A review of stability control technologies for power systems in China

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Abstract. During the transitional period of UHV network construction, the power grid’s characteristics of “Strong DC and Weak AC” are prominent. Moreover, the high penetration of renewable energies has made the characteristics of power systems profoundly changed facing high operation risks. The security and stability control technologies need to be reviewed considering current development situations and combine the characteristics of the grid to make innovation. This paper analyses the development and status quo of stability control technologies from the security and stability control systems which belong to the second defense line. Moreover, frequency and voltage emergency control devices and out-of-step separation devices which belong to the third defense line, as well as features of the security and stability control devices are investigated. According to the planning and development of the future power grid, the development directions of the security control technology is pointed out.

1. Introduction
The blackouts occurred in recent years, especially in large developing countries such as India [1] and Brazil [2], have improved public concerns on the reliable operation of power systems. These large blackouts have also made people fully aware of the importance of ensuring the safe and stable operation of the power grid. Therefore, it is necessary to strengthen and improve the security defense measures of power systems.

The power grids of mainland in China have entered a period of rapid development in the last decades without large-scale power outages which mainly relies on the three lines of defense. Among them, the emergency control in the second line of defense and the correction control in the third line of defense constitute stability control, which can prevent passive and disorderly large-scale blackouts from active and orderly small-scale power outages.

During the transition period of UHV (Ultra-High Voltage) AC/DC power grid construction in China, the interaction between AC and DC networks is intensified with the closely coupled power supply and consumption. The secure and reliable operation of the power grid puts forward new requirements for stability control technologies. It is necessary to adhere to the three lines of defense to
ensure the secure operation of power systems. Based on the engineering practice of stable operation, analyzing the status quo of stability control technologies is of great significance to continuously innovate its development.

2. Application and of stability control technologies

During the 1970s to 80s, the power grid of China has developed from a 110kV power grid to a 220kV interconnected power grid. Some low-frequency and low-voltage emergency control devices have been locally deployed. From the 1990s to the beginning of the 21st century, regional power grids were weakly interconnected through 500kV AC [3]. At the same time, with the construction of ±500kV HVDC (high-voltage direct current) networks, stability control systems for power transmission project have been extensively applied, such as the Three Gorges Power Transmission Safety and Stability Control System. Several DC project commissioning marks that China has stepped into the new era of large-capacity UHV AC/DC interconnection in regional power grids [4]. The corresponding security and stability control systems present characteristics of large scale, wide area and complex, which are oriented towards the direction of wide-area coordinated control.

Stability control systems have been successfully applied to various regional power grids, such as northwest areas of China and large enterprise grid running on isolated networks [5-7]. Relying on the good performance of these stability control systems, stability damage of the power systems can be effectively avoided. Widely applications manufacturers of stability control devices in China are mainly created by NARI, Beijing Sifang, etc., with the representative products such as SCS/SSP, PCS and SSC.

Such control systems in abroad are called SIPS (System Integrity Protection Scheme) and generally include Special Protection System (SPS), Remedial Action Scheme (RAS), and systematic solutions such as Low Frequency (UF), Low Voltage (UV), out of step (OOS) [8], [9].

The second line of defense is mainly composed of safety and stability control systems based on fault triggering and regional stable controllability to prevent system instability. Emergency control of the power grids through the strategy table has become the mainstream of regional stability control. At present, the policy-based transient stability emergency control decision-making methods mainly include two methods: “offline decision, real-time matching” and “online pre-decision and real-time matching”.

The “offline decision, real-time matching” method utilizes offline simulation to formulate the control strategy table for realizing the emergency control of the power grids. At present, it is still the mainstream technology for regional and inter-regional stability control in most power grids in China. The “online pre-decision and real-time matching” approach has strong adaptability to the development and changeable operating conditions of power systems. This method can achieve the stability control of adaptation, optimization and coordination for power systems, which is incomparable superior to the traditional offline control strategies. The Online pre-decision method is gradually promoting the application process, for example, the Electric power Alarming and Coordinated Control System (EACCS) developed by the State Grid of Jiangsu Province in 2007.

