Simulation and Experiment Research on Dynamic Stress of 21kV Equivalent Prototype of 500kV Current Limiter High Coupled Split Reactor

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Abstract. The dynamic stress simulation and experiment of the 21kV equivalent prototype of the 500kV current limiter high coupled split reactor are researched in this paper. A calculation model of dynamic stress of 21kV equivalent prototype of 500kV current limiter high coupled split reactor is established by using finite element simulation software, and the dynamic stress distribution is analysed with the calculation results. Then the dynamic stability experiments of the single arm of the prototype and analysis of the experiment and simulation results are introduced. The results of simulation and experiment prove that both of the dynamic stability of the 21kV equivalent prototype and the 500kV current limiter high coupled split reactor meet the design requirement.

1. Introduction

As a new equipment, high coupled split reactor has been applied to the large capacity parallel breaking of vacuum breaker in recent years [1, 2]. The 500kV high coupled split reactor is the core component of the new 500kV current limiter, which plays a key role in withstanding and limiting short-circuit current in the power grid [3, 4]. The dynamic stability experiment of the 500kV current limiter high coupled split reactor cannot be conducted directly because the laboratory can’t provide enough short-circuit current for the experiment. According to the description of GB 1094.5 on the equivalent verification of transformer dynamic stability test [5], equivalence test method can be used to replace the direct test. The short-circuit dynamic stability test can be conducted on the equivalent prototype, and the dynamic stability of the 500kV current limiter high coupled split reactor can be indirectly verified through the test results of the prototype.

The simulation and calculation method of the magnetic field and dynamic stress of the 21kV equivalent prototype of the 500kV current limiter high coupled split reactor are introduced firstly in this paper. Then, according to the structural parameters of the 21kV prototype, a simulation model is established to analyze the dynamic stress distribution of high coupled split reactor in the current limiting. Finally, the dynamic stability experiment of the 21kV prototype is introduced, and the simulation results are compared with the test results of the prototype to verify that the dynamic stability of the 500kV current limiter high coupled split reactor meets the design requirements.
2. Simulation method of magnetic field and dynamic stress of high coupled split reactor

The current limiting principle diagram of the 500kV current limiter high coupled split reactor is shown in Fig. 1. In normal state, the fast switch $S$ is closed and the current flows through the two arms of the reactor. The impedance of the reactor is small because of the magnetic couplings of the two arms. When the fault occurs, the fast switch $S$ opens and the current limiter enters normal working condition. At this time, the impedance of the reactor is large and the current only flow through one arm of the reactor. The 90kA short-circuit current is limited to 54kA, and the current limiting ratio is 40%.

![Figure 1. The current limiting principle diagram of 500kV current limiter.](image)

The finite element simulation software ANSYS and Maxwell are used to analyze the magnetic field of the high coupled split reactor in this paper. First, a three-dimensional simulation model of the reactor is established in Maxwell. Considering the difficulty of modeling and the calculation ability of software, the winding is equivalent to a hollow cylinder. Then the resistivity, dielectric constant and permeability of material are set according to aluminum wire parameters. Model is shown in Fig. 2.

![Figure 2. The model of high coupled split reactor.](image)

The inductance matrix $M$ of the reactor is obtained by setting the number of turns of each winding. Then the current of each winding are calculated by formula 1 and formula 2.

\[
j\omega M \cdot \bar{I} = U
\]

\[
\sum I = 54kA
\]

$U$ is the voltage of each winding, and $I$ is the current of each winding.

The source of model is set according to current size. The solver is set to a transient solver, and the current is set to winding mode. In this model, the encapsulations are numbered from 1 to 6 from inside to outside. №1, №3, and №5 encapsulations are connected in parallel as one arm, and №2, №4, and №6 encapsulations are connected in parallel as the other arm. The current directions of the two arms are opposite to form a reverse coupling, and the set excitation source is shown in Fig. 3. In Fig. 3, red means that current flow inward and grey means that current flow outward.

After the simulation parameters are set up, the volume density of the electric force is calculated by setting boundary condition and using iterative solution method. These calculated data are imported into Ansys Workbench and used as loads for structural stress simulation. Finally, a model including the encapsulation shell is built in Workbench.
3. Simulation and experiment analysis

3.1. Dynamic stress analysis of 21kV prototype

The dynamic stress of the high coupled split reactor on the harshest condition is studied in this paper. Therefore, the short-circuit current only flow through odd-numbered windings during simulation. The current distribution is shown in Tab. 1.

Table 1. The current distribution.

| Number of encapsulations | Short-circuit current/A |
|-------------------------|------------------------|
| 1                       | 9871.90                |
| 3                       | 17362.72               |
| 5                       | 26765.56               |

The current source is set according to Tab. 1. In order to obtain an accurate grid, the iterative simulation calculation of the steady-state electromagnetic field is carried out. After several iterative calculations, the grid that meets the accuracy demand is obtained, as shown in Fig. 4.

Figure 4. Grid obtained by iterative calculation of steady-state electromagnetic field simulation.

