Reliability analysis of security and stability control systems with remote redundancy in power systems

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Abstract. During the transition period of UHV AC/DC power grid construction in China, the dependence of the secure and reliable operation of power grids on the security and stability control system (SSCS) has been greatly enhanced. SSCS has shown a trend of large-scale, wide-area and complex in recent years. Considering the high reliability requirements of large-scale SSCS, the necessity of redundant configuration of important sites is first outlined in this paper. Moreover, the reliability indices including mis-operation rate and rejection rate of SSCS with and without remote redundancy are analyzed as well as the relationship between reliability indices and failure rate of single device. The key research directions of the reliability research of the SSCS under the new situation are further pointed out.

1. Introduction
The Security and Stability Control Systems (SSCS) [1] are the second defense for ensuring the reliable operation of power grids in China. Similar systems are also well-known as System Integrity Protection Scheme (SIPS) [2] including Special Protection System (SPS) [3-4] and Remedial Action Scheme (RAS) [5], which have been extensively applied to engineering systems. The power grid in China is in the period of rapid development with UHV, and the grid characteristics continue to undergo significant changes putting forward new requirements on the secure operation of power grids [6], where the dependence on the SSCS is also greatly enhanced [7]. In order to adapt to the global control requirements of UHV AC/DC faults, the control mode of SSCS has also changed from “small-scale and localized” to “large-scale and wide-area”.

The mis-operation and rejection of devices caused by the reliability problems of the large-scale SSCS will form an unbearable secondary disturbance impact on power grids. Therefore, ensuring its reliable function has become an important issue which cannot be ignored. In recent years, the reliability analysis for SSCS/SIPS mainly focused on the reliability of devices in SSCS [8], or quantitative analysis methods for SPS [9-11], factors affecting the reliability index of SPS such as failure rates and repair rates [12]. However, the reliability for new structure of critical sites with remote redundancy has not been evaluated yet.

With the development of large control scale of SSCS for the UHV AC/DC power grids, the objective necessity of the redundant configuration of important sites in practical engineering is
inevitable. The rest of this paper is organized as follows: the necessity for configuring remote redundancy of SSCS in significant sites is investigated first. The false rates and rejection rates for SSCS with and without remote redundancy are analyzed utilizing probabilistic approaches where results are compared. Conclusions and directions of future works are provided as well.

2. The necessity of remote redundancy for important sites

Traditional SSCS are usually configured with one main system and one redundancy which are installed in the same substation or power plant. Taking the frequency emergency coordination control system (referred to as frequency coordination control system) in a multi-DC feed-in network that has been put into operation by the completed project and take the impact of UHV DC fault as an example, this system can complete emergency control which interrupts load of thousands buses, starts nearly 10 pumping storage units, and upgrades emergency power of DC networks within 300ms according to the offline strategy table after monitoring the UHV DC blocking. The structure for the frequency coordination control system is presented in Figure 1.

![Figure 1. Architecture of the stability control system.](image)

In Figure 1, Resource control stations can be set by resource type. For example, DC control station can manage 10 sub-stations to achieve emergency control for UHV or conventional DC systems; interruptible load control station can be set by areas where provincial dispatching department guarantees full controllable interruptible load. The interruptible load control station is connected with multiple sub-stations by fiber channels to control thousands of switches of customers.

The central control station, the DC control station and the pumping control station, which are uniformly managed by the divisional scheduling, are installed in the relay chamber of the same DC converter station. As an important guarantee for the frequency stability of multi-DC feeding power grid under large frequency difference disturbance, the importance of frequency coordination control system is self-evident. For the central control station, the corresponding reliability requirement is higher. Therefore, dual configuration is usually adopted. However, there is a possibility that the dual-set devices might fail at the same time. For example, there have been real cases of collective failure of the secondary control system caused by the voltage loss of the substation DC bus (a 330kV substation explosion occurred in 2016).

Therefore, based on the dual configuration in the existing station, the engineering design and reliability research of the remote dual-station and the double-set configuration of each station at the critical control stations have become an important issue.
3. Comparison of reliability indices of systems with and without remote redundancy

3.1. Reliability of systems without remote redundancy

In the frequency coordination control system, control strategies including DC power enhancement, pumping units start-up, and interruptible load are similar. Taking the control strategy of DC power enhancement for example, as shown in Figure 2, the control system can be divided into three levels where 1, 2 and 3 respectively indicate central control station, control station and control sub-station. 1’, 2’ and 3’ denote the corresponding redundancy devices where they operate in parallel with the primary devices.

![Figure 2. Structure of the system without remote redundancy.](image)

For the system structure in Figure 2, if any one of the devices in any column is malfunctioned, the whole system is malfunctioning. The corresponding mis-operation rate can be formulated in Eq. (1).

\[
P_w = P_{1}P_{2}(1-P_3) + P_{1}'P_{2}'(1-P_3') + P_{1}''P_{2}''(1-P_3'') + P_{1}'''P_{2}'''(1-P_3''') = 1 - (1-P)^4
\]  

(1)

where \( P \) indicates failure rate of single device.

