Power System’s Optimal Coordinated Control System Based on Hierarchical Control

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Abstract. With the continuous expansion of the power system and access of renewable energy, AGC and AVC play more and more important roles. However, due to the interaction between AGV and AVC control target and controlled objects, it is easy to cause the problem of repeated adjustment. At the same time, it is difficult to achieve the goal of multi-objective optimal control. In this paper, based on the hierarchical control method, power system’s Optimal Coordinated Control System (OCCS) of AGC and AVC is established. In the time dimension, the active power and reactive power are decomposed and coordinated, and the design scheme of each control layer is given. In the upper layer, the active and reactive power of the power plant are optimized and coordinated, and the multi-objective reference setting value is given. In the lower part of the OCCS, the control strategy of the advanced AGC is proposed to realize the comprehensive power consumption reduction, and advanced AGC is coordinated with reactive power control. At the same time, the idea of cross iteration is used to check and modify the control commands of AGC and AVC, and the comprehensive coordination control instructions are obtained, which can minimize the negative effects of the two kinds of control commands.

Introduction

Now in the power system, active power optimization dispatching and automatic generation control has been widely used. Generally adopt a hierarchical active dispatching mode, which is the coordination of day-ahead generation scheduling, real time dispatching and AGC [1]. The actual power system has also been formed the EDC / AGC integrated system. As the traditional AGC power generation adjustment is always lagging behind the load changes, some scholars put forward that use the ultra-short-term load forecast to achieve AGC advance control, and has much researches on the control strategy [1, 2], it is proved to be practicable and effective in the practical application. At the same time, with the emphasis on voltage stability, research of automatic voltage control system tends to be complete. AVC mainly focuses on the automatic optimization control of reactive power / voltage from the global point of view, French Electric Power Company (EDF) first proposed a hierarchical voltage control scheme [3]. Secondary voltage control has operated well in China provincial-level power grid [4, 5].

Need to point out is, refer to the automatic control of grid operation, a large number of studies are based on the assumptions of decoupling active and reactive power without the coordination of them. In the actual operation of the system, active power and reactive power is not completely decoupled, AGC and AVC control commands will affect each other especially the system is in heavy-load situation, it may lead to the decline of control targets, repeated adjustment of control equipment and so on which is bad to the system security and robustness. Therefore, AGC and AVC can not be used as two completely independent closed-loop control system acting on an actual power system. Otherwise, the interaction between AGC and AVC will inevitably affect the performance of its own instructions, and may even lead to security problems. At the same time, the automatic coordination and control of
AGC and AVC system is also in line with smart grid integration of a variety of intelligent devices and control systems trends [6].

The Optimal Coordinated Control System (OCCS) proposed in this paper, which is considering the future development of the power grid, taking into account the coupling relationship between the active frequency and the reactive voltage, improving the conventional control algorithm, making full use of the adjustable resources and control degrees of freedom, improve the safety of power grid operation, economy and power quality in the utmost extent.

The Design of the OCCS

Optimize the Coordination Control Structure

The idea of hierarchical control, progressive refinement is used in this paper, which the coordinated control of active frequency and reactive voltage is decomposed into integrated optimal control, predictive control and real-time control in the time dimension. This paper mainly discusses the control algorithm and control effect of the integrated control layer and the predictive control layer. The upper controller optimizes active and reactive power, and then provides the reference setting for comprehensive optimal economic and security. The lower controller optimal coordinate the active adjustment commands of the advanced AGC generators and the voltage regulation commands for the controllable generators in each AVC zone improves the control strategy of AGC in advance thus actualized comprehensive energy saving, minimizing the negative impact between the two types of control instructions, and achieve optimal coordination of economy and security. The structure of OCCS is shown in Fig.1.

![Figure 1. Structure diagram of OCCS.](image)

Evaluation Index System

The objective of OCCS is to ensure the safety, economy and quality of the system, this requires the establishment of an effective measure of system security and economic evaluation of the level to evaluate system control effect. The following three types of control indicators will be used in this control system.