The third line of defense including frequency emergency control, voltage emergency control, out-of-synchronization has basically achieved the standardized design of local devices. With the development of power grids, stability control devices have completed the transition from local to regional and trans-regional in terms of control principle. Moreover, the control architecture has evolved from centralized to distributed, which can better support the safe and stable control requirements of power grids.

3. Challenges of stability control technologies

In the high-speed development period of UHV power grids, the characteristics of power grids continue to undergo important changes, which puts new challenges and requirements on the stability control technologies.
Under the framework of rapid development of UHV power grids in China, renewable energy sources such as wind power and solar power are integrated into the grid. The scale of long-distance trans-regional transmission continues to grow, and the structure of power systems have changed significantly, especially during the transition period of the power grid “strong DC networks and weak AC networks”. The characteristics have undergone profound changes, and grid security faces new challenges. The main performances are: AC/DC networks and the coupling between the transmitting and receiving ends are tight; the impact of faults on the grid operation is transformed from the local to the entire system; the power grid adjustment capability is declining where the frequency stability problem is gradually prominent; the voltage regulation capability of the terminal grid is weakened with prominent voltage stability problems. Moreover, the scope of power grid stability is further expanded, and the characteristics of power electronics are highlighted.

The rapid development of UHV power grids and renewable energy sources has brought about important changes in power grid characteristics, which puts forward new requirements for stability control technologies, and determines future development directions of stability control technologies. Possible directions include: engineering application of large-scale online pre-decision stability control systems; multi-measure wide-area real-time coordinated control which is supposed to match with UHV transmission systems; further improvement of the equipment tripping criterion for the stability control system; differential fortification of the disturbance mode or stable form beyond the fortification range of the existing stability control system (such as DC commutation failure, converter network stability problem, etc.); the systematization of equipment of the third line of defense; the reliability design and guarantee for large stability control systems.

4. Development outlook of stability control technologies

4.1. Online refresh of control strategies

Online safety analysis and decision-making are the basis of stability control in online pre-decision systems, which is mainly based on preventive control, and finally realizes online pre-decision control. The development goal of the regional stability control systems is to achieve online pre-decision for stability control. As mentioned EACCS, this is a successful example in online pre-decision.

Although online analytical decision-making technologies have obtained various attentions, the main problems in application are the reliability of online data and the practicability software. At present, the online closed-loop emergency control system of the Northwest Power Grid in China is operating in the system protection laboratory. By continuously improving the system’s practicability and operational reliability, it will lay the foundation for the online closed-loop emergency control technology engineering application.

4.2. Multi-measure wide-area coordinated control

4.2.1. Mining and real-time coordinated control of massive control resources. The faults of UHV DC systems are supposed to have global impacts on the entire systems. The scale of control resources mobilized under fault scenarios is unprecedentedly huge. Moreover, the faults of UHV DC systems are supposed to have global impacts on the entire systems, which might trigger multi-type and multi-site emergency control actions in a millisecond time scale with strict requirements on selection of control object and determination of control timing.

DC faults and the system response caused by them may trigger multi-type and multi-site emergency control actions on the millisecond time scale, and have strict requirements on the selection of control objects and the determination of control timing.

The demonstration project “Frequency Emergency Coordination Control Systems for Power Grids in East China” was the first to achieve frequency stability control of about 15 million kilowatts with thousands control objects including DC power emergency boost, pump-generating units and interruptible load. In the future, the framework of control systems with the capability of 10 million
kilowatts as well as the rapid coordinated control of multi-objective and multi-control measures are development directions and technical difficulties of the stability control.

