Step Coordination Control Strategy Based on WAMS for AC/DC Hybrid System

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Abstract. The power system’s stability is judged through the processing and analysis of wide-area information, and matching and executing the corresponding control measures based on data can be used as an effective backup and supplement to the security and stability control devices. This paper proposes an online additional emergency control strategy based on energy function for the situation that the security and stability control strategy formulated offline may have mode mismatch. This strategy relies on the energy function index that describes the unstable situation of the power system. Based on the real-time data from SCADA and PMU, it combines the energy function method and the trajectory prediction to achieve the function of additional control of the power grid in an emergency. The cases are analyzed to verify the effectiveness of the proposed method. The simulation results demonstrate that the step coordination control strategy could be realized, and the practicality is improved.

1. Introduction

The high-density access from DC systems to AC power systems makes the interaction of two systems increasingly complex so that the power grid's security and stability face enormous challenges. Commutation failures in high-power DC systems are more common, mostly caused by failures in the AC system recipients. During the commutation failure, the DC power drops significantly, and the synchronous generators of the DC grid accelerate. If the commutation failure lasts for a short time, the DC power can be recovered quickly, which doesn’t affect the system’s stability very much. However, continuous commutation failures have a severe impact on system stability. For example, the repeated effect of continuous commutation failure may cause the sending-end unit's relative power angle to be unstable and the important AC contact section disconnected. The security and stability control devices will implement emergency control measures such as machine cuts and load cuts when the power system is much disturbed to maintain a safe and stable operation. At present, for the blocking failure of the DC system of the sending-end AC power system, the security and stability control system devices can be used to cut the machines in an emergency to ensure the system's security and stability. However, the situation of continuous commutation failure in the DC system is relatively complicated. The number of commutation failures, the duration of single commutation failure, and the time interval between each commutation failure may be different. Various factors adversely affect the security and stability of the power system, which makes the strategies too complex and challenging to formulate offline. Ref [1] shows that the control and protective devices of the DC system may take 2.6s to block the DC system to respond to the commutation failure caused by faults of the AC.
system. At this time, the system is very likely to have lost its stability, which brings great security risks to the security and stability of the UHV AC/DC system. Ref [2] points out that after a large number of power flows are transferred to parallel AC transmission channels on a large scale, as the relative power angle of the generator set swings, the AC voltage of the receiving end grid will continue to drop, and the reactive power demand of the induction motor load of the receiving end grid increase rapidly. Meanwhile, the reactive power compensation provided by the parallel capacitor will be significantly increased. These interaction characteristics are likely to cause further transient voltage instability in the system. Ref [3] found that under the above-mentioned failure scenarios, the AC voltages of inverter stations of the DC system will also continue to drop, and the DC system may fail to commutation again, and the DC system will absorb great power from the receiving end grid during the recovery of the commutation failure. It may also cause transient voltage instability. The physical mechanism of the above voltage instability scenarios can be attributed to transient voltage instability caused by transient power angle instability. In fact, with the gradual increase in the number of DC drop points of the receiving end grid and the increasing proportion of the total transmission power from the DC system in the total load of the receiving end grid, the transient voltage stability problem of the multiple DC landing point system will become increasingly prominent. Short-circuit faults in the AC system of the power grid may also directly cause transient stability problems dominated by transient voltage instability [4-7]. Because the failure of continuous commutation failure is relatively complex and changeable, it is possible that some serious failures may not be covered by an emergency control scheme using only security and stability control devices.

Accompanied by the update of the technology, WAMS (wide area measurement system) is gradually improved and deployed to the power system. The power system’s stability is judged by processing and analyzing wide-area information, and matching and executing the corresponding control measures based on information can be used as an effective backup and supplement to the security and stability control devices [8]. This paper proposes an online additional emergency control strategy based on energy function for the situation that the security and stability control strategy formulated offline may have mode mismatch. This strategy relies on the energy function index that describes the unstable situation of the power system. And based on the real-time data of SCADA and PMU, it can achieve the function of additional control of the power system in an emergency in combination with methods of the energy function and track prediction.