1) Economic indicators. In order to achieve the comprehensive energy-saving of power system, the power generation cost index is corrected by the grid loss index. The objective function of the best comprehensive economic is:
\[ \phi(P_{Gi}, Q_{Gi}) = f_1(P_{Gi}) + \omega_{loss} f_2(V_i, \theta_i). \]  

(1)

F1 is the generation cost of the generator unit, expressed as a quadratic function:

\[ f_1(P_{Gi}) = \sum_{i \in S_G} \left( a_{2i} P_{Gi}^2 + a_{1i} P_{Gi} + a_{0i} \right). \]

(2)

F2 is the active loss of the grid, expressed as the sum of the injected power of the node:

\[ f_2(V_i, \theta_i) = \sum_{j \in N_i} V_i \sum_{V_j} G_{ij} \cos \theta_{ij}. \]

(3)

In the formula (1), \( \omega_{loss} \) is the weight coefficient of the grid loss in the economic index. In the formula (1), the coefficient is fuel characteristic coefficient of the generator unit. \( S_G \) is generator unit in control area. \( N \) is the number of nodes in the system.

2) Safety indicators. If the generator reactive margin is greater, the output is more balance, it will improve the stability of the system [7]. Define the reactive power uniform scale to measure the system voltage stability margin, like formula (4):

\[ M_{eq} = \left\lfloor \exp \left[ \sum_{k \in A} \left( \frac{Q_{lev,i} - \overline{Q}_{lev,A_k}}{Q_{lev,i} \max - Q_{lev,i} \min} \right)^2 \right] \right\rfloor^a. \]

(4)

\( k \) is the number of AVC partitions, \( A_k \) is the k-th partition, \( Q_{lev,i} \) is the output negative power of generator I, \( \overline{Q}_{lev,A_k} \) is the output negative power of the k-th partition, which are shown in formula (5).

\[ Q_{lev,i} = \frac{Q_{Gi} \max - Q_{Gi} \min}{Q_{Gi} \max - Q_{Gi} \min}, \quad \overline{Q}_{lev,A_k} = \frac{\sum_{i \in A_k} (Q_{Gi} - Q_{Gi} \min)}{\sum_{i \in A_k} (Q_{Gi} \max - Q_{Gi} \min)}. \]

(5)

\( Q_{Gi}, Q_{Gi} \max, Q_{Gi} \min \) is the current value and its upper and lower limits of the controllable generator I respectively.

3) Operating quality indicators. If control advanced AGC to eliminate the contact line power deviation, the control area to run in the ideal power generation operating point under the CPS standard, it will reduce the adjustment burden of real-time AGC generator unit, and reducing the meaningless exchange of electricity between regions. \( \Delta P_{tie} \) and \( \Delta V_{ref} \), which is the deviation of the exchange power of the tie-line from the planned value and the deviation of the central bus from the reference value, measure the control quality of AGC and AVC system.

**Integrated Optimal Control Model**

The optimization goal of conventional optimal power flow is the least cost of power generation or net loss, it is possible to adjust the reactive power output of some generators to the limit, which lead the system reactive margin may reduce, the unbalance of reactive power output between generators and deteriorate the voltage stability of the grid. In order to reduce the contradiction between economy and security, introduce the safety index into the optimization goal, which makes the reactive power the most balanced.
Considering the economy and security of the system, the optimization goal of the comprehensive optimal coordinated control strategy is:

\[
\min F = \min \left( \phi(P_{Gi}, Q_{Gi}) + \lambda \cdot \psi(P_{Gi}, Q_{Gi}) \right)
\]  

(7)

\( \lambda \) is the weight coefficient of reactive power uniform scale in the target. The equation constraints are system power flow equations:

\[
\begin{align*}
P_i &= V_i \sum_{j \in N} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad i \in S_N \\
Q_i &= V_i \sum_{j \in N} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad i \in S_N
\end{align*}
\]  

(8)

The inequality constraints are:

\[
\begin{align*}
P_{Gi}^{\text{min}} &\leq P_{Gi} \leq P_{Gi}^{\text{max}} \quad i \in S_G \\
Q_{Gi}^{\text{min}} &\leq Q_{Gi} \leq Q_{Gi}^{\text{max}} \quad i \in S_G \\
V_i^{\text{min}} &\leq V_i \leq V_i^{\text{max}} \quad i \in S_N \\
P_{gi} &\leq P_{gi}^{\text{max}} \quad (i,j) \in S_L
\end{align*}
\]  

(9)

The above inequation constraints represent the upper and lower bounds of the active power and reactive power output of the generator, node voltage amplitude constraints and transmission line flow constraints, respectively. \( S_G, S_N, S_L \) are the set of generator, node and transmission line in the system.

