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Winding Loss Mechanism Analysis of Magnetic Valve Controlled Reactor

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Abstract

With the increase of the magnetic valve controlled reactor capacity, winding loss brings more and more harm. Based on the physical model and mathematical model of magnetic valve controlled reactor, this paper proposes a valid method for calculating the winding loss .The proposed method calculates winding current harmonic content under different saturation, and obtains the leakage magnetic field distribution of magnetic distributed-valve reactor by using ANSYS. According to the leakage magnetic field distribution, winding loss can be calculated, and the loss curve can be deduced, which is only related to the saturation degree. The error between the ANSYS simulation results and the proposed method results is very small.

***Keywords**: Winding loss, Loss curve, Harmonic analysis, ANSYS*

1. Introduction

Dynamic reactive power compensation technology has the vital significance in improving economic efficiency of the power grid and ensuring the quality of power supply. At present, dynamic reactive power compensation equipment mainly include Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC) (Pranesh Rao. et al, 2000). As one of the SVC, magnetic valve controlled reactor has broad application prospects (YAO Yao, 2008).

With the rapid development of power system in recent years, the magnetic valve controlled reactor has become a hotspot of academia and engineering. Most researches focus on mathematical model, dynamic response and harmonic characteristic and so on currently (Chen Xuxuan, 2011). However, with the increasing of the capacity and application, the loss of MCR can't be ignored. MCR's loss mainly includes core loss and winding loss, and winding eddy current loss Occupy a certain proportion of the total loss, which is can' t be ignore.

Ref. (Frelin W., 2009) discussed the transformer winding eddy current loss calculation method under nonlinear load. Refs. (Waseem A. Roshen, 2007) discussed the leakage magnetic field and the air gap reactor winding eddy current loss calculation method. Refs. (M. Albach et al, 2001) discussed the air-gap reactor or air gap of transformer winding eddy current loss calculation method. Ref. (WANG Ziqiang et al, 2010) qualitatively compared the losses of six kinds of typical controlled reactor core structure, but further research in winding eddy current loss wasn't discussed. There isn't a precise calculation method for the winding eddy current loss.

A calculation method for the winding eddy current loss of MCR is proposed in this paper. The method is based on equivalent physical model and mathematical model and proposed the calculation method of winding eddy current loss under different saturation. Besides, the method is verified by ANSYS and analysis the influence on winding eddy current loss by distributed magnetic valves.

2. The Working principle

2.1. The Structure of MCR

Figure 1 and Figure 2 are the structure and the working circuit of single phase MCR. The main core of MSR is split into two parts. Each part has a small cross-section segment. This is known as the origin of the name "magnetic valve". Two windings are wound on the each part core. Each winding has a tap connected with the thyristor VT1 and VT2, respectively. The rate of tap are both $\delta = N_2 / N$ ($N = N_1 + N_2$). The upper winding of the left core is connected with the lower winding of the right core. The upper winding of the right core is connected with the lower winding of the left core. They are connected to power grid parallel.

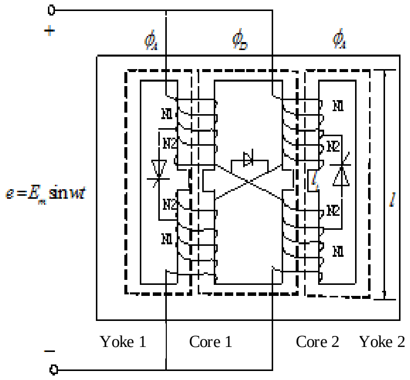

Figure 1. The Physical Model of MCR

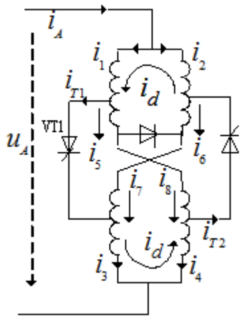

Figure 2. The Equivalent Circuit of MCR

When the voltage source e works in the positive half cycle and VT1 trigger is conducted, the voltage source e provides DC controlling voltage by self-coupling. In the same way, the voltage source e can provides DC controlling voltage when it works in the negative half cycle. By controlling the conduction angle, the DC excitation can be controlled. When the K1 and K2 is not conducted, the MCR and the ordinary are the same.

