Optimization on Two-stage Magnetic Valve Structure for Magnetic Control Reactor

Xiangzheng Xu

Department of Electronics Engineering, East China Jiao-tong University, Nanchang, Jiangxi, China

Abstract — This paper analyzes the power loss of magnetic control reactor based on the basic theory of the electromagnetic field. With two-stage magnetic valve structure model for the object, physics simulation model of magnetic control reactor is established. Using Ansoft Maxwell V12 simulation software, through the analysis of two-stage magnetic valve type reactor core and coil power loss, the cross sections of two-stage magnetic valve are optimized. The optimization results show that the optimal cross-sectional area ratio is 3:2:1 for two-stage magnetic valve type reactor. Total loss is 10.9348 W, and is lower than that of a single stage magnetic valve type reactor.

Keywords— power system; compensation equipment; magnetic control reactor; magnetic valve optimization

I. INTRODUCTION

The principle of magnetic control reactor is the use of DC excitation. That is the reactor core is magnetized by using additional DC excitation. Through adjusting the magnetic saturation degree of magnetic control reactor core, core permeability will be changed, so as to adjust the size of the reactor current and reactive power smoothly. It has significant advantages such as wide voltage range, high reliability, less occupied area, easy to maintenance and so on. And it is static type reactive power compensation device, which has a useful application prospect [1]. To reduce the loss and harmonic content, usually adopts magnetic valve type reactor. Single stage magnetic valve reactor can reduce the harmonic content. But depending on the related literature, the saturated with alternating magnetic valve, there is the horizontal magnetic field component near magnetic valve area, the additional loss of the reactor core and winding will increase [2]. Therefore it is necessary in order to optimize the existing magnetic valve structure. Based on the basic theory of the electromagnetic field, this paper will establish the simulation model of magnetic control reactor. Using the simulation software Ansoft Maxwell, reasonable two-stage magnetic valve structure is optimized, effectively reduce the power consumption of the core and winding for magnetic control reactor (MCR).

II. MAGNETIZATION CURVE MODEL OF SINGLE STAGE MAGNETIC CONTROL REACTOR

As figure 1 shown, it is a single-stage magnetic valve controlled reactor (MCR) schematic wiring diagram. The reactor core is composed of two sections of different cross section of the iron core in series. \(A_s\) is the core of large cross section area. \(A_o\) is the core of a small section area. \(l\) is the length of a small section length. The magnetic route of magnetic valve controllable reactor includes two parts of the air gap and a small section iron core. Single stage magnetic saturation refers to the reactor the adjustment range of capacity, only a small section of the magnetic circuit operates in the saturation region, and large cross section is always in the unsaturated linear region [3]. When small section core of MCR is magnetic saturation state, its reluctance is small, relatively magnetic saturation state of small cross-section of the core section is small, so it can be ignored in the analysis.

If the area of space air gap is \(A_o\), and the magnetic induction intensity is \(B_o\), the magnetic induction intensity of small section is \(B_q\), and when the small section is in saturation state the edge effect is ignored, then there is a equations as below [4].

\[
\phi = B A_q = B_q A_q + B_o A_{ls} \tag{1}
\]

The equation (2) can be obtained through equation (1).

\[
B = \frac{A_q}{A_b} B_q + \frac{A_{ls}}{A_b} B_o \tag{2}
\]

Because of two sections magnetic field intensities are equivalent, so \(B_q\) is given by

\[
B_q = \mu_0 f(B_l) \tag{3}
\]

Fig1 The structure of single-stage MCR
XIANGZHENG XU: OPTIMIZATION ON TWO-STAGE MAGNETIC VALVE STRUCTURE FOR . . .

To give equation (3) into the equation (2), so B is given by

$$B = \frac{A_s}{A_b} f(B_s) + \frac{A_{st}}{A_b} B_s$$  \hspace{1cm} (4)

According to the supposition of small slope magnetization curve, when $B_t \leq B_{ts}$, the magnetic field intensity of the small section iron core is zero, then B is expressed as follows [5].

$$B = \frac{A_{st}}{A_b} B_s$$  \hspace{1cm} (5)

So, the magnetic field intensity of the equivalent iron core is zero in $0 \leq B \leq (A_{st}/A_b)B_{ts} = B_s$ range. When $B_t \geq B_s$, then the fore small section area iron core is saturated, so magnetic field intensity is expressed as follows.

$$H = \frac{B_t - B_s}{\mu_0}$$  \hspace{1cm} (6)

To give equation (4) into equation (6), the magnetization curve model of single-stage magnetic valve type controllable reactor is shown as equation (7). And its magnetization curve is presented in figure 2.

$$H = \begin{cases} \frac{B + B_s}{\mu_0} & B < -B_s = -\frac{A_{st}}{A_b} B_{ts} \\ 0 & |B| \leq B_s = \frac{A_{st}}{A_b} B_{ts} \\ \frac{B - B_s}{\mu_0} & B > B_s = \frac{A_{st}}{A_b} B_{ts} \end{cases}$$  \hspace{1cm} (7)

III. MAGNETIC CONTROL REACTOR POWER LOSS ANALYSES

The core loss and winding loss constitute two heat sources of magnetic control reactor. And the two losses are closely related to the magnetic valve structure of the reactor. So, it is very important to calculate the two loss values of the reactor accurately.

