Wide-area Optimal Damping Control System Research with Grid and Generators Coordination

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Abstract—Due to the large number of renewable energy, the small disturbance stability of power system has drawn great concern. In order to damp small disturbance oscillation effectively, based on hierarchical control theory, the complex various power system control systems have been coordinated, and the Wide-area Optimal Damping Control System has been set up. In this system, the damping of the power system is taken as the index of the event, and the generation of the event is used as the driving force to control the system. The system can effectively solve the interaction between the AGC system and AVC system by means of the cross-iteration method, and realize the optimal control of these control systems. The IEEE system has been simulated under various operating states and the results show that the WODCS can effectively eliminate the weak damping mode of the system, and realized the optimal coordination.

Index Terms-- renewable energy; small signal stability; hierarchical control; Wide-area Optimal Damping Control System (WODCS); optimal coordination

I. INTRODUCTION

In recent years, the power system is developing rapidly all around the world, the scale expands unceasingly and the structure is increasingly complex, which also brings many new unfavorable factors for power system’s safe and stable operation. Among them, small disturbance stability (small signal stability) affects the dynamic safety of power system seriously [1-3]. Due to the rapid growth of load demands and the relative backwardness of grid construction, some transmission lines in power system are under heavy load or overload operation. The problem of small signal stability is becoming more and more prominent. Especially, low-frequency oscillation caused by weak damping mode has become an important factor affecting the safe and stable operation of power system [4].

Countermeasures to suppress low-frequency oscillation and improve small signal stability are generally divided into primary system and secondary system two aspects [5-6]. As an important control measure in secondary system, although the power system stabilizer(PSS) can effectively improve the damping of system, but due to its own limitations, it can’t completely solve the problem of small signal stability [7-8]. Recent years, power generation rescheduling technology based on primary system began to improve transmission capacity limited by small signal stability [9-11]. However, due to the closer connection between power grids, the capacity of network is getting closer to its limit, the coupling between active power and reactive power in power system has enhanced, which makes the key central node voltage changes and deviate from its set of reference values in voltage automatic voltage control (AVC) during the regulation process of automatic generation control(AGC) system, so that caused repeated regulation of AVC system. Similarly, the adjustment of AVC system can caused the adjustment of AGC and triggers repeated regulation. Therefore, when considering introducing AGC system to new function of suppressing small signal system, it is necessary to consider the interaction between AGC and AVC system, and it is necessary to coordinate and optimize the control instruction.

Considering the coordination between AGC and AVC system, this paper proposes and establishes a Wide-area Optimal Damping Control System (WODCS), which is based on idea and method of hybrid control system [12-15], in order to enhance the damping of system. Different from the traditional time-based control mode, WODCS “defines” the damping strength of system as the condition of occurrence and uses this event as the driving body of system regulation. At the same time, this system adopts the hierarchical control structure framework to achieve multi-objective optimization and coordination problem between AGC and AVC system. As an illustration, the proposed methods have applied to the IEEE 5-machine standard simulation system under various operation states and the computer simulation results demonstrate the correctness and effectiveness of the proposed theory and method.

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II. DESIGN OF WIDE-AREA OPTIMAL DAMPING CONTROL SYSTEM

A. Wide-area Optimal Damping Control System Model

The design of WODCS system in this paper is a coordinated optimal control system based on the hybrid control system. The WODCS system improves the damping values of power system through improving the operation mode of power system, so as to eliminate the weak damping mode of the system, so that the running power system has a good dynamic performance.

WODCS system usually consists of data processing interface link, event judgment link (event definition and generation link), the highest control decision level, the middle of coordination and optimization processing level, the underlying implementation device and human-machine interface, the model shown in Figure 1.

![Model of WODCS system](Figure 1. Model of WODCS system)

WODCS system gets access to real-time power system parameters and operation data through the EMS and WARM system, doing data validation and real-time storage through data processing link. The processed data of power system is transmitted to event judgment link, and it is judged whether or not an event happens by this link. If the system is running in “under-optimized” or “bad” state, the event judgment link will “trigger” the event and use this event to drive WODCS system to control the highest decision-making.

The advantage of WODCS system is that it is based on event to start control, which can avoid the shortcomings of adopting time-start in conventional control. Event judgment link can set the threshold according to the actual situation of power system. When the system operation index is below the set threshold, the event is triggered to drive the control so that power system can always run in the optimized or quasi-optimized state. Another benefit of event-based control approach is that it can avoid the increased cost due to frequent actions of controller.