There are two AC magnetic flux loop. The core 1 and 2 are composed the DC magnetic flux loop. Within the working scope of MCR, only the valves are saturated and the other parts are not saturated.

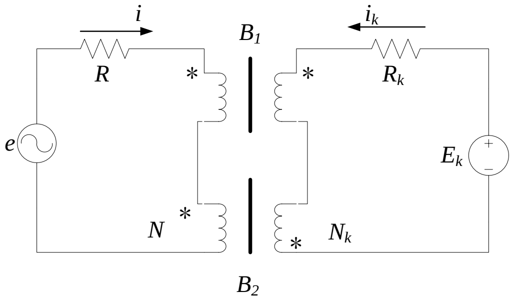

Figure 3. The Schematic Diagram of MCR

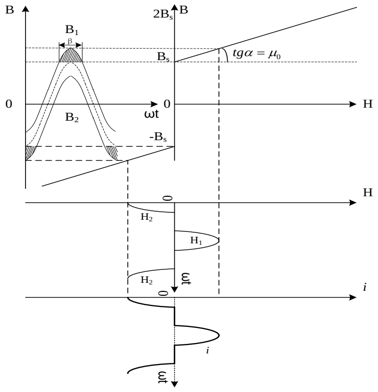

Figure 4. Relationship between Flux Density and Magnetic Intensity

3. Harmonic Principle

The schematic diagram of MCR is shown in the Figure 3. e is the voltage source. E_k is the DC controlling voltage.

According to the law of ampere loop, the magnetic circuit of MCR can be represented as:

$$\begin{cases} Ni + N_k i_k = l_1 \cdot f(B_1) \\ Ni - N_k i_k = l_1 \cdot f(B_2) \end{cases} \qquad (1)$$

Where l_1 is the length of saturated core, B1 and B2 are respectively magnetic strength of core 1 and core2, $f(B)$ is the magnetization properties of iron core, and it can be represented as:

$$H = \begin{cases} 0 & |B| \le B_s \\ \dfrac{B + B_s}{\mu_0} & B < -B_s \\ \dfrac{B - B_s}{\mu_0} & B > B_s \end{cases} \qquad (2)$$

AC current and DC current can be obtained by formula (1) and presented as:

$$\begin{cases} i = \dfrac{l}{2N}\left(f(B_1) + f(B_2)\right) \\ i_k = \dfrac{l}{2N_k}\left(f(B_1) - f(B_2)\right) \end{cases} \tag{3}$$

Made $N = N_k$, the winding current can be presented as:

$$i_W = i + i_k = \frac{l}{N} f(B_1) \text{或} i_W = i - i_k = \frac{l}{N} f(B_2) \tag{4}$$

Output current waveform under different saturation is shown in the Figure 4.

As can be seen from Figure 3, the harmonic amplitude varies with the amplitude of the output current. According to the symmetry working state of the core and the results of the Fourier transform, winding current can be obtained and presented as:

$$I_1^* = \frac{1}{2\pi}(\beta - \sin\beta)$$

$$I_{2n}^* = \frac{1}{2n\pi}\left(\frac{\sin(2n-1)\cdot\beta/2}{2n-1} - \frac{\sin((2n+1)\cdot\beta/2)}{2n+1}\right)$$

$$I_{2n+1}^* = \frac{1}{2\pi(2n+1)}\left(\frac{\sin(n\beta)}{n} - \frac{\sin((n+1)\beta)}{n+1}\right)$$

$$(n = 1, 2, 3, \cdots) \tag{5}$$

Where the current is expressed as per-unit value, and The fundamental wave current $l_1 B_S / N\mu_0$ (where $\beta = 2\pi$) is set as reference. N is the total number of turns on each core. The saturation degree is $\beta = 2\cos^{-1}((B_S - B_0)/B_S)$.

