Electromagnetic field simulation of large hollow reactor

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Abstract. The electromagnetic interference problems of large-scale hollow reactor equipment are special and increasingly widespread. In order to thoroughly understand the electromagnetic interference of large hollow reactors on various equipment in a substation, a field test was performed near a SVC in a substation, and the electromagnetic field was explained from three aspects: the main ground network induced circulation, the secondary cable shield current, and the DC system ripple interference. Interference issues. Furthermore, a three-dimensional electromagnetic field simulation model was established for SVC and nearby areas, and the equivalence of the model was verified by comparing it with the spatial magnetic field and induced current on the site. Based on this analysis, the electromagnetic interference improvement and the effect of inductance value changes at different reactor heights were analyzed. The results show that, during normal operation of large hollow reactors, the electromagnetic interference between the nearby grounding system and the DC system has approached or exceeded its rated operating conditions. In the design, attention should be paid to the spatial location of the reactor and the ground network, the control room and the secondary screen cabinet.

1. Introduction
The iron core reactor can restrain most of the magnetic induction lines in the iron core, so that the magnetic flux leakage is small, and the electromagnetic interference to the surroundings will not be too strong. However, at present, a large number of reactive power compensation devices, SVC, series compensation, etc. all use air core reactors, and the phenomena such as magnetic saturation will not affect the reactance parameters. But the spatial magnetic field of air core reactors is relatively divergent, so for high-power strong electric systems, the surrounding spatial magnetic field energy is so large that it can generate strong electromagnetic pollution to the surrounding environment [1-4]. The strong magnetic field generated under the working conditions can cause strong interference to the nearby secondary system and the grounding system, which has affected the safe operation of some domestic substations. As shown in Fig. 1, the fence door of a reactor is affected by the circular current, resulting in the temperature of more than two hundred degrees, and the door bolt has been blackened. As can be seen from Fig. 2, the cable shielding layer of the terminal box near a reactor is burned due to the heat generated by circle current, and the circular current of each cable shielding layer is up to about 10A. As shown in Fig. 3, the circular current of the metal parts of the terminal box near the reactor can reaches 16.1A. As shown in Fig. 4, the cable sleeves near a certain reactor generate heat and are corroded at the same time. Therefore, it is very necessary to simulate and analyze the electromagnetic interference generated by the air code reactor, so as to conduct an in-depth analysis of its causes.

In addition, aiming at the distribution characteristics and shielding method of the magnetic field of independent air core reactors, a lot of research has been carried out at home and abroad. For example, the references [5-12] utilized different numerical calculation methods to analyze the electromagnetic
induction mechanism of the reactor, and used different software to analyze the magnetic field around the reactor. Among them, the reference [9] also established a scaled model for study. Furthermore, the references [11-18] had studied in detail the improvement of the spatial magnetic field of the reactor and the variation of the reactor's parameters before and after the application of shields with different shielding materials and different geometry sizes. However, in actual substations, the electromagnetic interference problem of air core reactors in SVC is not only reflected in the enhancement of the spatial magnetic field. There are not enough reports on the real interference suffered by the grounding system and the secondary system near SVC, and not enough attention has been paid to the spatial installation location of reactors.

2. Basic overview of reactors
At present, dry-type air-core reactors generally adopt a structure in which multiple coaxial windings are encapsulated in parallel. Fig. 5 is the bottom view of a dry-type air-core reactor with multi encapsulation. Each encapsulation of the reactor is wrapped with long glass fiber impregnated with epoxy resin, and the polyester glass wires serve as the stays between encapsulations to form the insulation and heat dissipation channels between the encapsulations. The head and end of each encapsulated wire were respectively welded to the top and bottom of an aluminum star frame, and the star frame not only acted as an electrical connection but also to compress the coil, to improve the mechanical strength and overall stability of the air core reactor. In each encapsulation, there are several coils connected in parallel, and each layer of coil is made up of several metal wires with small cross-section wound in parallel (usually aluminum wires). Each wire is covered with polyester film or glass wire as turn insulation. After the winding of the air core reactor is completed, it is heated and solidified, and the entire winding is encapsulated to form a solid whole. Then a special layer of silicone organic paint resistant to ultraviolet radiation is sprayed after the surface is sandblasted. Fig. 5 shows the longitudinal section of the encapsulation structure of the air core reactor [5-9]. Three-phase dry-type air core reactors on site are generally arranged like a triangle or in a line. SVC reactors in the 500KV Wuzhou Substation and the reactors in Chuxiong Converter Station are arranged in a line, as shown in Fig. 7. Therefore, this paper carried out the simulation arranged in a line.
3. Simulation of reactors

