Magnetic Circuit Model of Magnetic Valve Controllable Reactor Considering Magnetic Flux Leakage Effect

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Abstract: The magnetic circuit model of the magnetic saturation characteristic magnetoresistance of the magnetically controlled shunt reactor (MCSR) nonlinear core is proposed by using the magnetic field division method, combining with the geometric parameters and working principle of the prototype. The magnetic circuit structure and working characteristics are analyzed. The calculation formula of the magnetic potential node of the magnetically controlled shunt reactor is derived by improving the node analysis method, and the simulation calculation and analysis of the working current of the magnetic control reactor under no-load and different DC bias are carried out. The conclusion shows that the accuracy of the magnetic circuit model can meet the needs of engineering, and the modeling method has the characteristics of clear principle, simple modeling, accurate model and engineering applicability, which can provide guidance for designers.

1.Introduction
As a large capacity reactive power compensation device, magnetic controlled shunt reactor (MCSR) has the advantages of low operation cost, simple control and continuous and smooth regulation of line reactance. Therefore, it is of great significance to conduct in-depth modeling and research. In reference \cite{ref1}, the mathematical model of magnetically controlled adjustable reactor considering magnetic flux leakage effect is established based on the equivalent magnetic circuit method, and the control characteristics of the reactor are obtained. In reference \cite{ref2}, the algorithm of MCSR instantaneous equivalent reactance is proposed, which decouples the complex nonlinear magnetic circuit and differential circuit equations to satisfy the dynamic simulation in power system. The above literature has guiding significance for the further modeling of MCSR. During the operation of MCSR, the magnetization characteristics, DC bias effect and magnetic flux leakage effect have an important impact on the accuracy of its modeling. Compared with the traditional finite element method, the magnetic circuit equation has few variables, simple solution and fast calculation speed\cite{ref5,ref7}.

2.Basic Structure and Working Principle of MCSR
Figure 1 is the single-phase structure of MCSR. The total turns of AC winding of the magnetic valve controllable reactor are \(N_A\). The main iron core of the magnetic valve controllable reactor is divided into two parts with the same size, length and symmetrical area. Each half of the iron core is made into a small iron core in the middle position, namely the magnetic valve. \(u_d\) and \(i_d\) in the figure represent
the control voltage and control current of MCSR respectively, \( u_A \) and \( i_A \) represent the working voltage and current of MCSR respectively.

![Schematic diagram of single phase MCR body structure](image)

Figure 1 Schematic diagram of single phase MCR body structure

For a single-phase MCSR\(^3\), its circuit model is shown in Figure 1. If the voltage drop of winding is ignored, the electromagnetic induction equation of MCSR winding is as follows:

\[
\begin{align*}
u_A &= N_A \frac{dB_A}{dt} = N_A \frac{d\phi_A}{dt} \quad (1) \\
u_D &= N_D \frac{dB_D}{dt} = N_D \frac{d\phi_D}{dt} \quad (2)
\end{align*}
\]

Where: \( N_A \) and \( N_D \) are the turns of working winding and control winding respectively; \( B_A \) and \( B_D \) are equivalent flux density of AC winding and control winding respectively. \( \phi_A \) and \( \phi_D \) is the equivalent flux of AC winding and control winding respectively.

When the DC control flux is zero, there is only AC flux in the core \( \phi_A \) flows along the core 1 and side yoke 1, the MCSR is in no-load working state, the magnetic valve is unsaturated, the inductance is the largest and the capacity is the smallest; When the DC control current is introduced into the DC control winding, the DC control flux is generated, the magnetic valve is in saturation state, the inductance value decreases gradually and the capacity increases. By changing the size of DC excitation, changing the magnetic saturation of the core, and then changing the equivalent permeability, so as to smoothly change the reactance value and the capacity of MCSR.

3. Magnetic Circuit Model of MCSR

When considering the calculation of the main magnetic circuit reluctance of the magnetic valve, the magnetic leakage of the winding part and the edge air gap should also be considered. The magnetic circuit model corresponding to a single core is shown in Figure 2. In the picture, \( \phi_m \) is the main core flux, and the corresponding magnetic resistance is \( R_m \); \( \phi_c \) is the edge leakage flux between the winding and the core, \( \phi_{co} \) is the leakage flux of the winding, and the corresponding leakage resistances are \( R_c \) and \( R_{co} \); \( F_m \) is the magnetomotive force of the main magnetic circuit.