4. Winding Eddy Current Loss

Owing to the length of valves are short enough, the effect of valves on magnetic field can be ignored. The magnetic flux leakage of winding on the horizontal direction shows standard triangular distribution. The magnetic flux leakage of winding on the vertical direction is same. According to the law of full current, the leakage flux density distribution formula can be obtained, and expressed as formula (6).

$$B_{x(n)} = \mu_0 \frac{I_{m(n)} W}{\sqrt{2} h} \rho \frac{x}{c} \tag{6}$$

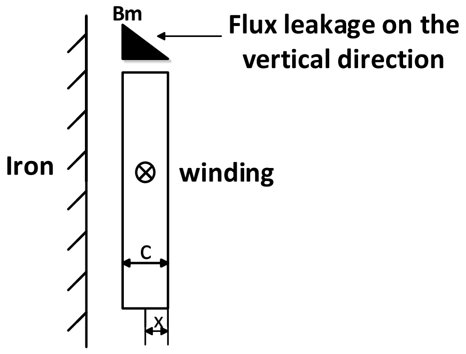

Figure 5. The Winding Leakage Magnetic Distribution

Where $B_{x(n)}$ the n-th leakage is flux density RMS at x, and $I_{m(n)}$ is the n-th harmonic current amplitude, and h is the winding height. ρ is the Rockwell coefficient, and c is the winding width as shown in the Figure 5, and W is the total number of turns and $W=N/2$.

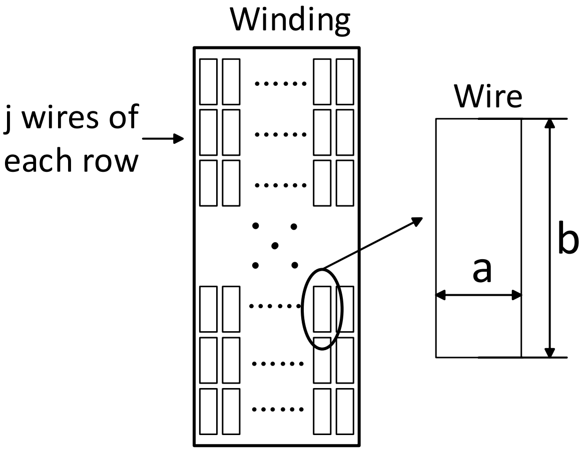

Figure 6. Winding Dimensions

The eddy current loss of j-th wires of each row (the total number of wires is n) is calculated as follows:

$$P_k=\frac{1}{24\gamma}\omega^2a^3blB_m^2\frac{\left[\left(k-1/2\right)^2+1/60\right]}{j^2},W \qquad (7)$$

Where γ is the resistivity of the wire, and a is the wire width, and b is the wire height, as shown is Figure 6.

Combined with formula (5), (6) and (7), the expression of winding eddy current loss is obtained as follow:

$$P_{k(1)}=\frac{1}{24\gamma}(2\pi f)^2a^3bl\left[\frac{B_sl_1\rho}{8\sqrt{2}\pi h}(\beta-sin\beta)\right]^2\frac{\left[\left(k-1/2\right)^2+1/60\right]}{j^2}$$

$$\begin{aligned}P_{k(2n)}&=\frac{1}{24\gamma}[2\pi(2n)f]^2a^3bl\frac{\left[\left(k-1/2\right)^2+1/60\right]}{j^2}\\&\times\left[\frac{B_sl_1\rho}{8\sqrt{2}\pi h(2n)}\left(\frac{sin(2n-1)\cdot\beta/2}{2n-1}-\frac{sin((2n+1)\cdot\beta/2)}{2n+1}\right)\right]^2\end{aligned}$$

$$\begin{aligned}P_{k(2n+1)}&=\frac{1}{24\gamma}[2\pi(2n+1)f]^2a^3bl\frac{\left[\left(k-1/2\right)^2+1/60\right]}{j^2}\\&\times\left[\frac{B_sl_1\rho}{8\sqrt{2}\pi h(2n+1)}\left(\frac{sin(n\beta)}{n}-\frac{sin((n+1)\beta)}{n+1}\right)\right]^2\\&n=1,2,3\cdots\end{aligned} \qquad (8)$$

When $\beta=0$, MCR is actually a no-load transformer. When under the different saturation, the eddy current loss of MCR can be divided into the fundamental component and ever harmonics component. Considering the seven harmonic and higher harmonic current is small enough, the loss of 7-Th and higher harmonic will be ignored.