Event judgment link of WODCS system can be defined as the formula (1) to form the logic of “event”. Assuming the system set the weak damping mode threshold as $\xi_{\text{min}}$, the weak damping mode damping ratio $\xi$ of the current operating point can be calculated by the data comes from the processing link, the event judgment link can automatically judging whether the event should be start up by comparing the size of the two values.

$$E_{\text{safe}} = \begin{cases} P_{\text{con}}, & \xi_{\text{ref}} - \xi_{\text{min}} > \Delta \xi_{\text{safe}} \\ P_{\text{non}}, & \xi_{\text{ref}} - \xi_{\text{min}} \leq \Delta \xi_{\text{safe}} \end{cases}$$

(1)

Where $\Delta \xi_{\text{safe}}$ is the set maximum deference value, which is dead zone of control. $P_{\text{con}}$ and $P_{\text{non}}$ represent need and not need to start event for damping control separately, which can be taken 0.05 as the lower limit of $\xi_{\text{min}}$ to ensure the stable operation of system[4,16]. It can also take the damping ratio of not less than 0.1~0.3[17]. Literature [5] and [9] regard the weakest damping ratio $\xi_{\text{min}}$ between 0.03~0.05 and $\xi_{\text{ref}} \approx \xi_{\text{min}}$ as the system is small signal stable[5,9]. The bigger of the value of $\xi_{\text{min}}$, the higher the level of system small signal stability. This paper take the $\xi_{\text{ref}}$ as 0.05.

In the WODCS system model, the data processing link also transfers the processed real-time data to the various control layers so that each control layer can perform on-line calculation and control.

B. Hierarchical Function of Coordination Optimization Damping Control System

1) The Function of the Highest Control Decision Layer

The highest control decision-making layer makes control decision driven by “event” which comes up in the event judgment link and sent the power system status indicators and control command reference value to the middle of coordination and optimization of the processing layer. The highest level will output the related instruction information and events information to the man-machine interface. The man-machine interface is the communication unit between the dispatcher and the control system. The dispatcher can know the current operation of the power system through this interface, the pre-control instruction provided by the highest level and the impact to power system operation situation if the control decision be taken, so that the dispatcher can evaluate decisions. At the same time, the dispatcher can also output the control decision obtained from other channels directly to the intermediate coordination and optimization processing layer, and make the WODCS system coordinate and optimize processing layer and the bottom control device to execute, which can make full use of the hardware and software resources of the control system.

The dispatcher can also modify the parameter of the event judgment link through the man-machine interface, adjust the threshold of event initiation in the event judgment link according to the system status and dispatcher experience or the assistance of the external software, and optimize the control decision of the WODCS system.

2) Function of Intermediate Coordination Optimization Processing Layer

According to the reference value of the key central node voltage provided by the highest control decision layer (or the man-machine interface) and the reference value of the generator output active power, the middle coordination and
intermediate coordination optimization processing layer, then according to the control reference value provided by the intermediate coordination optimization processing layer, and the relevant information of the underlying layer to the "quasi-optimized" state. The underlying control layer outputs so that the system operates in the non-event "optimized" or eliminate the event which started by the event judgment link, dispatcher can further monitor the control system and control information to the man-machine interface so that the middle coordination and optimization processing layer feedback the relevant control information to the man-machine interface so that the dispatcher can further monitor the control system and understand the power system state.

3) Function of The Underlying Implementation Device

The underlying power plant, the substation and the FACTS device controller can control the actual power system according to the control reference value provided by the intermediate coordination optimization processing layer, then eliminate the event which started by the event judgment link, so that the system operates in the non-event "optimized" or "quasi-optimized" state. The underlying control layer outputs the relevant information of the underlying layer to the intermediate coordination optimization processing layer, and receives the control of the intermediate coordination optimization processing layer.

III. ALGORITHM DESIGN OF WIDE-AREA OPTIMAL DAMPING CONTROL SYSTEM

A. Control Algorithm Design of the Highest Level of WODCS System

When the power system is running in the weak damping mode, the WODCS’s event judgment link will start the event-driven control, the start or not start result of event judgment is transmitted to the highest control decision-making level. Event judgment and control start-up link calculate and judge according to the logical link in equation (1).

Damping control module is the core of the highest control decision-making layer of the WODCS system. This module adjusts the power output of the generator according to the damping quantity needed to eliminate the weak damping mode of the system. The main function of this control module is to improve the minimum damping value of the system by adjusting the generator output, and to eliminate the influence of the reactive power control system on the system damping.