A. The Core Loss of the Magnetic Control Reactor

The core loss consists of three parts. That is the hysteresis loss, the eddy current loss and the residual loss [6]. In a periodic of the iron core magnetization, the each unit magnetic hysteresis loss is equal to the area surrounded by the magnetic hysteresis loop. The hysteresis loop of the soft magnetic material is narrow, and its hysteresis loss is relatively small [7]. The higher the frequency, the greater the flux density. So, the larger the area surrounded by the hysteresis loop, the greater the hysteresis loss. The eddy current loss is proportional to the flux change rate of the magnetic core. The longer the periphery of an iron core, the higher the frequency of the alternating magnetic field, and eddy current is bigger. The main method of reducing the eddy current loss is to increase the resistivity of the magnetic component [8]. The residual loss is due to the magnetization relaxation effect.

By the loss separation method, the magnetic core loss of the reactor P can be decomposed into the static hysteresis loss $P_h$, the dynamic eddy current loss $P_c$ and the residual loss $P_a$.

$$P = P_h + P_c + P_a$$

$$= K_B f B_m B_v + K_C (f B_m)^2 V_v + K_A (f B_m)^2 V_v$$

Where, $K_B$ is coefficient of hysteresis loss. $K_C$ is coefficient of eddy current loss. $K_A$ is coefficient of residual loss, they all depend on magnetic material. $f$ is core magnetization frequency. $V_v$ is core volume, and $B_m$ is the flux density in the iron core.

From the above analysis, in the alternative magnetic field, the core loss depends not only on the frequency and magnetic induction intensity of the alternating magnetic field, but also on the magnetic core itself. At low frequencies, the core loss is mainly hysteresis loss [9]. And at the high frequency, the eddy current loss and the remnant loss are significant.

B. The Coil Losses of the Magnetic Control Reactor

The losses of the windings are mainly divided into winding resistance loss and eddy current loss of windings. The eddy current loss is mainly determined by the size and the distribution of the leakage magnetic field [10]. Because the leakage magnetic field of reactor is closely related to the capacity of the reactor, the greater the capacity of the reactor, the greater the leakage magnetic field, and produced additional loss will grow. For the winding of the reactor, there will be a greater eddy current loss, so that the local temperature of the winding is raised, which can affect the insulation life of the winding [11].

The winding resistance loss of the magnetic control reactor can be expressed by the following formula.

$$P_r = \frac{I_2^2 \rho(\pi d N + h)}{S}$$  \hspace{1cm} (9)

Where, $\rho$ is resistivity of winding material. $d$ is the average diameter of windings, $N$ is winding turns, and $h$ is axial height for winding.
A lot of research and practice has proved that leakage magnetic flux of MCR is the main reason for the loss of the coil [12]. The transverse component of the leakage flux is perpendicular to the winding axis. The transverse component of magnetic flux leakage has caused bending and uneven distribution of magnetic force lines [13]. So, it is the main component of the eddy current loss in the coil. The greater the lateral component, the greater the loss.

For a volume of a tetrahedral element, the loss of the transverse vortex within the unit volume can be given as the following expression [14].

\[ P_{Eri} = \frac{1}{12\rho} (B_{ri}b\omega)^2 \pi R_i V_i \]  \hspace{1cm} (10)

Where, \( B_{ri} \) is the transverse magnetic induction intensity in the unit i. \( \omega \) is angle frequency. \( B \) is wire size. \( R_i \) is the distance between the center of gravity in the cell i and core center. \( V_i \) is the volume of the conductors within unit i.

The total windings loss of the magnetic control reactor can be expressed as follows [15].

\[ P = P_B + \sum_{i=1}^{N} P_{Eri} \]  \hspace{1cm} (11)

Among them, \( N \) is the total number of windings.

IV. OPTIMIZATION ANALYSIS FOR THE TWO-STAGE MAGNETIC VALVE

Literatures showed that the two-stage magnetic valve reactor can reduce the reactor harmonic content, but can produce certain power loss. Therefore, it is necessary to optimize the two-stage magnetic valve structure, search for an ideal cross-sectional area ratio of the two-stage magnetic valve. Taking the center of the reactor for reference to the original, according to the symmetry of the core structure, a layer of iron core lamination is as an object of reactor core magnetic field analysis. Set for core silicon steel core loss type, \( k_n = 201.758, k_c = 0.726, k_e = 0 \), \( \mu_n = 2000000 \text{s/m}, \) weight density \( \sigma = 7872 \text{kg/m}^3 \), model thickness \( \delta = 0.06 \text{m} \).