3.1 Simulation conditions

In the software COMSOL Multiphysics, numerical operations such as steady state, transient state, modal, eigenvalues, time and frequency domains, parameterized sweeps, etc. can be performed. Also, dependent variables and the grids used can be specified respectively to analyze the effects of different physical fields on the coupling of multiple physical field. When establishing the model of the whole system, the following simplification was made:

- Irrespective of the influence of the stays and ignoring the encapsulated end insulation, the encapsulations of the reactor was simplified to a coil wound by pure wires;
- Under the premise of ignoring the outer insulation of the encapsulations, each encapsulation was regarded as a whole with the same source current density;
- It was assumed that the reactor group operated in three-phase equilibrium, the phase angels of three-phase current varied by 120°, and the current phase of each encapsulation of the reactor in each phase was the same;
- In the simulation area, no other power source excitation was introduced except the current passing through the reactor;
- The eddy current effect per coil of the reactor was ignored;
- In the simulation area, the effects of the facilities with small volume and small effect on the space magnetic field were ignored.

3.2 Simulation model

The establishment of the reactor model is shown in Fig. 7. Because the inductance coil has many turns, modeling for each turn alone was not efficient. In this model, a ring cylinder of equal volume was used to replace the whole coil, in which the constant impressed current density inside the ring was equal to the sum of the current per turn in the coil. Since the cylinder model was utilized to replace the actual split-turn coil, a new issue was introduced that the cylinder model would generate eddy currents in the cross section after the current was supplied, which did not exist in reality. By setting the model material, setting the conductivity to a lower value (no more than 100S/m) could avoid the generation of eddy currents and achieve an agreement with the actual situation.

After the model was established, the materials of the reactor, air, land, and grounding network were defined respectively, and their electrical conductivity, relative dielectric constant, and relative permeability parameters were set to make them conform to the actual electrical characteristics. According to these known conditions provided by the user, COMSOL software combined the ampere law and electromagnetic induction law to solve the system in the calculation. The specific parameters of the materials are shown in Table 1.
Table 1. Physical model material parameters

| material       | Conductivity $\zeta$ (S/m) | Relative permittivity $\varepsilon_\gamma$ | Relative permeability $\mu_\gamma$ |
|----------------|----------------------------|------------------------------------------|---------------------------------|
| air            | 1                          | 1                                        | 1                               |
| Aluminum conductor | 3.774×10^7               | 1                                        | 1                               |
| Copper conductor  | 5.998×10^7                | 1                                        | 1                               |
| flat steel         | 1.122×10^7               | 1                                        | 300                             |
| land            | 0.01                       | 10                                       | 1                               |

The object of this simulation was a three-phase air core reactor, and power-frequency AC voltage was connected to each layer of aluminum wire of the air core reactor. In the process of solving, the computer iterated the finite element grid according to Ampere's loop law and electromagnetic induction law. According to the known conditions, the magnetic field and electric field in each region of the model were calculated, and in the cylindrical coordinate system, the vector magnetic potential had only the circumferential component. According to the Maxwell equations, the basic equation for solving the magnetic field of the area is:

$$\frac{\partial^2 A_\varphi}{\partial r^2} + \frac{\partial A_\varphi}{\partial r} \frac{1}{r} + \frac{\partial^2 A_\varphi}{\partial z^2} = -\mu J_\varphi$$  \hspace{1cm} (1)$$

where: $A_\varphi$ is the circumferential component of the vector magnetic potential $A$; $\mu$ is the magnetic permeability of the material; $J_\varphi$ is the current density; $\gamma$, $\theta$, and $z$ represent the radius, angle, and height coordinate axes in the cylindrical coordinate system, respectively.

