Frequency Stability and Coordinated Control Strategies of UHV AC/DC Receiving End Grid

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Abstract. In order to improve the control accuracy of UHV AC/DC receiving-end grid for DC blocking faults, method of making online strategies that coordinate different control measures including emergency DC power support, pumped storage control and accurate load shedding, is proposed considering safety and stability of system frequency and transmission sections. This paper analyzes the coordination principle of different control measures and processes frequency emergency control calculation first, assisted by overload sections corrective control as frequency meets stability requirement. The comprehensive evaluation indexes are present to formulate coordinated control strategies by decoupling and aggregation, which make grid frequency return stable and also eliminate the hidden overload dangers of transmission sections. Based on the typical operating mode of actual grid, the effectiveness of the proposed coordinated control decision making was verified.

Introduction

Due to the increase of transmission power capacity of UHV AC/DC grid, the coupling between sending and receiving ends is becoming increasingly closer. With the strong DC and weak AC characteristics, problems such as frequency drop caused by DC blocking and overload of 500kV AC grid have become increasingly prominent. At present, domestic and foreign scholars have made some achievements in frequency stability of the receiving end grid. Various measures like emergency DC power support (EDCPS), pumping and accurate load shedding are realized. However, the existing frequency emergency coordinated control system (FECCS) \cite{5-6} has not yet realized online coordination and accurate control of different control measures and multiple stability constraints.

Yusheng Xue \cite{7} first proposed an emergency control framework of “online pre-decision, real-time matching”, based on which, the coordination of preventive and emergency control was studied in \cite{8}. Paper \cite{9} proposed performance measures such as cutting machines, load shedding and DC modulation, and firstly calculated the stability of transient power angle before considering transient voltage and frequency stability. Paper \cite{10} considered a variety of stability issues and improved the emergency control algorithm. Paper \cite{11} proposed a harmonized coordination corrective control and preventive control calculation method for overload problems of equipment and transmission section. The difference between emergency control and corrective control was compared in terms of control criteria and cost performance in \cite{12}. However, an accurate and reliable coordination control decision has not yet been formed.

Based on the above reasons, the main contributions of this paper are three-fold: (1) Frequency characteristics after Jin-Su DC unipolar and bipolar blocking faults are analyzed. (2) The coordination principle of different control measures in the existing FECCS is proposed. (3) Based on the idea of decomposition-aggregation, an online control decision coordinating the controllable space of EDCPS, pumping and accurate load shedding is proposed to eliminate possibility of section overload. After checking frequency stability, the simulation results verify the necessity and effectiveness of coordinated control.
Frequency Emergency Control

Receiving End Grid

As shown in Fig. 1, Jiangsu Power Grid has built DC transmission lines of ±800kV Jin-Su DC and ±500kV Long-Zheng DC by 2015. In addition, there are 10 circuits of 500kV AC inter-province tie lines. The AC grid has presented a new distinctive feature of strong DC and weak AC [13]. The power capacity of transmission sections in AC power grid has grown limitedly, without enough stability margin to withstand DC blocking faults.

Frequency Characteristics after DC Blocking

A typical summer operation model of Jiangsu power grid is established by PSD-BPA transient stability program for simulation analysis, where Long-Zheng DC operates at 2200 MW and Jin-Su DC operates at 5600 MW. Under the effect of primary frequency modulation, the system has a good frequency performance after DC unipolar blocking. The frequency drops to 49.84 Hz in Fig. 2, which meets the requirement of frequency deviation security. However, in the case of bipolar blocking, the power shortage caused by momentary fault is so large that the frequency fails to keep stable within the safe range by only relying on the function of primary frequency modulation.

Frequency Emergency Coordinated Control

Considering the frequency problem, FECCS construction has been carried out in Fig. 3. The DC system has a 3s short-term and 1.4 times rated power overload capacity. EDCPS is to increase the transmission power of other normally operating DC lines, whose control cost performance is better. By pumped storage substations to quickly cut pumps at the same time or in multiple stages and even operate from pumping operation to power generation operation, the load is released to reduce power shortage. This measure has a negative impact on the operation of pumped storage power plants, while load shedding on grid companies and users is greater. In summary, FECCS coordination principle should be given priority to EDCPS, followed by pumping shedding, and finally accurate load control.