4.2.2. **Wide-area and refined control of resources.** DC technology is developing rapidly with a single-turn DC transmission level of 12 million kilowatts [10]. Relying on low-frequency load shedding measures to deal with the huge energy impact caused by DC blocking, the load shedding is difficult to bear with severe social impact. On the basis of fully exploiting control methods including the rapid control of DC power, it is necessary to develop millisecond precision load control technology, and utilize the latest stability control and communication technologies to accurately control objects within the inside of enterprise where the interruptible load is changed from the traditional centralized cutoff 110kV line to the interruptible 10kV or 380V load branch circuit. This technology raises the emergency response time of large power grid from the minute level to the millisecond level, which not only meets the emergency response, but also minimizes the economic loss and social negative impacts. Moreover, it effectively expands controllable resources in case of failure of power grid, which further enriches and improves the safety control methods with many advantages such as wide applications, strong selectivity and small impact on users.

The key technology of large-scale load precision control is that it needs flexible and scalable communication networking to meet the access requirements of massive users’ terminals where the emergency control function requires millisecond-level control delay. In the meanwhile, the accuracy of load control will lead to the wide-ranging and complicated control systems where further improvement of reliability for the corresponding technical support systems is essential. Similarly, in the large-scale transmission network with high renewable energy penetration, the panoramic monitoring of generating units of renewable energy is also one of the development directions of stability control technology.

4.3. **Perfection of equipment trip criteria**

4.3.1. **AC equipment trip criterion.** The trip criterion and the stability control strategy are the core technologies of the safety and stability control systems. Accurately determining the fault type of the equipment trip is an important premise of the device decision. The equipment trips indicated by the stability control include: fault trip and faultless trip of a transmission line, tripping of a transformer, tripping of a generating unit.

(1) **Fault trip criterion**

The fault trip is generally connected to the split-phase trip contact of the main protection, supplemented by the electrical quantity criterion. The operating experience shows that the criterion is secure and reliable. It can continue to be promoted and applied to stability control systems where identification of fault type and strict requirements of action time are required. Combined with the faultless trip criterion, the effect of CT tailing on fault-free trip criteria can be avoided.

(2) **No-fault trip criterion**

No-fault trip criterion generally only utilizes electrical quantity criterion. At present, there is no fully mature and reliable No-fault trip criterion based on pure electric quantity. In actual operation, a number of No-fault trip criteria have been misjudged causing device malfunction events [11]. The criteria for selection of specific scenarios are used with auxiliary verification and error prevention auxiliary criteria in some cases.

Based on the No-fault trip criterion of measuring point impedance [12], based on the traditional No-fault trip criterion, the misjudgment when the line is lightly loaded after the tidal current transfer can be effectively avoided. The criterion has higher security in identifying the No-fault trip of the AC line with AC/DC coupling. With the rapid construction of DC transmission projects, the use of criteria also requires the combination of external auxiliary conditions.

In the scenario where the traditional No-fault trip criterion and the No-fault trip criterion based on the measured point impedance are misjudged, the switch can be accessed for No-fault trip
identification [13]. The switching signal includes a switch position signal, a protection trip signal, or a contralateral switch signal. In order to be better combined with fault trip, reducing loop design and construction can be combined with protection trip signal to identify No-fault trip where the signal is drawn from the operation box trip output loop with the advantages of full protection signal and high reliability.

4.3.2. **DC equipment trip criterion.**

(1) Criteria for DC commutation failure and DC power speed drop

The existing safety and stability guidelines and calculation standards only consider the single pole or double-pole blocking fault modes of DC systems without the consideration of faults such as continuous commutation failure and DC speed drop [14-15]. The reason is that the conventional DC maximum power transmission power is 3- 4 million kilowatts. DC continuous commutation failure, DC speed drop and other common fault modes have limited impacts on the stability of the power systems.

The rapid development of UHV DC project has made the power transmission capacity of a single DC project increased to 6~8 million kilowatts. The continuous commutation failure of DC systems, DC speed drop and other disturbances can have a significant impact on AC cross sections, approaching to the stability limit of the existing AC cross sections. It poses a serious threat to the safety and stability of power systems which requires emergency control. Therefore, it is necessary to enrich the DC disturbance criterion and develop criteria for DC power speed drop and DC commutation failure.

