FEM Analysis of Iron Core Losses in Magnetically Controlled Shunt Reactor with Distributed Magnetic Valves

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Abstract. In this paper, the MCR with distributed magnetic valves is proposed. The magnetic valve is equally distributed in iron core, which is piled up by silicon-steel sheets and epoxy sheets. Field-circuit coupled simulation model is established in ANSYS software. The waveforms of electrical state variables, magnetic flux density distribution and iron core losses are acquired. The comparison with the MCRs with a single-stage magnetic valves and multiple-stage magnetic valves demonstrates the advantage of proposed magnetic valve structure.

1. Introduction

With the rapid development of ultrahigh-voltage long-distance transmission in China, as well as various load access to distribution grid, the need for flexible reactive power compensation becomes more and more urgent. The magnetically controlled shunt reactor (MCR) plays an important role in static reactive power compensation due to its advantages, including smoothly adjusting of inductance, limiting system overvoltage and high reliability and so forth [1] - [3].

The magnetic valve is a key component of MCR, the structure of which is related to core loss and harmonic characteristics. Several methods to optimize MCR’s magnetic valve have been investigated through simulation model [4] - [6]. These researches show that MCR with multi-stage magnetic valve presents better suppression of current harmonics than that with single-stage magnetic valve. However, the modeling and simulation methods used in the above research are all based on the equivalent circuit method, which is insufficient to analyze the effect of different magnetic valve structures on the iron core loss of MCR.

For MCRs applied in high-power applications, the evaluation of iron core loss becomes very important. In [7] - [8], by using finite element analysis software (ANSYS), the magnetic field of MCRs with different core structures are simulated, and the iron core losses are analyzed. However, in these researches the changes in magnetic valve structures only occurs at the external sides of core limb, and the central part of the magnetic valve section is still a continuous magnetic path. Furthermore, both the size and the capacity of MCR are small.

In this paper, the MCR with distributed magnetic valve is proposed. The magnetic valve is equally distributed in iron core, which is piled up by silicon-steel sheets and epoxy sheets. A single-phase full-size two-dimensional (2-D) MCR simulation model with distributed magnetic valve is established by finite element software ANSYS, and the field-circuit coupling method is used to simulate the practical operation of a 10MVA/10KV MCR in a substation. The waveforms of electrical state variables,
electromagnetic parameters, magnetic induction strength distribution, and iron core loss are acquired. The comparison with the MCRs with a single-stage magnetic valve and multi-stage magnetic valve demonstrates the advantage of proposed magnetic valve structure.

2. Configuration and Mechanism of MCR
The basic configuration of a single-phase MCR is shown in Figure 1. The iron core comprises of two parallel limbs (iron core 1, iron core 2) and side yokes. Working windings are installed on the limbs of the core, with taps connected to thyristors $V_{T1}$ and $V_{T2}$ (taping ratio $\delta = N_2/(N_1+N_2)$). The upper and lower two windings of different cores are cross-connected in parallel to the power grid, with a freewheel diode $V_D$ connected at the intersection. The two magnetic valves at middle concave part of the cores have smaller transverse areas than other parts of the limbs. When the MCR works and thyristors is conducting, both AC and DC flux occurs in the iron core, and the valves on the limbs are deeply saturated. Figure 2 illustrates that $V_{T1}$ and $V_{T2}$ are alternatively triggered at the two half-cycles of grid voltage. By changing the firing angle of the thyristors ($\alpha$), the DC magnetizing current is adjusted and then changing the magnetic saturation level ($\beta$) of the core.

![Figure 1. Schematic diagram of MCR.](image1.jpg)

![Figure 2. Control scheme of $V_{T1}$ and $V_{T2}$.](image2.jpg)

Table 1 summarizes the parameters of MCR which have been put into operation in a power substation in Zhejiang province, China. Simulation model of MCR is established based these parameters.

| Parameters         | Value  |
|--------------------|--------|
| Rated capacity     | 10 MVA |
| Rated voltage      | 35kV   |
| Rated frequency    | 50 Hz  |
| Rated current      | 165 A  |
| Tapping ratio      | 0.01   |

3. Settings of ANSYS Simulation

3.1. Three types of magnetic valve structure
The schematic diagrams of MCRs with three types of magnetic valve structures are illustrated in Figure 3. Figure 3 (a), (b) and (c) show MCR with single-stage magnetic valve, multi-stage magnetic valves and distributed magnetic valves respectively.
Except the different magnetic valve structures, other parameters of the three MCRs are same. The specific parameters are given by Table 2.

Table 2. The specific parameters of the MCR

|                  | Single-stage | Multiple-stage | Distributed |
|------------------|--------------|----------------|-------------|
| Length/m         | 2.534        | 2.534          | 2.534       |
| Height/m         | 2.832        | 2.832          | 2.832       |
| Depth/m          | 0.3          | 0.3            | 0.3         |
| Iron core diameter/m | 0.416    | 0.416          | 0.416       |
| Upper and lower yoke width/m | 0.416    | 0.416          | 0.416       |
| Side yoke width/m | 0.416        | 0.416          | 0.416       |
| Magnetic valve total height/m | 0.45      | 0.45           | 0.45        |
| Number of magnetic valves | 1         | 15             | 150         |
| Number of turns ratio | 1000/10  | 1000/10        | 1000/10     |

3.2. Material property of iron core and iron loss formula

In this work, the Japan Nippon Steel 20HX1200 is chosen as the material of the iron core. Based on Bertotti’s iron loss model, the iron loss of MCR is calculated as:

\[ P_{Fe} = P_h + P_c + P_e \] (1)

where the hysteresis loss \( P_h = K_h fB^2 \), eddy current loss \( P_c = K_c (fB)^{1.5} \) and additional losses \( P_e = K_e (fB) \). Using the B-H curve of Nippon Steel Silica, and the embedded fitting method of ANSYS, We obtain \( K_h = 142.846 \text{ W/kg} \), \( K_c = 0.140427 \text{ W/m}^3 \), and \( K_e = 0.89844 \text{ W/m}^3 \).

