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

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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 optimizet

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_b is the core of large cross section area. A_{bt} is the core of a small section area. l_t 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.

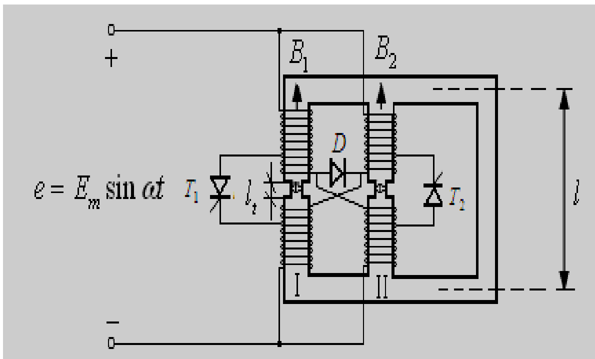

Fig1 The structure of single-stage MCR

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

$$\phi = BA_b = B_q A_q + B_t A_{bt} \tag{1}$$

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

$$B = \frac{A_q}{A_b} B_q + \frac{A_{bt}}{A_b} B_t \tag{2}$$

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

$$B_q = \mu_0 f(B_t) \tag{3}$$

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

$$B = \frac{A_q \mu_0}{A_b} f(B_t) + \frac{A_{bt}}{A_b} B_t \quad (4)$$

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

$$B = \frac{A_{bt}}{A_b} B_t \quad (5)$$

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

$$H = \frac{B_t - B_{ts}}{\mu_0} \quad (6)$$

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.

$$H = \begin{cases} \frac{B + B_s}{\mu_0} & B < -B_s = -\frac{A_{bt}}{A_b} B_{ts} \\ 0 & |B| \le B_s = \frac{A_{bt}}{A_b} B_{ts} \\ \frac{B - B_s}{\mu_0} & B > B_s = \frac{A_{bt}}{A_b} B_{ts} \end{cases} \quad (7)$$

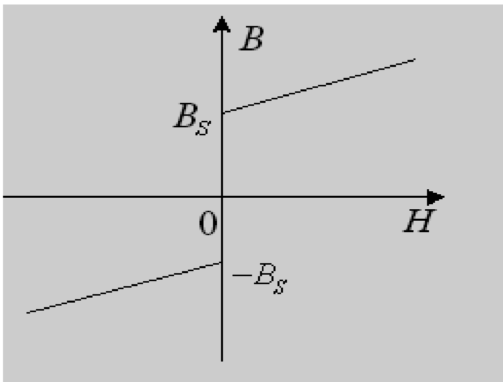

Fig.2 Ideal magnetization curve model

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_B, the dynamic eddy current loss P_C and the residual loss P_A.

$$\begin{aligned} P &= P_B + P_C + P_A \\ &= K_B f B_m{}^{\beta} V_e + K_C (f B_m)^2 V_e + K_A (f B_m)^{1.5} V_e \end{aligned} \quad (8)$$

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_e 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.

$$P_R = I_2 \frac{\rho(\pi d N + h)}{S} \quad (9)$$

Where, ρ 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].

$$P_{Eri} = \frac{1}{12\rho}(B_{ri}b\omega)^2 \pi R_i V_i \tag{10}$$

Where, B_{ri} is the transverse magnetic induction intensity in the unit i. ω 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].

$$P = P_R + \sum_{i=1}^{N} P_{Eri} \tag{11}$$

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, μ_n=2000000s/m, weight density σ =7872kg/m3, model thickness δ =0.06m. 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 μ_r=0.99996, μ_n =58000000s/m, weight density σ =8933kg/m3, air relative permeability μ_r = 1.

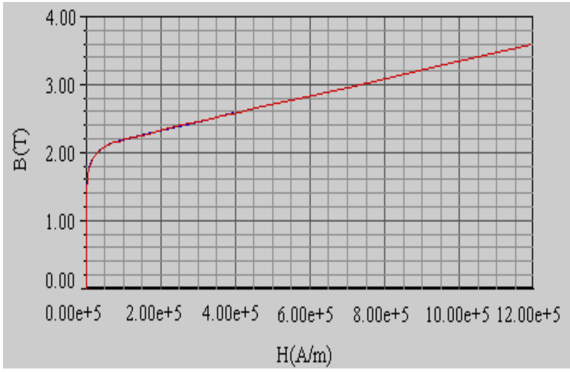

Fig 3 Magnetization curve of core silicon steel

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.