$$\frac{\partial^2 A_\varphi}{\partial r^2} + \frac{\partial A_\varphi}{\partial r} \frac{1}{r} + \frac{\partial^2 A_\varphi}{\partial z^2} = -\mu \frac{\gamma J_\varphi}{\zeta}$$  \hspace{1cm} (2)$$

The current density of the parallel winding area is $\frac{\gamma J_\varphi}{\zeta}$ (Ni is the amount of ampere turns on the i-th winding, Ni is the number of turns of the i-th winding, i is the current of the i-th winding, and Si is the area of the i-th winding), so the basic equation of the magnetic field is

$$\frac{\partial^2 A_\varphi}{\partial r^2} + \frac{\partial A_\varphi}{\partial r} \frac{1}{r} + \frac{\partial^2 A_\varphi}{\partial z^2} = 0$$ \hspace{1cm} (3)$$

In the region outside the winding, the current density is 0, and the magnetic field equation is For the boundary of the entire model, because only the magnetic field distribution within the boundary was required and the magnetic field and the electric field to cross the model boundary were not desirable, both magnetic insulation boundary and electrical insulation boundary were designed to ensure the convergence of the calculation of the entire model [14].

The rated current of the single-phase reactor in the SVC substation was 2000A, that was, the rated passing current in the loop of each turns was 2000A. The rated operating state of the reactor was simulated, and the flow current of single-phase reactor was I. According to the equivalence principle of surface current density, a ring cylinder of the same size was used to replace the original coil in the model, and the same current was injected into the radial section to achieve the equivalent surface current density of radial cross section. The current density of A-phase reactor was set as $J_A = J_\theta \angle 0^\circ$, and the other two-phase currents were $J_B = J_\theta \angle 120^\circ$, $J_C = J_\theta \angle -120^\circ$, respectively, while the current frequency was set to the power frequency of 50Hz.

3.3 Simulation of magnetic field

Three-phase current was applied to the three-phase reactor in the model. The initial phase of L1 was set as 0o, the initial phase of L2 was set as 120o, and the initial phase of L3 was set as 240o. Three-
phase current would generate three-phase superposition magnetic field in space, and the simulation results were shown in Fig. 9. The magnetic field distribution of the ground surface sectioned in the model was shown in Fig. 10. The magnetic field was strongest in the center area of the three-phase reactor, and the peaks formed in the corresponding area of the three-phase reactor were similar, while the magnetic fields in other areas farther from the reactor were weaker. The surrounding area had a flat magnetic field.

Comparing the size of the magnetic field simulated by the simulation software with that of the field magnetic of SVC could evaluate the accuracy of the simulation. 16 typical locations as shown in Fig. 11 were selected for comparison, obtaining the magnetic flux density shown in Table 2.

| Test point | Actual magnetic induction/ uT | Simulated magnetic induction/ uT |
|------------|------------------------------|---------------------------------|
| 1          | 215                          | 205.37                          |
| 2          | 322                          | 129.07                          |
| 3          | 309                          | 83.764                          |
| 4          | 1572                         | 1500                            |
| 5          | 723                          | 1100                            |
| 6          | 384                          | 328.16                          |
| 7          | 407                          | 596.19                          |
| 8          | 512                          | 519.41                          |
| 9          | 460                          | 557.42                          |
| 10         | 980                          | 1000                            |
| 11         | 923                          | 990.16                          |
| 12         | 306                          | 150.34                          |
| 13         | 883                          | 988.43                          |
| 14         | 296                          | 199.97                          |
| 15         | 233                          | 146.13                          |

All the measurement points in the model were the same as the actual measurement points, and the vertical height was uniformly 1m above the ground. As can be seen from Table 2, the distribution trend of the magnetic induction intensity of all points was consistent with the actual measured values,
among which the measured values of positions 1, 4, 6, 8, 10 and 11 had good equivalence with the simulated value; Due to the fact that the vertical height of the test point in the actual measurement was not uniform, there was a deviation between the measured value and the simulated value at other locations, as well as some accumulative errors of the simulated values far away from the reactor. Nevertheless, the simulation results could better reflect the magnetic field distribution in the field as a whole.