(2) Improvement the traditional DC blocking criterion

DC faults can interact with changes in AC electrical quantities, which makes system fault characteristics complex. While developing stability control criteria for DC commutation failure and DC power rapid drop, it is necessary to perfect the widely-used DC blocking criterion to avoid the stability control system refusal in extreme cases such as DC control system crash.

4.4. **Fortification and monitoring of new disturbance and stability form**

The failure of simultaneous commutation of two or more UHV DCs poses a serious threat to the safety and stability of power systems. The present stability control systems for UHV DC systems have broaden the scope of the traditional stability control systems.

Moreover, with the development of renewable energy integration and DC-intensive operation, the power electronic characteristics of power systems are prominent, where the system oscillation characteristics are becoming more and more complex, and large-scale renewable energy bases have experienced secondary and super-synchronous oscillations. The oscillation exhibits a wide-band characteristic, and the oscillation frequency covers 0.05 to 100 Hz. Moreover, the amplitude fluctuation range is large, which brings difficulty in accurately identifying the oscillation. The mechanism of sub-synchronous and super-synchronous oscillation is more complicated with long duration and interaction between different oscillations interact with each other, leading to difficulties for accurate control of oscillation.

4.5. **Systematization of the third line of defense**

Under the complex situation of UHV AC/DC grid dynamic characteristics, the control coordination requirements of targets and measures are higher. The frequency-voltage emergency control devices and the out-of-step disengagement devices of the third line of defense are isolated to a certain extent. The function of the line defense devices proposes a systematic coordination requirement. The so-called systematization mainly refers to the stabilization and control of the functions of the third line of defense devices to achieve space-time coordination of multiple control objectives and control resources. For example, the event-driven and response-driven frequency coordination control can be implemented in the stability control system to avoid the strategy mismatch. Moreover, multiple out-of-
step de-sequecing devices form the system can capture the oscillation center, and implement active de-column.

For the systemization of the third line of defense devices, it is not a substitute for independent configuration of the third line of defense, but a layer of barrier to be built before the third line of defense according to specific control requirements.

4.5.1. Voltage emergency control. For complex power grids, the voltage stability problem cannot be effectively solved by decentralized installation of low-voltage load shedding devices. For example, in a typical area of a large-area power grid: UHV DC blocking causes large-scale power flow transfer which in turn leads to local voltage instability. It is necessary to study the voltage emergency control technology by constructing the voltage coordination control system, where after the UHV DC is locked, the voltage-coordinated control system can quickly cut off the low-resistance/generator excitation to achieve rapid voltage recovery.

4.5.2. Out-of-step oscillation and its control. The principle of out-of-step criterion based on impedance, phase angle is derived from a simple two-machine system [16], which is compatible with the regional network using the edge networking model. With the complexity of AC/DC dynamic interaction behaviour, these criteria have the risk of disoperation and the inability to accurately determine the position of the oscillation centre. The disadvantages of unsuccessful determination of the optimal solution point in the first oscillation period, which lead to occurrence of multi-machine multi-frequency oscillation and dynamic migration of oscillation centre, are the reasons to correctly discriminate and achieve global coordinated control.

(1) Active decoupling control

Using the characteristic information in the process of power grid disturbance and advance prediction for breaking static stability limit of critical section, the active decoupling control is adopted to block the large-scale fault chain and ensure the stable operation of power grids. The technologies that need to be tackled include: the active disjunction criterion combined with the fault event and the system response characteristics; the selection of the dissection section considering the stability and reliability; the decision of the stable control measures such as the cutting machine after the disengagement.

(2) Out of step disengagement systems

The AC/DC networks are becoming more and more complex, and the out-of-step oscillation center mostly falls on a section. After the out-of-step oscillation, the oscillation center may migrate with the change of the grid structure and various electrical parameters. If out-of-step disengagement devices are independently configured on multiple sections, there may be a risk that these disengagement devices cannot cooperate with each other and the network is decomposed into multiple sub-networks. If de-column devices are arranged only in a single section, there is a possibility that an oscillation center does not fall in the section and oscillate might last for a long time with serious accidents.