The primal-dual interior point method is used to solve the optimal power flow problem[8]. The active power reference value of the advanced AGC generator unit and the voltage reference value of the AVC partition center node are obtained.

**Predictive Control Model**

**Improved Advanced AGC Control Strategy**

The traditional algorithm determines the total adjusted power required of the AGC advance control according to the load forecast and the tie-line switching power plan, and the generating cost is the only basis for power distribution, but there is a deviation between the power of the tie-line obtained by the conventional method and the planned value, because the grid loss of the control area is ignored. In this paper, the power deviation of tie-line is eliminated by iterative solution, and achieve a comprehensive minimum of power generation costs and grid losses by improving the distribution of power.

The total adjusted power of the area is as follows:

\[
P_R = \begin{cases} 
  P_L^f + P_{tie}^f + P_{loss}^f - \sum_{i \in S_G} P_{Gi}^f & k = 1 \\
  P_{tie}^f - P_{tie}^{f-1} & k \geq 2 
\end{cases}
\]  

(10)

\( P_L^f \) is Short-term load forecast value, \( P_{tie}^f \) is the exchange power plan value at the predicted time, and the outward delivery direction is positive. \( P_{Gi}^f \) is the active power output reference value of each
generator given by the optimal control layer. $P'_{\text{loss}}$ is current active loss of the system, $k$ is number of iterations.

Regard the comprehensive minimum of the power generation cost and grid loss as the advanced control target, the model establishment of the total adjustment power in the AGC generator unit ahead of the distribution is as follows:

$$
\begin{bmatrix}
\min \kappa \sum_{i \in S_{\text{AGC}}} C_i (\Delta P_{G_i}) + \sigma \sum_{i \in S_{\text{AGC}}} S_i \Delta P_{G_i} \\
\text{s.t.} \sum_{i \in S_{\text{AGC}}} \Delta P_{G_i} = P_R \\
\Delta P_{G_i}^{\text{df}} \leq \Delta P_{G_i} \leq \Delta P_{G_i}^{\text{av}}
\end{bmatrix}
$$

(11)

$\kappa, \sigma$ is the weight coefficient, $S_{\text{AGC}}$ is the set of advanced AGC generator unit in the area, $C_i$, Purchase cost of generator unit $i$, $S_i$ is grid loss sensitivity of generator unit $i$. $\Delta P_{G_i}^{\text{df}}, \Delta P_{G_i}^{\text{av}}$ is the upper and lower limits of the unit adjustable power within the control cycle $T$, respectively. In the formula (12)

$$
\begin{bmatrix}
\Delta P_{G_i}^{\text{df}} = \min (P_{G_i}^{\text{max}} - P_{G_i}^{\text{av}}, R_{G_i}^{\text{df}} \cdot T) \\
\Delta P_{G_i}^{\text{av}} = \max (P_{G_i}^{\text{min}} - P_{G_i}^{\text{av}}, -R_{G_i}^{\text{df}} \cdot T)
\end{bmatrix}
$$

(12)

$P_{G_i}^{\text{av}}$ is the reference value of the active output of unit $i$ given to the optimal control layer. $P_{G_i}^{\text{max}}, P_{G_i}^{\text{min}}$ is the output upper and lower limit values of generator unit $i$. $R_{G_i}^{\text{df}}, R_{G_i}^{\text{df}}$ is turn up and down rate of generator unit $i$. $T$ is predictive control cycle. he above optimization problems are solved iteratively until satisfy $P_R \leq \varepsilon$ in (12).

**Coordinate the Advanced AGC and AVC Control Strategy**

System load and generator active power change will cause the generator reactive power changes [10], which will affect the system voltage level. The adjustment of advanced AGC is considered to be a disturbance, maintaining a reasonable voltage distribution from the global point of view, considering the AVC partition voltage level and reactive margin, re-coordinate and optimize the main reactive power of the grid, updated in time the voltage setting of the master node, So that the reactive power distribution of the system is more reasonable. Regard active power adjustment and load fluctuations of advanced AGC generators as a disturbance, simulate the steady-state response of the system with AVC like the method in Ref. [11], and consider the central bus voltage $V_p$ and the control generators reactive power level $Q_{\text{lev}}$ as input, the reactive power of each generator as the optimization variable, calculating the generator reactive power adjustment according to formula (14), and sending the corrected central bus voltage, which is considered as an updated reference value to the real-time control layer.