The "Guidelines for limiting exposure of time-varying electric fields, magnetic fields, and electromagnetic fields (under 300 GHz)" stipulates that the magnetic field of the general public's living environment does not exceed 100μT, and the magnetic field of the working environment for professional staff does not exceed 500μT. When the three-phase reactor was working at full load near the reactor, the strongest magnetic field has exceeded 1000μT, which has exceeded the specified standard. In the field test, the magnetic field strength of most areas was less than 500μT. As the test points 4, 5, 7, 8, 9 near the guardrail were close to the reactor, the magnetic field values were close to or exceeded 500μT, among which the position 4 was closest to the transformer in the cell, with a magnetic field up to 1572μT. In the protective chamber, the magnetic field distribution varies greatly. The magnetic field far away from the wall of the reactor is between 200–400μT, while the magnetic field size near the wall of the reactor can reach 800–1000μT, indicating that effect of shielding magnetic field of the protective chamber was not obvious.

If the effect of electromagnetic field can be effectively considered at the beginning of the design, setting the fence wider and the protective chamber and field terminal box farther from the reactor, to effectively reduce the magnetic field intensity.

4. Simulation of ground network circulation and disturbance

The horizontal grounding body of the main grounding grid was constructed by galvanized flat steel of 60 × 6 mm2. The grids directly below the three reactors were selected as the research object, and the main grounding grid about 40m long was abstracted as a resistance with a resistivity of 0.138 Ωmm2/m. The total resistance value could be calculated as 15.33 mΩ. However, the contact resistance between the horizontal and vertical main grounding grids was ignored in the calculation process. The actual resistance value was larger than the theoretical value. The grounding resistance of the main grounding grid measured on site was approximately 41.41mΩ, while the induced AC voltage of the main grounding loop was 24.81V. According to the measured values, the calculated induced current was 599.13A.

The shielding layer of secondary cables was formed by overlapping and wrapping copper strips with a thickness of 0.05-0.15 mm. Taking the diameter of the secondary cable as 20mm, the cross-sectional area of the cable shield could be calculated as 12.60mm2. The 79 m long loop of the secondary cable shield could be abstracted as a resistor with a resistivity of 0.017241 Ωmm2/m. The calculated total value of was 108mΩ, not large, but the grounding resistance of the shield at the grounding point should be considered. In the on-site field test, the induced electric potential at the end of the shielding layer at single point grounding was measured to be 10.47V, and the induced current in the circuit after the grounding of the shield layer at two points was 10.2A. The loop resistance formed by the control cable shielding layer and the grounding network could be calculated as 1.03Ω, which included the equivalent resistance of the grounding loop materials and the contact resistance of the grounding point. The induced AC voltage of the loop in the secondary cable shield was 12.51V and the induced current was 12.15A.

| LINE                | inductive voltage (V) | Loop resistance (mΩ) | Induced current (A) |
|---------------------|-----------------------|----------------------|---------------------|
| Cable shield        | 12.51                 | 1030                 | 12.15               |
| Main grounding      | 24.81                 | 41.41                | 599.13              |
| circuit loop        |                       |                      |                     |

Table 3. Circulation of grounding body
Simulation calculations showed that the induced current in the loop of the secondary cable shield was 10.16 A. In engineering, the shielding thickness of the secondary cable was 0.1 mm, the diameter was 20 mm, and the rated current-carrying capacity of the shield was 63 A. Although the induced current did not exceed the standard, the contact resistance at the junction of the shielding layer was very large with serious heating, resulting in the heating and ablation of the grounding terminal of the control box. Such problems were also exposed in the actual site. On the other hand, the induced current in the highest area of the main grounding network loop reached 599.13A, while the grounding carrying capacity in the main grounding network of 60 × 6 was 540A. At present, the grounding network of the simulated location had reached or exceeded its rated value, and other locations of the main grounding network might be under full load or even overload for a long time, which led to the underground main grounding grid to be heated for a long time and accelerated its corrosion rate. Therefore, it was necessary to study suitable shielding methods to reduce the induced current in the grounding grids.