By constructing the out-of-step disengagement system, it is possible to solve the problem that the dynamic change of the oscillation center is difficult to be accurately distinguished and reliably solved by the isolated out-of-step disengagement devices.

4.6. Reliability design and guarantee technology for large-scale stability control systems

With the increasing of control scale and control importance, the requirements for reliable control of large-scale stability control systems have surpassed any previous stage of power grid development. However, the reliability research on current stability control systems lacks systematicity. There is an urgent need for advanced and applicable technologies that can guide the reliability optimization design of stability control systems.

Reliability research of stability control system can be carried out from the following directions: reliability data collection and analysis of stability control systems, failure mode and its influence of
various control systems, reliability modeling and evaluation of stability control systems, establishment of management and analysis systems for reliability data collection of stability control systems [17].

Stability control systems have strong practicality and high reliability requirements. The reliability evaluation indices and reliability improvement methods proposed are supposed to have engineering applicability to effectively guide and standardize the design, development, and commissioning of the safety and stability control system for complex power systems.

5. Conclusions
With the rapid development of UHV networks in China, the grid characteristics continue to undergo important changes, where stability control technologies face new opportunities and challenges. The main performances lie in: under the general situation of fault impact from UHV DC systems, the coordination difficulty of control objectives and control measures becomes greater; under the trend of large-scale, wide-area and complex security and stability control systems, reliability design and protection requirements are higher; under the prominent form of power grid electronic characteristics, the mechanism of disturbances such as sub-synchronous oscillation is complex and difficult to control; during the dynamic and complex changes of AC and DC systems, the oscillation centre changes dynamically and is difficult to accurately capture.

Adapting to the development of power grids, the development direction of stable control technology is mainly reflected in: online refresh of control strategy, wide-area precise and rapid coordinated control with multiple objectives and measures, reliability research to guarantee and improve of secondary equipment of power systems, event-driven and response-driven integration emergency coordination control method, identification and control of new faults or disturbances that pose a greater threat to grid stability, construction of out-of-step disengagement system, enrichment and improvement of equipment tripping criteria for stability control.

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References
[1] Lai, L L, Zhang H T, Mishra S 2012 International Conference on Advances in Power System Control 2012
[2] Xue X, Wang S, Yan C 2015 Applied Energy 2015 1
[3] Tang Y, Zhu F, Zhang D 2001 Power System Technology 2001 11
[4] Han Q, Zhao Z 1994 Power System Technology 1994 18
[5] Zhao L, Wang M, Ni M 2016 Power System Protection and Control 2016 13
[6] Ma G, Xiao S, Lei R 2009 Power System Protection and Control 2009 17
[7] Qi Z, Shi Z, Li F 2016 Power System Protection and Control 2016 1
[8] Vahid Madani, Damir Novosel, Stan Horowitz 2010 IEEE Transactions on Power Delivery 2010 4
[9] Jorge Cardenas, Fatih Koksal, Francesco Iliceto 2011 International Conference on Actual Trends in Development of Power System Protection and Automation 2011
[10] Yang W, Yin Y, Ban L 2015 Power System Technology 2015 10
[11] Dong X, Li X, Qin T 2015 Power System Protection and Control 2015 17
[12] Fang Y, Xu H 2008 Automation of Electric Power Systems 2008 3
[13] Wang W, Chen J, Yu R 2012 Power System Protection and Control 2012 2
[14] DL/T 755 Guide on security and stability for power system 2001
[15] DL/T 1234 Technique specification of power system security and stability calculation 2013
[16] Dong X, Zhao J, Ling C 2010 Power System Protection and Control 2010 7
[17] Luo J, Dong X, Cui X 2018 Power System Protection and Control 2018 8