Simulation Analysis and Experimental Verification of Dynamic and Thermal Stability Characteristics of 500kV High Coupling Split Reactor

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Abstract. This paper introduces the basic principle of 500kV high coupling split reactor, and the simulation analysis of leakage magnetic field, temperature field and winding electromagnetic force of maneuvering thermal stability characteristics. The feasibility of the design scheme is verified by the equivalence test of mechanical strength of small prototype.

Keywords: High coupling split reactor, Magnetic field, Temperature field, Electromagnetic force.

1. Introduction
Large-capacity short-circuit current breaking technology has always been a key research topic in large international power grids. It is an effective measure to improve the capacity of circuit breakers by running circuit breakers in parallel and sharing rated current and fault current. In the large-capacity parallel circuit breaker device, HCSR (High Coupled Split Reactor), as a special reactor, can realize high-efficiency current sharing and current limiting, thus ensuring the reliability and safety of multi-circuit breakers to break short-circuit fault current in parallel.

"Development of Economical High Voltage AC Current Limiter with Voltage Grade of 500kV and Above" was supported by the National Key R&D Project (2018YFB0904300) and the Science and Technology Project of China Southern Power Grid Corporation (GZHKXJM20180055). In this paper, the magnetic leakage field analysis, temperature field analysis, electromagnetic force and stress analysis of the 500kV HCSR maneuvering thermal stability characteristics are mainly carried out, and the feasibility of the design scheme is verified by the equivalence test of the mechanical strength of the small prototype.

2. Working Principle and Design Parameters of HCSR

2.1. Working principle
HCSR refers to a reactor composed of two groups of inductance coils with mutual coupling coefficient greater than 0.8. Based on the circuit breaker parallel technology of automatic current sharing and
current limiting of highly coupled reactors, it realizes automatic current sharing and current limiting. The principle of parallel circuit breaker based on HCSR is shown in Figure 1.

![Figure 1. Schematic diagram of parallel circuit breaker based on HCSR](image)

The odd-numbered envelopes (1, 3, 5, …11) constitute 1# branch, referred to as I arm for short; Even-numbered envelopes (2, 4, 6, …12) constitute 2# branch, which is referred to as II arm for short. Both arms run normally, and both arms are electrified at the same time; Single arm operation is fault operation. HCSR is composed of inductive coils coupled with each other, which is similar to a 1:1 transformer with reverse high coupling. One end of two sets of coils is short-circuited, and the other ends of two sets of coils are respectively connected with circuit breakers connected in parallel to form two parallel branches. During normal operation, the common magnetic circuit of the two coils produces opposite magnetic flux, and the currents of the two coils are equal and opposite, with small impedance and negligible voltage drop; If the currents flowing through the two branches are unequal, the alternating electromotive force is induced in the inductance coils of the two branches, which can force the two parallel branches to flow equally; When the parallel circuit breakers are inconsistent in action or cannot be opened at the same time due to other reasons, the HCSR presents excitation inductance, and externally presents large inductance, which can effectively limit the fault current of the circuit breakers, play the role of current limiting, and ensure that the post-opening branch can independently open short-circuit current.

Due to the above effects of the coupling coil, the parallel circuit breaker based on HCSR can realize the automatic current sharing and current limiting of the parallel circuit breaker, and ensure the reliable parallel connection of multiple circuit breakers, thus effectively improving the current carrying and breaking capacity of the circuit breaker.

2.2. Design value

HCSR design parameters are as follows.

1. Product type: dry, hollow, outdoor, natural cooling;
2. Rated frequency: 50Hz;
3. The rated operating voltage is 550kV;
4. Loss: 40kW;
5. Rated current: 2×2000A, 4s single arm thermal stability current: 52kA, 4s double arm thermal stability current: 90kA, 0.5s single arm dynamic thermal stability current: 133kA, 0.5s double arm dynamic thermal stability current: 230kA;
6. Temperature rise limit of winding hot spot: 100K;
7. Environmental temperature: maximum+45℃, minimum-10℃, maximum daily temperature difference 30K;
8. Seismic resistance: horizontal acceleration 0.25g, vertical acceleration 0.125g, seismic safety factor ≥1.67.
3. Simulation Analysis of Magnetic Field, Temperature Field and Stress of HCSR

3.1. Magnetic field simulation

The finite element analysis software of electromagnetic field is used to simulate and analyze the magnetic field of HCSR winding under current sharing and current limiting conditions.