The normalized curve of eddy-current loss can be obtainedwhen formula (8) divides by $(1/24\gamma)(2\pi f)^2 a^3 bl\left(B_s l_1 \rho/8\sqrt{2}\pi h\right) * \left\{\left[(k-1/2)^2+1/60\right]/j^2\right\} \left\{\left[(k-1/2)^2+1/60\right]/j^2\right\}$ as shown in Figure 7. As seen in Figure 8, before half saturated, winding eddy current loss is given priority to with harmonic loss, while winding eddy current loss is given priority to with fundamental wave loss more than half saturated.

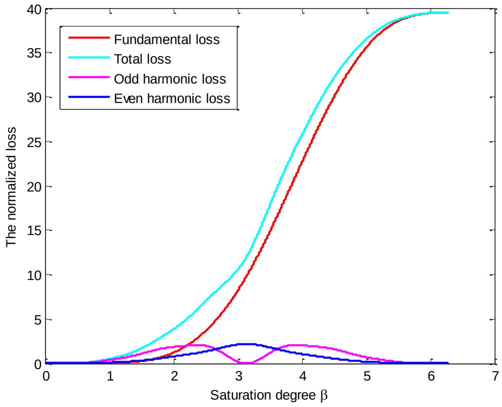

Figure 7. The Normalized Curve of Eddy-Current Loss

5. Simulation Results

The finite element software ANSYS can accurately solve complex electromagnetic problems through field-circuit coupled method. Figure 8 is the field-circuit coupling unit CIRCU124 in ANSYS. In order to reduce the amount of calculation, the two-dimensional model is used in this paper. The MCR finite element model is shown in the Figure 9. The rated voltage is 220v, rated current is 220 A.

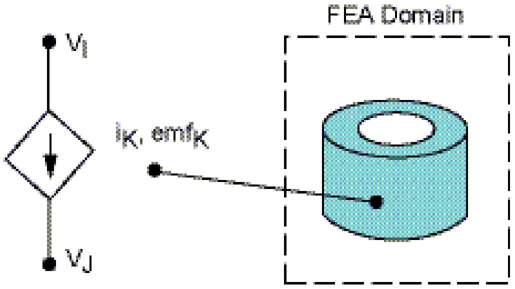

Figure 8. The Field-Circuit Coupling Unit

Part of the required parameters is shown in Tab.1. The winding eddy current loss is analysis, when the saturation degree is $\beta=0.968\pi$. The Figure 10 is the steady state current waveform of winding, and its peak is. The Figure 11 is the magnetic induction intensity waveform of winding. As seen from the figures, the waveform of magnetic flux leakage is consistent with the current waveform.

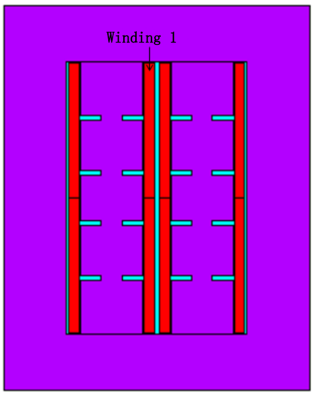

Figure 9. The Distributed Magnetic Valve Reactor

The theoretical maximum calculation of the leakage magnetic field is 0.28 T. The simulation result is 0.287 T, in conformity with the theoretical calculation values.