4. Results and Discussion

4.1. External electrical characteristic of MCR

Figure 4 shows the external electrical characteristic of MCR with distributed magnetic valves. The output current of the MCR is shown in Figure 4(a). The left and right winding currents are shown in Figure 4(b). Figure 4(c) shows the current flowing through thyristors \( V_{T1} \) and \( V_{T2} \). It can be seen that when \( V_{T1} \) and \( V_{T2} \) are triggered alternatively, there are DC currents flowing through the left and right windings. The corresponding iron core becomes deeply saturated. The bias of two winding currents continually increases and the MCR enters steady state. Figure 4(d) shows the diode current which play the role of continuous flow to ensure the smooth operation of MCR. As can be seen in Figure 4, when \( t = 1000 \text{ms} \), MCR gets into steady state. The calculation formula of rising time is:

\[ t_r = \frac{1 - \delta}{2\delta} \cdot T = \frac{1 - 0.01}{2 \times 0.01} \times 20 = 990 \text{ms} \] (2)
The calculation result is consistent with the simulation.

Figure 4. Current waveforms of MCR with distributed magnetic valves.

4.2. Distribution of magnetic flux density
Figure 5 shows the magnetic flux density distribution of three types of MCR in the 59th cycle.

Comparing the three different magnetic valve structures, it can be found that at the same time, only one core limb of MCR is deeply saturated, which corresponds to the working principle of MCR. The flux leakage of MCR with distributed magnetic valve is less than the one with single-stage or the multi-stage magnetic valves.

Figure 6 is a graph of magnetic flux density distribution in several typical straight lines in MCR with distributed valves shown in Figure 5(c). Figure 6(a) represents magnetic flux density distribution of non-magnetic valve on a horizontal line, and Figure 6(b) represents magnetic flux density distribution of magnetic valve on a horizontal line. In the two diagrams, it can be seen that the magnetic flux density is mainly concentrated in four regions, the middle two area corresponds to two iron core limbs, and the sides of areas correspond to two side yokes. Figure 6 (a), the flux density at a silicon sheet is extremely strong, while the magnetic flux density at the epoxy plate position is zero. In the vertical direction (Figure 6(b)), the flux density of the magnetic valve that intersects the silicon steel is larger, and the flux density of the part which intersects the epoxy plate is small. Figure 6(c) gives the flux density on the vertical line of the magnet valve, and Figure 6(d) gives the flux density distribution of the vertical line on the non-magnetic valve. As shown in Figure 6(c) and Figure 6 (d),...
the flux density distribution is roughly symmetrical. There are 15 turning points in both Figure 6(c) and Figure 6(d), which correspond to the 15 distributed magnetic valves of the actual MCR.

![Flux Density Distribution](image)

**Figure 6.** Distribution of magnetic flux density on typical straight lines.

### 4.3. Comparison of Iron Loss and Operating Current

Figure 7(a) shows a comparison of the operating currents of three kinds of MCR. As can be seen from Figure 7(a), under the same conditions, either the MCR with multi-stage magnetic valves or the MCR with distributed magnetic valves has larger total current than the one with single-stage magnetic valves. This means that in the case of the same transmission voltage, to meet the same capacity requirements, the MCR with multi-stage magnetic valves or distributed magnetic valves requires less coil turns than the MCR with single-stage magnetic valve.

As shown in Figure 7(b), the iron loss of MCR with single-stage valve is 0.703 W/kg, the iron loss of MCR with multi-stage magnetic valves is 0.675 W/kg, and the iron loss of MCR with distributed magnetic valves is 0.668 W/kg. It is easily found that core loss of MCR with single-stage magnetic valve is the largest, while the core loss of MCR with the distributed magnetic valves is the smallest. This simulation results can be explained by the result given in the Figure 4, that is, dividing the single-stage magnetic valve into distributed magnetic valves can reduce the edge effect and decrease the inductance value in the working winding of MCR.

![Operating Currents and Iron losses](image)

**Figure 7.** Operating Currents and Iron losses
5. Conclusion
Based on the geometrical dimensions and parameters of an actual operating 10MVA/10kV MCR, this paper establishes the field coupling simulation model of three types of MCR by using finite element simulation software ANSYS. The working currents and the distribution of magnetic flux density of the iron core are simulated, and the iron core loss of three types of MCR are compared. From the simulation, the following results are obtained:

(1) Compared with the MCR with single-stage magnetic valves, the MCR with distributed magnetic valves can effectively reduce the magnetic leakage and decrease the eddy current loss, making the operation of equipment more energy-saving and stable.

(2) Under the same parameters, the MCR with distributed magnetic valves can obtain a larger operating current. In the case of rated capacity, the number of coil turns can be reduced, and the volume and production cost of the equipment could be decreased.

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