Different strategies of Jin-Su DC bipolar blocking are simulated respectively. The emergency control pre-decision is set according to FECCS coordination principle: (1) 10% of Long-Zheng DC is urgently promoted; (2) 500MW pumping units are cut in approximately 300ms; (3) 1000MW millisecond accurate load control is started at 500ms and completed within 1min. As shown in Fig. 4, the frequency recovers to nearly 49.9Hz quickly after emergency control. Compared with other strategies, the frequency deviation after emergency control decreases and the recovery time shortens. It can be seen that FECCS emergency control pre-decision can get a good control effect.
Coordination Strategy of Emergency Control and Corrective Control

Necessity of Coordinated Control

Frequency emergency control is a type of predictive control. Under specific conditions, it is indexed according to the fault, while decision tables are set up in advance. After the confirmation of fault information, the real-time decision tables are matched and delivered to the execution station, which makes control rapid. If online pre-decision is set on conservative principles, the control effect will be great but not economical, carrying negative effects of over-controlling. If they are not following the most serious failure, it tend to be under-control and fail to take into account safety. In short, it is difficult for emergency control pre-decision to avoid under-control or over-control caused by other uncertainties, which will lead to stability problems such as transmission sections overload.

Corrective control is a type of feedback control performed when detecting transmission sections overload problem in the current power grid. The timing of corrective control is after emergency control, and the decomposition and aggregation method should be used to formulate coordinated control strategies instead of two decisions set in isolation. Emergency control decisions are set as fixed external scenes before iterative coordination.

Coordinated Strategy Formulation Steps

The emergency control sets the decision with frequency deviation as constraint target, and the corrective control is driven by detecting transmission sections overload. Before the blocking, multi-DC coordinated control stations calculate the total capacity of EDCPS, $\Delta P_{\text{dc}}^{\text{max}}$, in real time according to DC lines operating status. Pumped storage control stations record the total capacity of pumping units, $\Delta P_{\text{pump}}^{\text{max}}$. Accurate load control stations collect interruptible load information and get the capacity, $\Delta P_{\text{load}}^{\text{max}}$. The control flow is shown in Fig. 5.

**Frequency Emergency Control Decision Steps**

- **a.** After the blocking faults and information confirming, frequency deviation of the receiving end grid, $\Delta f$, is determined whether to meet safety and stability control objectives, $\Delta f_{\text{s}} < \Delta f < \Delta f_{\text{f}}$, where $\Delta f_{\text{s}}$, $\Delta f_{\text{f}}$ are the upper and lower limits of frequency deviation.
- **b.** If the grid frequency deviation does not meet the target after the blocking faults, implement the strategy according to priority of control measures. First, modulate the other DC power lines. Second, control pumping units if $\Delta P_{\text{dc}}^{\text{max}} < \Delta P_{\text{load}}^{\text{max}}$, the lost power in the receiving end grid. Finally, adopt accurate load shedding if $\Delta P_{\text{dc}}^{\text{max}} + \Delta P_{\text{pump}}^{\text{max}} < \Delta P_{\text{load}}^{\text{max}}$. 

![Figure 3. Frequency emergency coordinated control system.](image3.png)

![Figure 4. Frequency curves after different strategies.](image4.png)
Transmission Section Overload Corrective Control Decision Steps

a. Based on power flow data of the receiving end grid after the blocking faults, it is judged whether transmission sections have exceeded their limits. Calculate the power margin \( \eta_x \) of transmission section \( x \):

\[
\eta_x = 1 - \frac{P_x}{P_{x,\text{max}}} \quad x \in X
\]  

where \( P_x \): active power of transmission section \( x \); \( P_{x,\text{max}} \): active power stability limit of transmission section \( x \); \( X \): all transmission section collections. When \( \eta_x < \eta_{\text{min}} \), threshold of the power margin, the section is determined to exceed limit. The selected overload section sets are sorted according to \( \eta_x \), the smaller \( \eta_x \) is, the more emergency fault is.

b. Based on the DC power flow model and real-time AC power flow data, the sensitivity of section active power to each controllable measure of corrective control decisions is calculated.

c. Calculate overlimit control quantity of section \( x \):

\[
\Delta P_x = P_x - \mu_x (1 - \eta_{\text{min}})P_{x,\text{max}}
\]  

where \( \mu_x \): overlimit corrective factor which is 1 at first. Based on \( \Delta P_x \) in the AC power flow verification result, \( \mu_x \) is adjusted according to Eq. 2 to reduce the DC power flow calculation error.

d. Comprehensively consider the adjustment rates and costs of control resources, an optimization model is established with the goal of fastest rate and minimizing adjustment costs:
\[
\text{min} \left\{ \sum_{i-j} c_{dc} \frac{\Delta P_{i-j}^{dc}}{R_{dc}} + \sum_{k} c_{pump} \frac{\Delta P_{k}^{pump}}{R_{pump}} + \sum_{l} c_{load} \frac{\Delta P_{l}^{load}}{R_{load}} \right\}
\]

(3)

where \(\Delta P_{i-j}^{dc}, c_{dc}, R_{dc}\) are respectively absolute value of EDCPS adjustment amount, unit cost and rate; \(\Delta P_{k}^{pump}, c_{pump}, R_{pump}\) and \(\Delta P_{l}^{load}, c_{load}, R_{load}\) respectively correspond with pumped storage and load control.