2. Coordinated Control Analytical Method Based on WAMS Information and Energy Function

2.1. Additional Control Based on the Energy Function
Considering the system is an independent physical system, the normalized transient energy of the normalized power system \( P_{EF} \) is defined by the following formula.

\[
P_{EF} = P_{KE} + P_{PE} = \frac{1}{2} a_b^2 + \int_{R(t)}^{R(t_f)} -a_b + \frac{a_b^2}{R} \, dR
\]

In the formula, \( P_{KE} \) and \( P_{PE} \) respectively represent the normalized kinetic energy and potential energy of \( P_{EF} \). The above formula describes the relationship between the execution time of additional control measures and the required amount of machine-cutting control. When the two cooperate to make \( P_{KE_{min}} \) equal to 0, a critical control scheme is obtained. The control effect of the strategy can be described by a mathematical model based on the projection normalized energy function method.

\[
P_{KE_{min}} = F(t_f, t_{shed}, \Delta P)
\]

Among them, \( P_{KE_{min}} \) represents the minimum projected kinetic energy, \( t_f \) represents the fault removal time, \( t_{shed} \) represents the operation time of the security and stability control devices, and \( \Delta P \) represents the generators’ cut-off amount. The physical meaning is expressed as follows: when the initial
state of the system is constant, the fault is removed at time $t_{cl}$, and the security and stability control devices operate at time $t_{shed}$ to remove the active power of generators ($\Delta P$) so that the only minimum projected kinetic energy value ($PKE_{\text{min}}(t_{cl}, t_{shed}, \Delta P)$) can be determined. The control goal of security and stability measures is ensuring that the system is in a stable state. So on the basis of the minimum projection kinetic energy’s definition, we can know the formula.

$$PKE_{\text{min}}(t_{cl}, t_{shed}, \Delta P) = 0$$  \hspace{1cm} (3)

Through analysis, we can see that for a certain cut-off time, the $PKE_{\text{min}}(\Delta P)$ of the unstable system has good linear characteristics, so the ratio of $PKE_{\text{min}}(\Delta P)$ to $\Delta P$ can be used as the sensitivity of the stability margin of the system. It is worth noting that the sensitivity is different for different faults and different node cutoffs.

On the basis of the extraction of the power system’s information, through theoretical analysis and simulation methods, the relationship between the normalized transient energy function and the stability control measure of cutoff is obtained. The result of the calculation of this relationship can be obtained through a 5-minute cycle scan. On the one hand, using these relationships can form a supplementary additional strategy table for the offline control strategy table in response to mode mismatch; on the other hand, these relationships can also be applied to online faults to address failure mismatch and other situations by quickly finding the volume of resection of generators’ loads [9].

2.2. Using Difference Method to Calculate Critical Cutting Machine Capacity

Based on the relationship between values of $PKE_{\text{min}}$ obtained from twice calculations and the corresponding cut-off amount ($\Delta P$), the critical cut-off amount can be obtained by the difference method in order to make $PKE_{\text{min}}$ equal to 0.

The critical cutoff amount ($P_c$) of the additional emergency control strategy can be obtained by the relationship between the minimum projected kinetic energy ($PKE_{\text{min},i}$, $PKE_{\text{min},j}$) and the corresponding amount ($P_i$, $P_j$) of cutoff using stability measures obtained from the two transient instability time-domain simulation results of the power system. It can be calculated by the following formula. And its principle is shown in Figure 1.

$$P_c = \Delta P_i + \frac{\Delta P_i - \Delta P_j}{PKE_{\text{min},i} - PKE_{\text{min},j}} \times PKE_{\text{min},j}$$  \hspace{1cm} (4)

![Figure 1. Schematic diagram of the principle of the sensitivity relationship between $\Delta P$ and $PKE_{\text{min}}$.](image)

For the generators connected to bus node $i$, the sensitivity of $PKE_{\text{min}}$ and the corresponding cutoff amount ($\Delta P$) can be obtained by measuring the difference of $PKE_{\text{min}}$ in the case of instability.

$$K_{PKE}(t_{cl}, t_{shed}, i) = \frac{P_{e1} - P_{e2}}{PKE_{\text{min},i} - PKE_{\text{min},j}}$$  \hspace{1cm} (5)
The fault of sensitivity is related to the removal time ($t_{clt}$) and the additional cutting time ($t_{sct}$). At the same time, the value of $K_{pke}$ is negative, indicating that the greater is the amount of stable cutting, the smaller is the minimum kinetic energy.

3. Generation of Coordinated Control Scheme Based on the Energy Function

According to the method of obtaining critical machine cutoff and the method of generating additional control strategy for serious faults, it can realize the verification of stability control strategy of the generator set and the generation of additional emergency control strategy under severe system fault conditions. Combined with the operating features of SCADA/EMS that is actually running, a process method for generating additional emergency control strategies for power grids based on the energy function is raised, which is shown in Figure 2.