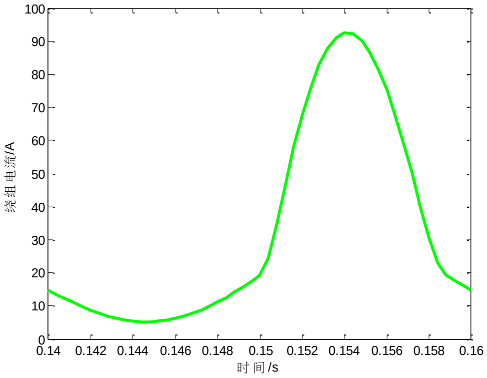

Figure 10. The Winding Current

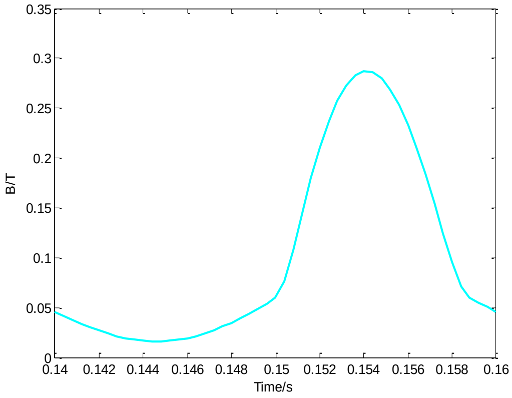

Figure 11. The Magnetic Field Intensity in Winding Inside Point

The flux leakage at the top of winding 1 is shown in the figure 11, which is typically triangle distribution. As seen in figure 11, the flux leakage of winding on the horizontal direction is very small, and the magnetic flux leakage of winding on the vertical direction is almost equal to the total magnetic flux leakage. So the flux leakage of winding on the horizontal direction can be ignored when calculating the winding eddy current loss.

Table 1. Simulation Parameter

Parameters	
Thickness a/m	0. 00125
Width b/m	0. 0033
Length l/m	$2\pi(0.00125k+0.000785)$
Resistivity $\gamma/\Omega\cdot m^{-1}$	1.75×10^{-8}
Height h/m	0. 13228
Roche coefficient ρ	0. 96
Saturated flux density B_s/T	1. 63
Total length of valves l_1/m	0. 1
Total wire number of each row j	8
The number of turns W	320

The Fourier transform result of winding flux leakage combines with the formula (7), and then fundamental and other harmonic eddy current loss can be obtained as shown in the table 2. As seen in the Tab. 2, the even harmonic eddy current loss takes a certain proportion. Even harmonics don’t appear in the output current, and easily to be ignored.

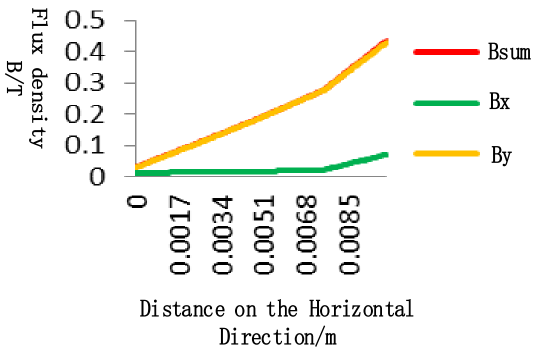

Figure 11. The Axial Leakage of Winding

ANSYS takes the function of calculating eddy current loss. The eddy current loss calculation result is 0.4502W, and the theoretical calculation result is 0.4458W. The error is 3.27%. Error is in the acceptable range.

According to the loss calculation and normalized loss curve, harmonic eddy current loss takes a large proportion before half saturated, especially even harmonics. However, the output current even harmonics current doesn’t exist in the output current. With the increasing of the capacity of MCR, even harmonics will have a significant impact on the performance of MCR.

Table 2. MCR Winding Loss

	Flux density amplitude B/T	Eddy current loss/W
DC	0.216	0
Fundamental	0.143	0.229
2-nd harmonic	0.063	0.1627
3-rd harmonic	0.041	0.0354
4-th harmonic	0.0032	0.00091
5-th harmonic	0.004	0.0142
6-th harmonic	0.0036	0.00012
7-th harmonic	0.00063	0.00037
Asum	——	0.4458
ANSYS caculation	——	0.4502

6. Conclusion

Wingding eddy current loss is closely related to the winding current. According to the deduced formulas and the normalized loss curve, the eddy current loss takes a large proportion in the total loss when the saturation degree is still small. With the increase of saturation, the fundamental eddy current loss take more and more proportion. The even harmonics don't exist in the output current, but they exist in the winding current. ANSYS simulation and numerical calculation show that even order harmonic eddy current loss takes a considerable proportion.

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