The contact surface of the windings and encapsulations are set to bonded-mode, and the surface of the epoxy glass shell is set to fixed-mode. The material properties of winding and encapsulation shell are shown in Tab. 2.

Table 2. Material parameters.

| Material            | Density/(kg/m³) | Elastic Modulus/GPa | Poisson's ratio |
|---------------------|-----------------|---------------------|-----------------|
| Aluminium wire      | 2700            | 62                  | 0.33            |
| Epoxy glass fibre   | 2000            | 20                  | 0.33            |

The dynamic stress distribution of high coupled split reactor is shown in Fig. 5. It can be seen from Fig. 5 that the force trend of the inner encapsulation is outward, and the outer encapsulation is inward. The direction of the electric forces which are received by most of the windings are radially outwardly from the center.
From the simulation results in Fig. 6, it can be seen that the peak value of dynamic stress is 69.90 MPa in the №1 encapsulation. The allowable stress of epoxy FRP materials is generally above 300 MPa [6, 7], so the dynamic stress of the encapsulations is in the acceptable range.

Figure 6. The dynamic stress distribution.

In order to observe the deformation of the reactor due to the dynamic stress, the deformation effect is magnified. The result is shown in Fig. 7. Since the place with the greatest dynamic stress is at the middle position of the reactor, there is a significant outward expansion trend in the middle of the inner encapsulation. The outermost encapsulation tends to contract inward under tensile stress. The deformation trend is consistent with the stress distribution. The simulation results show that the middle position of the innermost encapsulation of the 21kV prototype is most likely to crack under tensile stress in the short-circuit current limiting.

3.2. Experiment of 21kV prototype

The purpose of the dynamic stress test of the equivalent prototype is to indirectly verify whether the dynamic stability of the 500kV current limiter high coupled split reactor meets the requirement. Therefore, the prototype should have the same operation mode, physical structure, conductor material
and manufacturing process with the 500kV current limiter high coupled split reactor. In order to make the prototype bear the same dynamic stress as the 500kV high coupled split reactor, the prototype should withstand the short-circuit current with a peak value of 76kA, which is identical to the 500kV high coupled split reactor.

The test loop is shown in Fig. 8. The generator voltage is 21kV and the loop impedance is 0.70Ω. The peak value of short-circuit current is 76kA and the current RMS value is 30kA. The duration of short-circuit condition is 0.5s. During the test, the assessment requirements for the dynamic stability of the prototype are as follows: There should be no significantly increase in the number of cracks on the surface of the encapsulations. The test results are shown in Tab. 3.

![Figure 8. Test loop.](image)

![Table 3. Test results.](image)

| Peak value of short-circuit current/kA | RMS value of short-circuit current/kA | Duration of short-circuit/ms | State of HCSR |
|--------------------------------------|--------------------------------------|-----------------------------|---------------|
| 79.7                                 | 30.2                                 | 527                         | Normal        |
| -76.5                                | 29.8                                 | 515                         | Normal        |

The short-circuit duration of both two tests were no less than 0.5 seconds. The surface of the reactor remained normal and there is no significantly increase in the number and size of cracks on it. The experimental results prove that the dynamic stability of reactor meet the requirement, and these experimental results are consistent with the simulation results.

A destructive test is carried by increasing the level of short-circuit current. The generator voltage is 21kV and the loop impedance is 0.34Ω. The peak value of short-circuit current is 99.2kA and the current RMS value is 61.0kA. The duration of short-circuit condition is 135ms.

![Figure 9. Destructive test.](image)

When the experiment is complete, it can be found that the encapsulation of the prototype is obviously deformed and different cracks arise in several positions inside reactor. The cracks positions of the prototype are shown in Fig. 9. The positions of the cracks are mainly in the middle area of the inner encapsulation, which is consistent with the simulation results.

4. Conclusion

The dynamic stability of the 21kV equivalent prototype of the 500kV current limiter high coupled split reactor is researched through simulation and experiment in this paper. According to the loop parameters and the structure of the prototype, the finite element simulation software Maxwell and Ansys workbench are used to calculate the dynamic stress distribution of the equivalent prototype. The following conclusions are obtained by analyzing the simulation and experiment results.

The simulation results prove that the main stress type of the high coupled split reactor is tensile stress. Under the dynamic stress, the inner encapsulations are forced to expand outward and the
outermost encapsulation is forced to contract inward. When the prototype withstands the short-circuit current with a peak value of 76kA, the maximum tensile stress of the reactor is 69.90 MPa and located in the middle area of the reactor. The dynamic stress of the encapsulation is in the acceptable range of epoxy FRP.

The results of dynamic stress experiment prove that the dynamic stability of the high coupled split reactor meet the requirement since there are no cracks in the encapsulations during the test. And the result of the destructive experiment proves that the position of the maximum stress of the 21kV equivalent prototype is consistent with the simulation results.

According to the results of simulation and experiment research on 21kV equivalent prototype, it is shown that the dynamic stability of the 500kV current limiter high coupled split reactor meets the design requirement.

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