The designed algorithm of damping control module is

\[
\min \sum_{i=1}^{n} \xi_i \Delta P_{i}^{ref}
\]

s.t. \[\Delta \xi_i = k \xi_i - \zeta = \sum_{i=1}^{n} S_{ij} \Delta P_{j}^{ref} \]

\[\sum_{i=1}^{n} S_{ij} \Delta P_{j}^{ref} = 0 \]

\[\Delta P_i \leq \Delta P_{i}^{ref} \leq \Delta P_{i}^{\text{max}}, \quad i = 1, 2, \cdots, n\]

In this formula, n is the number of controllable AGC units. \(\Delta P_{i}^{ref}\) is the output adjustment reference quantity of AGC unit i, \(k\xi_i\) is the weight of the reactive power of the corresponding unit (generally considering the coal consumption index of the unit, etc). \(\zeta\) is the weak damping value of current operating point (including the operation point before cross optimization process). \(\zeta T\) is the damping threshold of control system. \(k\zeta\) is the control margin (generally based on engineering experience to determine, and \(k\zeta > 1\)). \(S_{ij}\) is the sensitivity between the weak damping mode damping value and the active power of AGC unit i, \(S_{ij}^{\text{ref}}\) is the sensitivity between active power of the contact line section and the active power of AGC unit i. \(\Delta P_{i}^{\text{max}}\) and \(\Delta P_{i}^{\text{min}}\) is the lower and upper limits of active power adjustment of AGC unit i. According to this model can obtain the active power adjustment reference \(\Delta P_{i}\) of AGC unit i.

For the sensitivity \(S_{ij}^\xi\) between the weak damping mode damping value and the active power output of the AGC unit i, it can be obtained by set active power as \(\Delta P_{i}^{\max}\) and keep other parameters the same, then calculate the weak damping mode damping \(\zeta (P_i + \Delta P_{i}^{\max})\) after setting, and then get the sensitivity value.

\[S_{ij}^\xi = \frac{\partial \zeta (P_i + \Delta P_{i}^{\max})}{\partial P_i} - \zeta (P_i) \]

(3)

The sensitivity \(S_{ij}^{\text{ref}}\) between active power of the contact line section and the active power of the AGC unit i can be obtained by subtracting \(\Delta P_{i}^{\max}\) from the active power of the unit i and keeping the other operating parameters unchanged. Thus, calculate the active power \(f_{ij} (P_i + \Delta P_{i}^{\max})\) and then sensitivity value is obtained.

\[S_{ij}^{\text{ref}} = \frac{\partial f_{ij} (P_i + \Delta P_{i}^{\max})}{\partial P_i} - f_{ij} (P_i) \]

(4)

For each other AGC unit can use the above method to obtain the sensitivity relationship between this unit’s active power and weak damping mode damping value and the contact line section’s active power value.

At the highest level, the optimal power flow of the whole power system can be calculated, and the voltage reference value (or the man-machine interface) of the key node in the current state can be obtained and sent to the middle layer as the control command.

B. Control Algorithm Design of the Intermediate Layer for WODCS System

When the top of the WODCS system gets the active power adjustment reference value \(\Delta P_{i}^{ref}\) of the AGC unit i or the key central node voltage reference value, it is sent as the control command to the intermediate coordination and optimization control layer. Because the active power of the generator set is adjusted in the damping control module at the highest level, the power flow in the system will change, especially when some active power and reactive power coupling are strong. Changes in the system power flow will cause the voltage deviation of the key central node from the set value, at this time, it is necessary to do some AVC adjustment. AVC adjustment will also lead to changes in the system’s power flow, and then change the active power value of contact line section, which lead to the AGC system to adjust. So it is
necessary to optimize the coordinated control between AGC and AVC in the middle layer of WODCS system.

In this paper, the idea of cross iteration between active AGC and reactive AVC operation is proposed, and the control instructions of AGC and AVC are calculated alternately until the whole control target converges. In view of the fact that the iterative process may lead to not convergence, the maximum number of iterations is set to ensure the effective operation of the control system in this paper. The calculation flow of the intermediate coordination optimization processing layer is shown in Figure 2.