The magnetization curve of iron core material is presented in figure 3. The magnetization curve is in line with the ideal model of the magnetization curve, and it is like figure 2. It has been found that, with an ideal model of the magnetization curve for the analysis of magnetic control reactor, not only can get simple mathematical expressions, and can reflect the physical process of reactor. At the same time, set the coil relative permeability \( \mu_r = 0.99996 \), \( \mu_n = 5800000 \text{s/m} \), weight density \( \sigma = 8933 \text{kg/m}^3 \), air relative permeability \( \mu_a = 1 \).

Two-stage magnetic valve structure model is shown in figure 4, assuming that step height remains the same, horizontal length is a variable in large and small steps, that is long1, long2, long3 and long4. Set the step length of long1 and long2 is 2.5mm, set the step length of long3 and long4 is 2.5mm. The area ratio of the two-stage magnetic valve has a total of eight kinds of combinations, as showed in figure 5. When the coil has appropriate current value, the reactor is at limit saturated state, optimizing magnetic valve is carried out using Ansoft Maxwell software.

Core eddy current loss curve is shown in figure 6, and coil eddy current loss curve is as shown in figure 7. As can be seen from the figure 6 and figure 7, the core power loss of magnetic valve type reactor is usually the biggest when the current is largest gradient. Coil windings of the magnetic valve type reactor have larger power loss during the current increasing. Due to MCR of multistage magnetic valve structure is to restrain the edge effect. It greatly will reduce the loss of the core and coil, control the MCR internal local overheating, and improve the thermal stability of the insulating material.
To be sure, the optimal value almost equals the single-stage magnetic valve total loss. In fact, eddy current loss of the coil is actually improved, although the total loss is not to reduce greatly, but due to its own little harmonic content, it can replace single stage magnetic valve reactor and applied to engineering practice, such as reactive power compensation, motor soft starter and so on.

**TABLE I. SUMMARY TABLE OF CORE AND COIL LOSS FOR THE TWO-STAGE MAGNETIC VALVE**

<table>
<thead>
<tr>
<th>Area ratio</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>Core loss</th>
<th>Coil loss</th>
<th>Total loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:2:1</td>
<td>-10</td>
<td>10</td>
<td>5</td>
<td>-5</td>
<td>6.0393</td>
<td>4.8955</td>
<td>10.9348</td>
</tr>
<tr>
<td>6:4:3</td>
<td>-7.5</td>
<td>7.5</td>
<td>5</td>
<td>-5</td>
<td>10.7076</td>
<td>3.7338</td>
<td>14.4414</td>
</tr>
<tr>
<td>3:2:2</td>
<td>-5</td>
<td>5</td>
<td>5</td>
<td>-5</td>
<td>12.0477</td>
<td>1.9455</td>
<td>13.9932</td>
</tr>
<tr>
<td>6:4:5</td>
<td>-2.5</td>
<td>2.5</td>
<td>5</td>
<td>-5</td>
<td>12.6903</td>
<td>1.6526</td>
<td>14.3429</td>
</tr>
<tr>
<td>6:5:2</td>
<td>-10</td>
<td>10</td>
<td>2.5</td>
<td>-2.5</td>
<td>13.0544</td>
<td>1.5379</td>
<td>14.5932</td>
</tr>
<tr>
<td>6:5:3</td>
<td>-7.5</td>
<td>7.5</td>
<td>2.5</td>
<td>-2.5</td>
<td>13.9197</td>
<td>0.7582</td>
<td>14.6779</td>
</tr>
<tr>
<td>6:5:4</td>
<td>-2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>-2.5</td>
<td>13.0544</td>
<td>1.5379</td>
<td>14.5932</td>
</tr>
<tr>
<td>6:5:5</td>
<td>-2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>-2.5</td>
<td>13.9197</td>
<td>0.7582</td>
<td>14.6779</td>
</tr>
</tbody>
</table>

Notes: L1 represents long1 and the other is the same meaning.

**V. CONCLUSION**

Through analyzing the reactor power loss of two-stage magnetic valve type, it shows that the optimal cross-sectional area ratio is of 3:2:1 for two-stage magnetic valve type reactor. Total loss is 10.9348W, which is slightly lower than single stage total loss of 11.36W. Due to the two-stage magnetic control reactor can reduce the reactor ontology harmonic content, in terms of technology, price and maintenance than other compensation device has strong competitiveness, therefore, in recent years, the two-stage magnetic valve type reactor has been widely used to adjust the system voltage, reduce volatility and reactive power.

**ACKNOWLEDGMENT**

This work was supported by Jiangxi Province Department of Science and Technology, P.R.China under grant No. 20142BBG70028.

**REFERENCES**


XIANGZHENG XU: OPTIMIZATION ON TWO-STAGE MAGNETIC VALVE STRUCTURE FOR . . .


