation results show that the proposed method can solve the problem of “grabbing reactive power”, which improves voltage quality and reduces loss as well as ensures safe, economical and high-quality operation of the power grid.

The relevant research results of this method have been applied for invention patent (application number: 201710002001.3), hoping to provide reference for further improvement of AVC system.

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