In the AVC operation link, according to the traditional two-level voltage control method to adjust and optimize, the model is as follows.

\[
\begin{align*}
\text{min} & \quad \sum_{j=1}^{N_S} y_j (U_j^C - U_j^{ref})^2 \\
\text{s.t.} & \quad 0 = U_j^{ref} - \sum_{i=1}^{N_G} S_{ji} (U_i^C - U_i^{ref}), \quad j = 1, 2, \ldots, N_S \\
& \quad \Delta U_i^C \leq U_i^C \leq \Delta U_i^C, \quad i = 1, 2, \ldots, N_G
\end{align*}
\]

\(U_j^{ref}\) is the voltage reference value of AVC unit (including SVC unit) after the optimal power flow calculating taken by the highest level. \(U_i^C\) is the voltage control command value come up with the secondary voltage calculation. \(y_j\) is the weight of voltage adjustment of unit \(i\). \(N_G\) is the number of generator sets (including SVC device) in the secondary voltage control area. \(U_j^{ref}\) is the key central node voltage settings which is released by the highest level. \(S_{ji}\) is relatively sensitivity between voltage of key central node \(j\) and the voltage of point \(i\) in AVC units (including SVC device). \(N_S\) is the number of key central nodes throughout the system. \(\Delta U_i\) and \(\Delta U_i\) are the upper and lower boundaries of voltage adjustment for AVC unit (including the SVC device) node \(i\).

AGC calculation is mainly to achieve the active power control of the contact line section in the reference value dead zone, when the previous control adjustment makes the active power section of the contact line deviation from the reference dead zone, the control will take adjustment, the model is

\[
\begin{align*}
\min & \quad \sum_{j=1}^{N_A} \beta_j (\Delta P_j^C - \Delta P_j^{ref})^2 \\
\text{s.t.} & \quad 0 = \sum_{i=1}^{N_i} S_{ji} \Delta P_i^C \\
& \quad \Delta P_i^C \leq \Delta P_i^C \leq \Delta P_i^C
\end{align*}
\]

Where: \(N_A\) is the number of controllable AGC units in the control area. \(\beta_j\) is the weight of the active output of the corresponding unit (generally consider the coal consumption index of the unit, etc.). \(\Delta P_i^{ref}\) is the output reference quantity of the given AGC unit \(i\). \(\Delta P_i^C\) is the active power control command value calculated by the AGC. \(S_{ji}\) is the active power of the active power of the contact line section for the AGC unit \(i\). \(\Delta P_i^C\) and \(\Delta P_i^C\) are the upper and lower limits of the active power adjustment of the AGC unit \(i\).

When the AGC and AVC coordination optimization control is finished, the critical central node voltage and the active power value of the contact line section have been controlled within the dead zone of the set value and the power system has basically eliminated the weak damping mode. After the calculation of the intermediate coordination and optimization processing layer is completed, the control command value \(\Delta P_i^C\) of the active power output by the AGC unit and the AVC voltage control command value calculated by the secondary voltage are output from the calculation result and transmitted to the underlying execution device.

C. The Underlying of WODCS System

The bottom control device controller adjusts the parameters according to the AGC unit active power reference value, the AVC machine terminal voltage reference value and the SVC device voltage reference value issued by the intermediate coordination and optimization processing layer. As the intermediate coordination and processing layer has the output and voltage of every control devices been optimized and coordinated control, the bottom of the controller can be adjusted directly to optimize the parameters without the need for new settings, directly through the collection of local feedback to make the equipment and components of the device to meet the demands of middle layer, so that the system can effectively eliminate a variety of security and stability events and make the actual power system run in a safe and stable state. The underlying control layer feedback the relevant information to the intermediate of the coordination and optimization of the processing layer at the same time, so that the middle layer of the coordination and optimization can take the corresponding treatment.

IV. SIMULATION CALCULATION

A. The Underlying of WODCS System

This paper uses the IEEE 5-machine 14-node system.
shown in Fig. 3 for simulation. The simulation process is realized by means of the PSAT software package and the self-programming (the parameters of simulation system comes from the 5-machine parameters of the software package in PSAT). In the IEEE 5-machine 14-node system, No. 1 machine is the balancing machine, 2, 3, 6, 8 are the PV node, others for the PQ node. Considering the dynamism of five generators and the corresponding excitation dynamics. The excitation using the conventional PID control model without PSS control. In order to make the simulation more normalized, those following data are all using the own data carried by PSAT software package, the system load value, output active power value of generators and the terminal voltage value of generators, network parameters, synchronous motor parameters, excitation system parameters, etc.

In order to simulate AGC and AVC functions, the system is divided into two AGC regions and three AVC secondary voltage regions. Among them, 1, 2, 3, 4, 5 are AGC region 1, 6, 7, 8, 9, 10, 11, 12, 13, 14 are AGC region 2, two AGC regions are connected by line sections 4-7, 4-9, 5-6, regard the sum of active power of the three lines as the power set value and the controlled objects. Maintain the contact line power at a certain set value dead zone during the system weak damping control process. AVC is divided into three regions, the load node 5, 9, 11 as a key hub node. Maintain the key central node voltage at the set value during the generator reactive power control process, so as to achieve function of AVC.