![Magnetic circuit model of magnetic control reactor core](image)

Figure 2 Magnetic circuit model of magnetic control reactor core

The magnetic circuit model considering magnetic flux leakage effect is obtained, as shown in Figure 3.
In this structure, the flux leakage field of MCSR is divided, and the flux leakage of windings is equivalent to the flux leakage resistance, which is paralleled at both ends of the main magnetic circuit. When the leakage flux is neglected, the leakage resistances $R_c$ and $R_{co}$ are infinite. The advantage of this kind of magnetic circuit topology is that it can improve the accuracy of magnetic leakage resistance as needed, and then control the calculation accuracy of MCSR magnetic circuit model.

After that, the node analysis method is used to solve the problem. By changing the DC control current and AC working current, the flux and control characteristics of each branch of MCSR can be obtained.

4. Magnetoresistance Calculation

Under the existing shape and size conditions, the magnetoresistance can be calculated everywhere. Due to the different shapes of the magnetic poles, the uneven distribution of the magnetic flux under the magnetic poles and the existence of edge leakage flux, it is difficult to get accurate results in the calculation of the magnetoresistance. In this paper, the magnetic resistance of the fluxtube considering the edge flux and air gap flux leakage at the magnetic valve is calculated by dividing the magnetic field method, so as to accurately calculate the magnetic circuit model.

The circuit is similar to the magnetic circuit in mathematical form. The magnetic resistance of any section of magnetic circuit core is calculated as follows:

$$R_m = \frac{L}{\mu(B)S}$$

(3)

Where: $L$, $S$, and $\mu(B)$ are the length, cross-sectional area and permeability of the I-section core respectively.

When the geometry size and magnetization characteristics of the core are known, it can be used to study various characteristics of the reactor. This paper mainly discusses the influence of the topology structure on the accuracy of the magnetic circuit model. At the same time, considering that the small slope magnetization characteristic model is widely used in the research of MSCR characteristics, Therefore, this paper chooses the piecewise small slope magnetization model as the research object.

The magnetization characteristics of segmented small slope are as follows:

$$B = \begin{cases} \mu(H), & \frac{1}{4}H_s \leq H < \frac{1}{4}H_s \\ \mu\left[H - \frac{1}{4}H_s\right] + B_s, & H \geq \frac{1}{4}H_s \\ \mu\left[H - \frac{1}{4}H_s\right] - B_s, & H \leq -\frac{1}{4}H_s \end{cases}$$

(4)

According to the magnetization characteristic data of 30Q130, a ferromagnetic material commonly used in MCSR, the critical saturation magnetic field strength $H_s$ is 480A/m, and the critical saturation magnetic induction strength $B_s$ is 1.8T. The non-linear magnetization of ferromagnetic materials makes the permeability of the core $\mu(B)$ change with the saturation degree of the magnetic circuit. Due to the asymmetric superposition of AC and DC magnetic flux, the magnetic resistance of the core at each symmetrical position is different.
It can be seen from the previous paper that the shape of the air gap flux at the MCSR magnetic valve is a hollow cylinder, and the magnetic field in the air gap is divided into a typical hollow cylinder magnetoresistance by the magnetic field division method. The surface of the iron core is regarded as an equipotential surface, as shown in Figure 4.

![Figure 4 Typical hollow cylinder magnetoresistance](image)

The air gap magnetoresistance at the magnetic valve is:

\[
R_i = \frac{l_g}{\mu_0 (S_1 - S_0)}
\]  

(5)

Where: \(\mu_0\) is the air permeability; \(l_g\) is the air gap length of the magnetic valve.

### 5. Solution of Magnetic Circuit Model for MCSR

Figure 3 is a complete magnetic circuit model of MCSR. The corresponding magnetic circuit equation can be obtained by the improved nodal analysis method:

\[
AYA^TP = A\Phi
\]  

(6)

Where \(Y\) is the branch permeance matrix; \(A\) is the incidence matrix of magnetomotive force; \(P\) is the node magnetic alignment vector; \(\Phi\) is the vector of flux train corresponding to magnetic circuit excitation.

When calculating the magnetic circuit model, set the magnetic flux of core 1 column as \(\phi_1 = \phi_a + \phi_b\) and core 2 column as \(\phi_2 = \phi_a - \phi_b\), select 4 nodes as the reference point, and write the node equation of 4 nodes; The parameters of the incidence matrix and branch permeance matrix are as follows.

For the four kinds of topology magnetic circuit models, the branch permeance matrix \(Y\) has different values. The magnetic flux of each branch and the magnetic potential of each magnetic potential node can be obtained by solving the improved node equation (6). The working current of the reactor can be obtained by using Kirchhoff’s law of magnetomotive force and Ampere’s loop law and formula (7).

\[
i = \frac{\sum \Phi_m \cdot R_m}{N_i}
\]  

(7)

Where: \(\phi_m\) and \(R_m\) are the corresponding magnetic flux and resistance of the \(m\)-section core respectively; \(\sum \Phi_m \cdot R_m\) is the loop magnetomotive force.