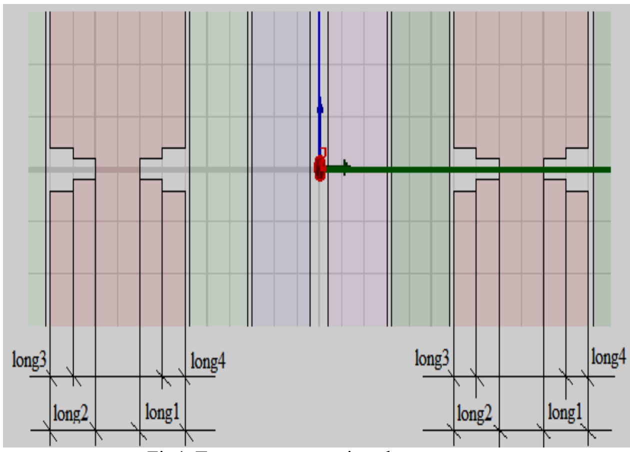

Fig4. Two-stage magnetic valve structure

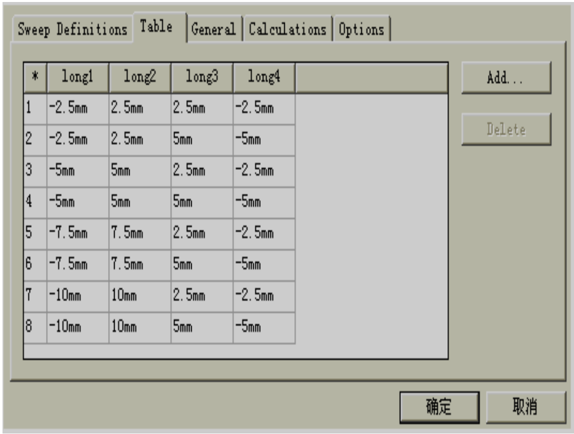

Fig.5 Two-stage magnetic valve size

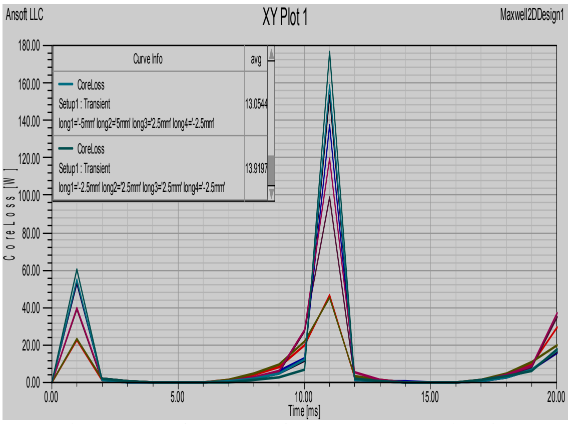

Figure.6. Core loss curve of a two-stage magnetic valve

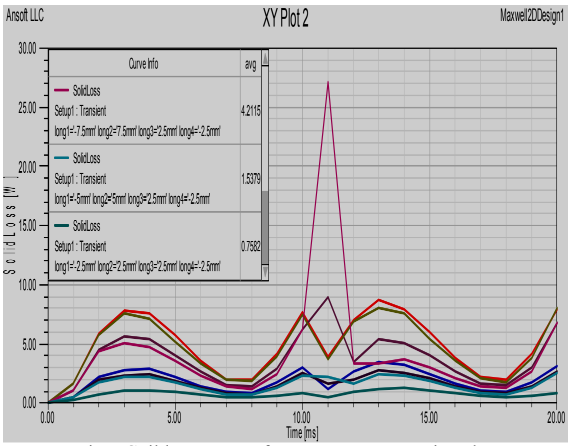

Fig.7 Coil loss curve of a two-stage magnetic valve

The results of the power loss optimization analysis are as showed in table Ⅰ. As can be seen from the table I, the optimum area ratio is 3:2:1, it has lower loss of 10.9348W. The sub prime area ratio is 6:5:2. Its loss is equal to 11.9241W. The worst area ratio is 6:5:3. Its loss is equal to 16.3549W. So, area ratio changes a little, its loss would be a big change.

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

Area ratio	L1	L2	L3	L4	Core loss	Coil loss	Tatol loss
3:2:1	-10	10	5	-5	6.0393	4.8955	10.9348
6:4:3	-7.5	7.5	5	-5	10.7076	3.7338	14.4414
3:2:2	-5	5	5	-5	12.0477	1.9455	13.9932
6:4:5	-2.5	2.5	5	-5	12.6903	1.6526	14.3429
6:5:2	-10	10	2.5	-2.5	7.2775	4.6466	11.9241
6:5:3	-7.5	7.5	2.5	-2.5	12.1434	4.2115	16.3549
6:5:4	-5	5	2.5	-2.5	13.0544	1.5379	14.5932
6:5:5	-2.5	2.5	2.5	-2.5	13.9197	0.7582	14.6779

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.

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