**B. Results of Simulation**

In the simulation, the initial state is sending electricity from region 1 to region 2, where the active power flow of tie line 4-7 section is 0.3972pu, which is 0.2170pu for tie line 4-9, and line 5-6 is 0.6283pu. The simulation takes comparative study of the following two cases: 1) Regard the operation mode consists of own carried data which includes active and reactive load value and the generator active power output value and terminal voltage value by software package as case 1. 2) Regard the operation mode which consists of active load value and the generator active power reducing 5% as case 2. In these three cases, adopt the method mentioned in this paper to adjust the system respectively. So as to control the system to eliminate the weak damping mode, while the central node voltage and tie line section active power value are maintained at the set value, take the set value before control and adjustment as the standard. The results shown in Table 1.

**TABLE I. SIMULATION RESULT COMPARISON UNDER STATE 1**

<table>
<thead>
<tr>
<th>Status</th>
<th>Key Central Node</th>
<th>Voltage/pu</th>
<th>Tie-line power/pu</th>
<th>Value of Minimum Damping Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>9</td>
<td>1.012 9</td>
<td>1.2425</td>
<td>0.0034</td>
</tr>
<tr>
<td>After</td>
<td>9</td>
<td>1.012 9</td>
<td>Reduce 0.003%</td>
<td>0.0517</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1.035 7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The simulation results show that the original system has weak damped oscillation mode, the oscillation frequency is 1.39Hz, which belongs to the local oscillation of generator 2 respect to the generator 1. It can be seen from Table 1 that the damping ratio of the weak damping mode of the system after adjustment has increased from 0.0034 to 0.0517, the voltage of the key central node has not changed and maintained at the set value, the active power of the tie line has changed by 0.003%, and it maintained at the set value area, which has achieved the desired results. In the cross-iteration, the system does not repeat the iteration and only experienced a round of adjustment, the minimum damping value has met the threshold requirements after the coordination of AGC and AVC, the adjustment process of system operation mode is shown in Table 2.

**TABLE II. ADJUSTMENT UNDER STATE 1**

<table>
<thead>
<tr>
<th>Number of generator</th>
<th>Adjustment value of active power output/pu</th>
<th>Adjustment value of terminal voltage/pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.173 5</td>
<td>-0.003 2</td>
</tr>
<tr>
<td>3</td>
<td>-0.027 4</td>
<td>-0.000 2</td>
</tr>
<tr>
<td>6</td>
<td>0.475 6</td>
<td>-0.001 4</td>
</tr>
<tr>
<td>8</td>
<td>0.026 9</td>
<td>-0.002 3</td>
</tr>
</tbody>
</table>

From Table 2, it can be seen that the terminal voltage of the generator has decreased slightly, but the degree is pretty small (the maximum is only 0.3%). So that the voltage of key central node can be maintained and it will not influence the damping ratio of weak damping mode because of changes of terminal voltage.

For Case 2, when the generator output and the load active power are reduced by 5%, the voltage of the critical central node of the system increases, the power of the tie line decreases and the damping value of the weak damping mode increases, but it still belongs to the local oscillation mode between generator 2 and generator 1. This simulation calculation only has one round of cross-iteration to achieve the desired results. The simulation results are shown in Table 3, and the cross-iterative adjustment process is shown in Table 4.

**V. CONCLUSION**

This paper combined the concepts and methods of hybrid control system, used the theoretical results and practical
application of hybrid electric power control system and finally

<table>
<thead>
<tr>
<th>Status</th>
<th>Key Central Node</th>
<th>Voltage/pu</th>
<th>Tie-line power/pu</th>
<th>Value of Minimum Damping Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>5</td>
<td>1.0051</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.0144</td>
<td>1.18</td>
<td>0.0178</td>
</tr>
<tr>
<td>After</td>
<td>5</td>
<td>1.0051</td>
<td>Reduce 0.20%</td>
<td>0.0589</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.0144</td>
<td>relative to initial status</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1.0366</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

presented and set up the Wide-area Optimal Damping Control System (WODCS) system based on hierarchical control. This paper introduced the concepts of WODCS system, the control structure diagram and the function description of module. The weak damping problem and multi-objective optimization problem of power system have been solved effectively by hierarchical control and the design of event-driven function, etc. In addition, it has also solved the strong coupling problem between the active power and the reactive power in the power system and improves the safety and stability of the whole power system by the method of cross optimization and coordination. This paper realized the optimal coordinated control between the active and reactive power in the power system, avoiding the huge computational burden caused by the simple modeling of two active and reactive power subsystems. Finally, the simulation results validated the correctness of the proposed theory.

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