### 6. Experiment and Verification Analysis

In order to further study the magnetic circuit model of the reactor, this paper adopts the laboratory single-phase controllable reactor prototype for test and analysis. Given the AC winding port flux depending on the grid voltage, the flux is controlled by \(\phi_D\) as the parameter, the full load current waveforms of reactors with different magnetic circuit topologies can be obtained. In order to facilitate comparison, calculate and draw the current waveform based on MATLAB simulation, as shown in the figure(5-9).
Figure 5 Comparison of MCR current measurement under DC bias $\phi_b = 0.00466$Wb

Figure 6 Comparison of MCR current measurement under DC bias $\phi_b = 0.003495$Wb

Figure 7 Comparison of MCR current measurement under DC bias $\phi_b = 0.00233$Wb

Figure 8 Comparison of MCR current measurement under DC bias $\phi_b = 0.001165$Wb
The simulation results show that the magnetic circuit topology model is consistent with the basic working principle of MCR. But whether magnetic flux leakage is considered or not has a great influence on the simulation results.

Because of the superiority of magnetic circuit extension modeling, the dynamic magnetic flux, dynamic magnetic resistance and dynamic magnetic field intensity of each branch can also be calculated by the node magnetic potential. The results show that the magnetic circuit model considering magnetic flux leakage effect has high accuracy for the current calculation results of reactor dynamic magnetic circuit model, and the method given in this paper can be used to calculate the current characteristics of magnetic controlled reactor.

7. Conclusion
To sum up, this paper establishes a magnetic circuit model to analyze the DC bias of MCSR products. The topology of the magnetic circuit is established according to the geometry of the core and winding. The circuit magnetic coupling model of MCSR has the following characteristics.

1. The topological structure of the magnetic circuit model corresponds to the core structure. The magnetic circuit diagram reflects the core structure and coupling characteristics of MCSR. The magnetoresistance RM can be calculated according to the B-H curve of the core silicon steel sheet, so the nonlinear characteristics of the core material can also be considered in the model.

2. The magnetic circuit model established in this paper can calculate the electromagnetic transient process of MCSR by combining the magnetic field distribution inside the core and the output characteristics of external current.

3. The magnetic circuit modeling method has the characteristics of simple modeling method, consistent with the basic principle, controllable accuracy and suitable for engineering design.

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Reference
[1] Lin Keman, Li Nian, Lin Mingyao, Wan Qiulan. Magnetic circuit modeling and characteristics of a novel magnetically controlled adjustable reactor considering magnetic flux leakage effect [J]. Acta electrotechnics Sinica, 2015,30 (02): 114-121.
[2] Zheng Weijie, Zhou Xiaoxin. Equivalent reactance transient model of magnetically controlled shunt reactor based on dynamic reluctance [J]. Chinese Journal of electrical engineering, 2011,31 (04): 1-6.
[3] Tian Ming Xing, Li Qing Fu, Wang Shu Hong. Equivalent physical model and mathematical model of magnetically saturated controllable reactor [J]. Acta electrotechnics Sinica, 2002 (04): 18-21 + 35.

[4] Deng Zhanfeng, Wang Xuan, Zhou Fei, Lei Xi, Yu Kunshan, Qiu Yufeng. Simulation modeling method of UHV magnetically controlled shunt reactor [J]. Chinese Journal of electrical engineering, 2008, 28 (36): 108-113.

[5] Zhang Huiying, Tian Mingxing, Jing Pei, Wang Dongdong. Loss calculation and analysis of magnetic valve controllable reactor [J]. Journal of measurement science and instrumentation, 2020, 11 (01): 54-62.

[6] Zheng Weijie, Zhou Xiaoxin. Dynamic adaptive inverse control algorithm for magnetically controlled shunt reactor [J]. Chinese Journal of electrical engineering, 2011, 31 (19): 1-7.

[7] YAO Y, CHEN B, TIAN C. Modeling and characteristics research on EHV magnetically controlled reactor [C]//2007 international Power Engineering Conference, December 3-6, 2007, Singapore: 425-430.

[8] KARYMOV R R, EBADIAN M. Comparison of magnetically controlled reactor (MCR) and thyristor controlled reactor (TCR) from harmonics point of view [J]. International Journal of Electrical Power & Energy Systems, 2007, 29(3): 191-19.