$$
\begin{align*}
\min & \left[ V_p + C_p \Delta Q_G - V_{p,\text{ref}}^{\text{H}} \right]^T R \left[ V_p + C_p \Delta Q_G - V_{p,\text{ref}}^{\text{H}} \right] + \left[ Q_{\text{ref}} + \Delta Q_G - \bar{Q}_{\text{lev,\text{A}}_i}^{\text{ref,\text{H}}} \right]^T W \left[ Q_{\text{ref}} + \Delta Q_G - \bar{Q}_{\text{lev,\text{A}}_i}^{\text{ref,\text{H}}} \right] \\
\text{s.t.} & \begin{bmatrix}
Q_G^{\text{min}} \leq Q_G + \Delta Q_G \leq Q_G^{\text{max}} \\
V_{G_i}^{\text{min}} \leq V_{G_i} + C_{\text{PS}} \Delta Q_{G_i} \leq V_{G_i}^{\text{max}} \\
V_p^{\text{min}} \leq V_p + C_p \Delta Q_G \leq V_p^{\text{max}} \\
V_{\text{PS}}^{\text{min}} \leq V_{\text{PS}} + C_{\text{PS}} \Delta Q_{G_i} \leq V_{\text{PS}}^{\text{max}}
\end{bmatrix}
\end{align*}
$$

(13)

$Q_{\text{lev}}$ is reactive power level of each generator, $\bar{Q}_{\text{lev,\text{A}}_i}^{\text{ref,\text{H}}}$ is the reference value of reactive power output level in the generator located area, the optimal power flow calculation is given by the highest level. $R, W$ is weight matrix, $Q_G, Q_G^{\text{min}}, Q_G^{\text{max}}$ is respectively, the current value, the lower limit and the upper
limit controlling the generator reactive power output. $V_G$, $V_G^{\min}$ and $V_G^{\max}$ are the current value, the lower limit and the upper limit of generator voltage. $V_P$, $V_P^{\min}$, $V_P^{\max}$ and $V_P^{\text{ref,H}}$ are the current value, the lower limit, the upper limit and the reference value sent by highest layer of the center bus voltage, respectively. $V_{PS}$, $V_{PS}^{\min}$, $V_{PS}^{\max}$ are the current value, the lower limit and the upper limit of the key node in system, respectively. $C_P$, $C_G$, $C_{PS}$ are the sensitivity matrix of the generator reactive power to the generator voltage and the key node voltage, respectively.

**Coordination Part Based on Cross Optimization**

AVC on the reactive voltage adjustment will cause changes in system power loss, which destroys the control effect of the AGC on the tie-line power, and brings about the repeated adjustment problem of the AGC and the AVC, based on the idea of active and reactive power cross-iteration, the control instructions of AGC and AVC are alternately calculated until the control target converges. The flow chart of iterative algorithm is shown in fig.2.

![Flow chart of iterative algorithm](image)

Figure 2. Flow chart of iterative algorithm.

In the advanced AGC and AVC improved model proposed in this paper, the optimization target is the decrease of system active loss, that is, the optimization direction of each iteration is the same, so the adjustment will be decreased with the iteration continue. The influence between active and reactive power is positively related to the amplitude of the adjustment. Generally, after 3 ~ 4 crossed iterations, it can be converted to the threshold set by the quality index system.

**Summary**

In this paper, the automatic optimization coordinated control system is based on a reasonable hierarchical scheduling model of active power, combining with requirements of the existing AGC and AVC closed-loop system for coordinated control, through the combinational optimization of active and reactive power and the improvements to the conventional control strategy, which realizes decomposition coordination in time, space and target dimensions for the automatic generator control and automatic voltage control. According to different time scales and control targets, the automatic
coordinated control system makes full use of the original control method and algorithm coupling active and reactive power, incorporates the need for coordinate indicators into the control area, reconstructs modeling to solve. Under the coordinated control strategy, the tie-line for power of control area and central bus voltage is maintained at the reference value, and the economy and voltage stability margin of the system compared to conventional control is considerably improved, multi-objective coordinated optimization operation is achieved.

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