According to the overlimit section sequence from step a., \(\Delta P_{x}\) is divided by three control measures: EDCPS, pumped storage control and load shedding to determine the constraints:

\[
\begin{align*}
\sum_{i-j} S_{x-(i-j)} \Delta P_{i-j}^{dc} + \sum_{k} S_{x-k} \Delta P_{k}^{pump} + \sum_{l} S_{x-l} \Delta P_{l}^{load} &= \Delta P_{x} \\
\sum_{i-j} \Delta P_{i-j}^{dc} &\leq \Delta P_{x}^{dc} \\
\sum_{k} \Delta P_{k}^{pump} &\leq \Delta P_{x}^{pump} \\
\sum_{l} \Delta P_{l}^{load} &\leq \Delta P_{x}^{load}
\end{align*}
\]

(4)

where \(S_{x-(i-j)}, S_{x-k}, S_{x-l}\) are respectively sensitivity of active power adjustment of DC line \(i-j\), pumping unit bus \(k\), and load bus \(l\) to the active power of section \(x\).

Comprehensively consider sensitivity of control measures, control cost and adjustment rate, the comprehensive evaluation indexes of three measures are proposed:

\[
\begin{align*}
E_{i-j} &= \frac{R_{dc}}{c_{dc}} S_{x-(i-j)} \\
E_{k} &= \frac{R_{pump}}{c_{pump}} S_{x-k} \\
E_{l} &= \frac{R_{load}}{c_{load}} S_{x-l}
\end{align*}
\]

(5)

In the same type of control measures, the specific implementation measures are sorted according to the comprehensive evaluation indexes, and the cluster analysis method is adopted to divide measures into third-order priorities. Then adjustments of three types of measures, \(\Delta P_{i-j}^{dc}\), \(\Delta P_{k}^{pump}\), \(\Delta P_{l}^{load}\) are obtained by priority and Eq. 4.

e. Considering the stability constraint of frequency security, the power grid after the implementation of corrective control decision is checked by online AC power flow.

Coordination control effect

Based on the simulation of Jin-Su DC bipolar blocking, key sections such as 500kV AC tie lines in four provinces are mainly monitored. As in Fig. 6(a), after the fault, the power flow of 500kV channels in Hu-Su section and South Jiangsu increase significantly. Huangdu-Shipai power flow exceeds the stable limit of 2400MW, which is closely related to the boot mode in Wuxi, Shanghai and Anhui. Due to the emergency increase of Long-Zheng DC transmission power, the power flow of some lines increases, and the transmission power of Zhengping-Wunan lines in Fig. 6(b) is much higher than that of Fig. 6(a) without strategy, exceeding the stability limit. Wunan-Huquan lines has also risen to near the limit; while the Huangdu-Shipai trend has been relatively balanced.

According to the steps of the coordinated control decision, the adjustment strategy is: (1) Increase Long-Zheng DC power by 5%; (2) Cut 500MW pumping units and complete it within 300ms; (3) 1000MW millisecond accurate load control is started at 500ms; (4) Accurately control 300MW sub-millisecond load in South Jiangsu which is started at 6s, and finished within 13s. As in Fig. 6(c), under the coordinated control, the power transmission overlimit problem of Zhengping-Wunan and
Wunan-Huiquan lines is better alleviated, which shows the importance of coordination between corrective control and emergency control.

Summary

Based on the simulation analysis, the following conclusions can be drawn: (1) The system primary frequency regulation performance is sufficient to ensure frequency recovery after Jin-Su DC unipolar block; (2) With the measures priority of EDCPS, pumping and load shedding, the pre-decision of FECCS can better improve frequency deviation problem; (3) The online coordination strategy of emergency control and corrective control that integrates rapidity of DC power flow and accuracy of AC power flow, has enabled frequency stable while also eliminating section overload problems. The decision has achieved security control with multi-resource and multi-target coordination.

![Figure 6. Section power curves after different strategies.](image)

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References