As shown in fig. 2, a three-dimensional simulation analysis model of magnetic field is established, and parameter attributes such as encapsulated material, conductivity, structure type of each encapsulated coil, number of turns and wire gauge are set. The calculation model is considered as follows:

1. The structure is symmetrical, and the solution area is 1/2 of the overall HCSR;
2. The encapsulation is replaced by a thin cylinder, ignoring its microstructure;
3. (1) generating a coil on the basis of the number of wrapping turns and the cross section of a wire.

![Figure 2. Schematic diagram of reactor model](image)

3.1.1. Component circuit diagram

(1) Current sharing condition (double-arm operation)
The odd-numbered envelopes are connected in parallel, and the even-numbered envelopes are connected in parallel. To ensure the calculation accuracy, the air bag around the reactor is about 2.5 times the body size. The circuit diagram is shown in Figure 3, and the two branches are loaded with equivalent current of 2000A at the same time.

(2) Current limiting condition (single arm operation)

The model of one-arm operation is the same as that of two-arm operation, except that the circuit diagram is different. The circuit diagram is shown in Figure 4. One branch is loaded with a peak value of 133kA, and the other branch winding is connected in parallel.
3.1.2. Calculation result. According to the time harmonic field analysis, the current value, magnetic field energy and magnetic density of each envelope are calculated respectively, and the inductance value is calculated by using the magnetic field energy through the inductance calculation formula.

(1) Current sharing condition (double-arm operation)
When operating with both arms, the magnetic field distribution and current distribution around each envelope are obtained by magnetic field simulation, as shown in Figure 5. The magnetic density around the envelope is about 0.011T, the magnetic field energy is 286J, and the external inductance value is very small, only 36uH.

![Figure 5. Magnetic field distribution and current distribution of windings in dual-arm operation](image1)

(2) Current limiting condition (single arm operation)
When one arm runs, the magnetic field distribution and current distribution around each envelope are obtained by magnetic field simulation. As shown in Figure 6, the magnetic density around the envelope is about 4.03T, the magnetic field energy is 18,296,223 J, and the inductance value is 4.137mH.

![Figure 6. Distribution of winding magnetic field in single arm operation](image2)

According to the results of magnetic field simulation analysis:
(1) Under current sharing condition, the currents in two parallel branch windings are equal, and the reactor only shows leakage impedance with small impedance value;
(2) When the current is limited, the winding shows great inductance to the outside, which can effectively limit the fault current of the corresponding branch;
(3) Under current limiting condition, the upper and lower ends of two branch windings are connected together, which makes the adjacent windings form a loop. When a branch has current passing through, opposite magnetic flux will be generated in the loop, and induced current will exist.
3.2. Temperature field simulation
The detailed temperature distribution of HCSR, including the average temperature rise of encapsulation and the temperature rise and location of hot spots, was obtained by CFD analysis software. The analysis model is established according to axial symmetry, and the effects of filling coefficient, turn insulation, encapsulation insulation and drawing strip in air duct on heat dissipation are considered for aluminum wire.

![Cloud picture of encapsulation temperature distribution](image)

**Figure 7.** Cloud picture of encapsulation temperature distribution

According to the current sharing condition and the cooling mode is AN mode, the temperature distribution nephogram of each envelope is shown in Figure 7, and the average temperature rise and hot spot temperature rise distribution curves of each envelope are shown in Figure 8.

![Encapsulation temperature rise distribution curve](image)

**Figure 8.** Encapsulation temperature rise distribution curve

The analysis results show that the average temperature rise of the winding is 46.6K, and the hot spot temperature rise is 61.2K K. The temperature rise of each envelope gradually increases from the low end to the top end, and the temperature rise of the innermost and outermost envelopes is obviously lower, while the temperature rise of other envelopes is evenly distributed, indicating that the structural design is reasonable.

3.3. Simulation calculation of reactor winding stress
Based on the classical ANSYS finite element analysis software, the magnetic field force and mechanical stress are modeled and analyzed respectively. HCSR adopts scalar potential method of three-dimensional static field to build the global model. Because the resin encapsulation has solidified all
layers of turns into a whole, each layer of wire is modeled as a thin cylinder, and the elastic modulus, Poisson's ratio and inner surface load of aluminum conductor are set. Load the single arm dynamic stable current and calculate the magnetic field force, as shown in Figure 9. Solve the total electromagnetic force on the conductor in the envelope, distribute its internal stress according to the inner and outer diameters of the conductor, and calculate the resultant force on each layer of coils.

Figure 9. One-arm HCSR magnetic field force nephogram

Figure 10 and Figure 11 are the simulated stress distribution cloud diagrams of aluminum wire under single arm I and single arm II dynamic stable current.