On the other hand, in the model, the on-site DC system interference was simulated, and the selected line is shown in Fig. 2. The DC line started from the main control building of the substation and was distributed along the cable trench to the vicinity of the reactor, forming an induced potential with the entire main grounding grid. The common mode interference in the measurement and control screen of the protective chamber and the common mode interference in control cabinet of reactor and breaker, were respectively measured on site. Simultaneously the same position in the simulation model was simulated, and the simulation results are shown in Table 4.

| Table 4. DC system interference |
|--------------------------------|
| Protection room common mode interference/V | Common mode interference of reactor control cabinet of reactor circuit breaker/V |
| Measured value | 14.53 | 9.22 |
| Simulation value | 14.60 | 11.88 |

The actual measurement results showed that the further the distance between the control cabinet of reactor and breaker and control building, the larger the interference in theory, but in practice, its interference voltage was smaller than that of the measurement and control panel of the protective chamber. After field investigation, it was found that the secondary cable was laid along the cable direction, which first passed the control cabinet of reactor and breaker, then entered the protective chamber, and finally came out from the protective chamber through the same line and connected to the control cabinet. In the simulation model, the layout was arranged according to the line, and the simulation results were shown in Table 4, close to the measured results, which again proved the correctness of the simulation results.

5. Influence of the reactor position

The position of the reactor had a great influence on the interference. For example, increasing the height of the reactor from the ground could effectively reduce the interference of the magnetic field under the ground. The space magnetic field generated by the air core reactor was relatively divergent, and the magnetic induction intensity in the space was attenuated by a square multiple. When the reactor height had been raised, the space magnetic field in the underground area would be greatly reduced. The influence on the ground network interference was calculated by simulating the reactor at different heights from the ground, as shown in Table 5.

| Table 5. Magnetic flux density table |
|-------------------------------------|
| Reactor height/m | Secondary cable induced current/A | Induction current of main grounding grid/A | Protection room common mode interference/V | Common mode interference of reactor control cabinet of reactor circuit breaker/V |
|------------------|----------------------------------|------------------------------------------|---------------------------------|----------------------------------------|
| 0                | 12.15                            | 599.13                                   | 14.60                           | 11.03                                  |
| 0.1              | 10.87                            | 388.31                                   | 14.59                           | 10.65                                  |
raising the reactor height. After that, the spatial magnetic field in the underground area will be greatly reduced. By simulating the reactor at different heights from the ground, the calculated impact on the ground network interference is shown in Table 5.

The simulation results showed that increasing the height of the reactor from the ground could reduce the circular current across the shielding layer of the underground secondary cable, the induced current of the main grounding grid, and the common mode interference of the DC system. When the height of the reactor was raised to four meters, the current of the shielding layer could be reduced to 1.27A, the current of the main grounding grid could be reduced to 92.73A, the common mode interference of the protective chamber was reduced to 6.85V, and the common mode interference of the control cabinet of reactors and breakers was reduced to 4.96V. It could be seen from the effect of this measure that raising the reactor could effectively weaken the circular current of the shielding layer and the circular current of the main grounding network, and also reduce the common mode interference to some extent.

Three-phase air core reactors should not be arranged in a line but like a triangle. The three-phase symmetrical structure like a triangle was beneficial to offset the three-phase magnetic field when SVC worked normally, and could greatly reduce the impact of the low-frequency strong magnetic field on the surrounding environment.

The location of the SVC reactor in the substation was highly relevant to the electromagnetic interference suffered by the secondary equipment in the station. In the new substation, the SVC equipment could be arranged at the edge of the substation to keep the interference source as far away from the complex secondary cable in the station as possible, as shown in Fig. 13. The original reactor was in the middle of the secondary cable layout, and the reactor was recommended to be outside the secondary cable layout.
6. Conclusions
This paper combined the field data of the large air core reactor with the simulation results of the equal-ratio model, illustrated the electromagnetic compatibility of the current reactor in detail, and put forward the following suggestions:

- The electromagnetic compatibility of large reactors has become a serious problem, and its interference is mainly reflected in the three aspects: the induced circular current of the main grounding network, the current of the secondary cable shield and the ripple interference of the DC system.
- In design, electromagnetic simulation should be carried out for the reactor to provide a basis for its spatial arrangement.
- The height of the reactor had a great influence on the common mode interference of the grounding circular current and DC system. It is recommended to increase the height of the reactor.
- Equipment such as the protective chamber, the fence of the reactor, and the field terminal box should be kept away from the reactor, thereby reducing its circular current.

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