Based on the offline control strategy table of the power grid, a serious fault set ($F = \{ f_i | k = 1, 2, ... n \}$) is generated, and $k=1$; Among them, the offline control strategy table is pre-generated by the offline-control system of the power grid. The serious fault refers to the fault, which leads to the transient instability of the power grid or the fault that has reached the stable boundary of the power system under the offline simulation of this fault condition. Extract the severe fault ($f_j$) from the severe fault set ($F$) and perform time-domain simulation based on the condition of no offline control strategy. Calculate the first minimum projection kinetic energy ($PKE_{pre}$) and determine whether the power system maintains the power angle transient stability according to the results of the time-domain simulation. Perform time-domain simulation based on offline emergency control strategy. Calculate the second minimum projected kinetic energy ($PKE_{sec}$) and judge the power angle stability according to the time domain simulation results.

4. Case Analysis

The improved Kundur system and the improved New England system are used as examples to verify the proposed modular hybrid simulation algorithm's effectiveness. Terminal 1 and terminal 2 represent
two converter stations separately, which constitute the LCC-VSC DC transmission system. It draws on the CIGRE HVDC standard test system's design plan and makes appropriate parameter modifications for the AC system of the VSC inverter side. In this simulation, generators adopt the classic model, and loads adopt the constant impedance model. The various parts that make up the system are shown in Figure 3. And DC part is designed as follows: Node 7 is a conventional DC LCC converter station, and node 9 is a flexible DC VSC converter station. The hybrid DC transmission system adopts a complete bipolar design so that both ends can complete power transmission independently. Moreover, LCC is only used as a rectifier station to outputs DC power, but VSC can work in rectifier mode, inverter mode, or STATCOM mode. The DC voltage and DC current ratings of this transmission line are 500kV and 2kA, respectively.

![Figure 3. The 4-generation AC/DC hybrid power system of IEEE.](image)

In the case of using HVDC fuzzy controllers, the following two disturbances are simulated: Case 1, No.6 Bus has a three-phase short circuit, and the fault disappeared after 0.15 seconds (the line was not cut off).

The results of the simulation under case 1 are shown in Figure 4 and Figure 5, respectively. $\delta_{59}$ in Figure 4 represents the phase angle’s difference between No. 5 and No. 9 bus voltages, $\delta_{G3}$ and $\delta_{G1}$ respectively represents the power angle values of No. 3 and No. 1 generator, respectively. Curve $(P_{DC})$ in Figure 5 represents the active power transmitted by the DC line and $P_{59}$ represents the AC active power flowing from the No. 5 bus to the No. 9 bus.

![Figure 4. The curve of $\delta_{59}$ and the difference between $\delta_{G3}$ and $\delta_{G1}$.](image)

![Figure 5. The curve of $P_{AC}$ and the sum of $P_{AC}$ and $P_{DC}$.](image)

Through Figure 4 and Figure 5, it can be seen that the regional mode oscillation after the fault is quickly suppressed, and the phase angle’s difference between No. 5 and No. 9 bus voltages, and the power angle’s difference between No. 3 and No. 1 generator are also adaptively adjusted to the steady-state value after the fault. At the same time, the active power transmitted by lines is also restored to the steady-state value before the failure.

Use the 4-Generation AC system to simulate and verify the adaptive controller. In the simulation, the dynamic characteristics of TCSC are represented by a variable capacitor with a first-order inertia link. The generator uses the biaxial model, the excitation system uses the third-order model, and the load uses the constant impedance model. In the steady state, the equivalent comprehensive reactance of TCSC is $-X_q$ which equals to 0.267, and the initial value of the amplitude gain of the adaptive controller is $G_{\Delta X_{\alpha 1}}$ which equals to 0.015.

Figure 6 and Figure 7 respectively show the change curves of the system tie-line power and TCSC equivalent comprehensive reactance under the a-type and b-type disturbances based on the condition of the 4-machine system with additional controller between No. 8 and No. 12 bus. Case 1: The transmission...
power of the tie line is 400MW in normal operation, and the fault is a three-phase short circuit of No.7 bus. The fault disappears after 0.1s. Case 2: The transmission power of the tie line is 400MW in normal operation. The disturbance is that the mechanical power of No.4 generator reduces from 700MW to 630MW.

![Figure 6. System response under case 1.](image1)

![Figure 7. System response under case 2.](image2)

5. Conclusion
The paper proposes an additional control strategy for dealing with the situation of mismatch combined with the theory of projection energy function. It effectively solves the unconsidered ways of deteriorating the stability of the power system or the situation that generator units available for removal under the current mode are less than the planned removal value in the strategy table. It also effectively deals with the phenomenon that part of the generator units refuses to move due to the security control system during the order of the security and stability control device.

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