Picture 10. Stress distribution cloud diagram of single arm I aluminum wire (outward)
Fig. 12 and fig. 13 are the graph curves of the stress and deformation of the winding under the dynamic stable current of single arm I and single arm ii, respectively. From the summary results, the maximum stress of single arm I is 64.7 MPa of envelope 1; The maximum stress of single arm ii is 66 MPa of envelope 4. The maximum deformation of single arm i is 0.58 mm for envelope 7, and that of single arm ii is 0.53 mm for envelope 4.

**Figure 11.** Stress distribution nephogram of single arm II aluminum wire (outward)

**Figure 12.** One-arm I chart curve
The simulation results show that:

1. The stress of single-arm encapsulation decreases from inside to outside, but some of them rebound, and the encapsulation deformation is larger in the middle than the inner side.

2. The maximum deformation is 0.58mm, the maximum stress is 66MPa, and the safety factor is 1.14.

4. Simulation Analysis and Experimental Verification of Small Prototype

According to the design parameters of 500kV HCSR prototype, using the same design algorithm and margin criterion, the equivalent small prototype model for testing is designed, and it is required that they should ensure the same materials, process and insulation structure.

4.1. Simulation analysis of small prototype

See table 1 for design parameters.

| Package title | Reactance height | Winding height | Average diameter of encapsulation | Number of turns | Axial dimension of conductor | Radial dimension of conductor |
|---------------|------------------|----------------|-----------------------------------|----------------|-----------------------------|------------------------------|
| 1             | 974.2            | 989.6          | 400                               | 63.25          | 14.9                        | 10.9                         |
| 2             | 976.5            | 995.4          | 450.7                             | 51.75          | 18.3                        | 10.6                         |
| 3             | 976.8            | 998.6          | 501                               | 44.75          | 21.2                        | 10.5                         |
| 4             | 979              | 1003.2         | 551.1                             | 40.5           | 23.5                        | 10.4                         |
| 5             | 983.2            | 1008.9         | 601.1                             | 38.25          | 25                          | 10.4                         |
| 6             | 979.2            | 1005.3         | 651.2                             | 37.5           | 25.4                        | 10.5                         |

According to the parameters of the small prototype, the magnetic field of the single arm is simulated and analyzed. According to the time harmonic field, calculate the current value and magnetic density...
value of each envelope when the peak current of single-arm dynamic thermal stability is 110kV. Table 2 shows the current distribution of odd-numbered 1, 3, and 5 encapsulated parallel single-arm operation. The magnetic field distribution is shown in Figure 14 and Figure 15. The maximum peak magnetic density near the winding is about 5.6T. It can be found from the nephogram that the maximum value of the magnetic density peak of Envelope 1 is about 5.5T, that of Envelope 3 is about 4T and that of Envelope 5 is about 2T.

![Shaded Plot](image)

**Figure 14.** Distribution of winding magnetic field in single arm operation
4.2. Small sample maneuvering stability test

The purpose of small sample maneuvering stability test is to simulate whether the maneuvering stability performance of 500kV sample reaches the standard. Figure 16 shows the photos and wave forms of small sample maneuvering stability test.

Considering the influence of DC component, the single arm is loaded with short-circuit current with peak value of 79.7kA, the waveform is stable, and the encapsulation of the small prototype is intact.
without abnormality. In theory, the short-circuit force should be considered as 1.1 times of the design value according to the square of current. In addition, the resin insulation layer of the small prototype is thinner than the actual prototype, and its mechanical yield strength is smaller. For the same stress design value, its stress test examination is more severe. Therefore, through the dynamic stability current impulse test, the small prototype indirectly proves that the design margin of the actual sample is sufficient.

5. Summary
Through the simulation research and analysis of magnetic field, temperature field, dynamic thermal stability of winding and seismic strength of body in HCSR design scheme, it is shown that the external inductance value is very small, which is 36uH, showing leakage impedance with very small impedance value; Under single arm operation condition, the inductance value is very large, which is 4.137mH, which can effectively limit the corresponding branch current, realize automatic current sharing and current limiting, and meet the parallel operation requirements of large capacity circuit breakers. The average temperature rise of winding is 46.6K, the hot spot temperature rise is 61.2K, and the seismic safety factor of reactor body is 2.68, which meets the standard requirements. The maximum calculated stress of the encapsulated winding is 66MPa, and the equivalent dynamic stability test of the small prototype has passed the examination. Therefore, the design scheme is feasible.

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