Moreover, if any device in the same column refuses to operate, the entire column is seen as rejection operation. The corresponding rejection rate for one column is presented in Eq. (2).

\[
P_{r1} = 1 - (1-P)^4
\]  

(2)

The system suffers from rejection operation if two columns refuse to operate. Therefore, the rejection rate for the entire system is shown in Eq. (3).

\[
P_{r2} = P_{r1}^2 = (1 - (1-P)^4)^2
\]  

(3)

3.2. Reliability of systems with remote redundancy

The control structure after redundant configuration with one identical systems in a different place is presented in Figure 3. In this control structure, assuming that the commands in the control sub-station of the third level adopt “two out of four” method. In other words, the system will operate if receiving control commands at least from two devices at the same time.

The corresponding mis-operation rate of the whole system is formulated in Eq. (4).

\[
P_w = 1 - C_1'P(1-P)^3 - C_1''P(1-P)^3 - (1-P)^8
\]  

(4)

Furthermore, if any device in the same column refuses to operate, the entire column is seen as rejection operation. The corresponding rejection rate for one column is the same as that in Section 3.1.
as presented in Eq. (2). However, the system suffers from rejection operation if at least three columns refuse to operate. Therefore, the rejection rate for the entire system with remote redundancy is shown in Eq. (5).

\[ P_{rj} = C_A^1 P_A^1 (1 - P_A) + C_A^3 P_A^3 = 4 \times (1 - (1 - P)^3)^1 \times (1 - P)^1 + (1 - (1 - P)^3)^3 \]  

(5)

4. Comparison of reliability indices of systems with and without remote redundancy

![Graphs showing comparison of mis-operation and rejection rates](image)

(a) Relationship between failure rate of single device and mis-operation rate for the system without remote redundancy

(b) Relationship between failure rate of single device and mis-operation rate for the system with remote redundancy

(c) Relationship between failure rate of single device and rejection rate for the system without remote redundancy

(d) Relationship between failure rate of single device and rejection rate for the system with remote redundancy

**Figure 4.** Mis-operation rate and the rejection rate with different failure rate of single device.

4.1. Preliminary analysis of system reliability indices

Referring to the failure rates of the relay protection devices, the failure rate of a single device is 0.006. The reliability indices including mis-operation rate and rejection rate of two different system structures are presented in Table 1.
Table 1. Reliability indices of systems with and without remote redundancy.

| Stability control systems | Reliability indices | Mis-operation rate | Rejection rate |
|---------------------------|---------------------|-------------------|---------------|
| Without remote redundancy | 0.023784            | 1.4313×10⁻⁴       |
| With remote redundancy    | 8.4519×10⁻⁴         | 6.788×10⁻⁶        |

It can be seen in Table 1 that the mis-operation rate and rejection rate of the SSCS with remote redundancy are reduced to 1/28 and 1/21 of those of systems without remote redundancy, respectively, which breaks the general understanding that the method used to reduce the mis-operation rate and the rejection rate of the secondary control system is contradictory and difficult to coordinate.

4.2. Relationship analysis of reliability indices

4.2.1. Relationship between system reliability and failure rate of single device. The mis-operation rate and the rejection rate with different failure rate of single device are presented in Figure 4.

It can be seen from Figure 4 that the rejection rate of the system without remote redundancy and with remote redundancy are both lower than the failure rate of single device. When the failure rate of single device exceeds 0.05, the mis-operation rate of the system with remote redundancy is higher than the failure rate of single device. Increasing the reliability level of a single device is a sufficient condition to enhance the system reliability.

4.2.2. Comparisons between two systems.

(1) Comparison of mis-operation rate of systems with and without remote redundancy

![Figure 5. Mis-operation rate comparison of two systems.](image)

It can be seen in Figure 5 that the mis-operation rates of two systems is varying with the change of failure rate for single device. When the failure rate is lower than 0.42, the mis-operation rate of system with redundancy is lower than that of system without redundancy. When the failure rate exceeds 0.42, the mis-operation rate of system with redundancy is higher than that of system without redundancy.

(2) Comparison of rejection rate of systems with and without remote redundancy
Figure 6. Rejection rate comparison of two systems.

It can be seen in Figure 6 that when the rejection rate is lower than 0.18, the rejection rate of system with redundancy is lower than that of system without redundancy. When the failure rate exceeds 0.18, the rejection rate of system with redundancy is higher than that of system without redundancy.

When the mis-operation rate and rejection rate of a single device are lower than 0.18, the system with remote redundancy is more reliable than system without redundancy with higher mis-operation rate and rejection rate. When the mis-operation rate and rejection rate of a single device are higher than 0.42, the system without remote redundancy is more reliable than system with redundancy with higher mis-operation rate and rejection rate. In view of the fact that the failure rate of single device is generally much less than 0.1, the redundant configuration of the important control device significantly improves the reliability of the control system.

5. Conclusions

It is a necessary configuration method to implement remote redundancy for important sites in large-scale SSCS. It is significantly different from traditional dual-station configuration, and its reliability is worthy of attention and research. This paper analyzes the necessity of the configuration of this new type of SSCS in the background of UHV AC/DC power grids. Comparisons of reliability indices of the two SSCS with and without remote redundancy are provided in this paper as well. Through reasonable design, it is possible to reduce the mis-operation rate and rejection rate of the system at the same time. The mathematical relationship between system reliability indices and the failure rate of single device are presented, which can provide a scientific basis for the reliability research for large-scale grid security and stability control systems of power systems.

With the emergence of different stability control requirements of power grids, the control architecture of SSCS, the transmission time of control commands, and the processing method of the receiver from multi-directional control commands might have significant impacts on the reliability of the entire SSCS. The reliability of SSCS under the new background will be further studied.

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