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An investigation on Harmonic Features of MSCR using MATLAB/Simulink

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Abstract

The saturation characteristic of the core varies with operation of magnetically saturation controlled reactor's (MSCR). Consequently its harmonic characteristic is needed to take in consideration. The arithmetic representation of MSCR is derived in accordance with the structural characteristic and operational rules. The characteristic analysis investigates the function of voltage as well as current over all magnetic field parameters of harmonics. After that, it concludes that the working current of MSCR's is an odd harmonic function, including primary and odd harmonic components; controlling current and voltage are even harmonic functions, restraining DC and even harmonic components; Again magnetic point of view, the magnetic components are also surrounding the DC and its own fundamental part too. Finally, a simulation model for MSCR is fabricated with MATLAB/Simulink. This paper demonstrates that the analysis is very precise. So, this paper can be a reference to provide further instruction for analysis and proposition of new harmonic suppression methods of MSCR.

Keywords: *controlled reactor; magnetically saturation; harmonic characteristic; simulation; MATLAB*

1. Introduction

The controlled reactor plays an important role in guaranteeing the grid's safety, reliability and efficiency, especially to the EHV long distance transmission. There are many kinds of controlled reactors; literature [1] made a general and split-new summary. The research about MSCR has been paid high attention and many achievements have been gotten, also the MSCR has been put into application [2-3]. But the biggest disadvantage of MSCR is that greater harmonic current will be brought to the grid if no measures are taken, especially to the single-phase operated MSCR in the electrified traction railway power supply system [4]. So, the harmonic characteristic of MSCR should be taken in consideration. The existing literatures are aimed to study the law of operation current distortion with the working condition and the way to suppress current harmonic [5-6], but the analysis of harmonic content of controlling current, magnetic field density and flux is little and not very systemic, so, it is difficult to understand some relevant conclusions, make further analysis and propose the new harmonic suppression methods. In this paper, the mathematical model of MSCR is derived according to the structural characteristic and working principle. And the harmonic constituents of physical quantities such as current, voltage and magnetic field parameters are analyzed by function characteristic analysis. Later, in this paper, analysis and conclusions are verified and tested by the simulation.

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2. Basic Structure and Working Principle

As Figure 1 shows in single form, MSCR is composed by two cores with the same structure and two side yoke (not illustrated for the disregarding of the yoke reluctance) [6]. There two windings with same total number of $N_A = N_1 + N_2$ turns are wounded on each of the core as the upper and lower winding, and each winding has a tap connected with thyristors T_1 and T_2 . The tap ratio $\delta = N_2/N_A$, the upper and lower winding wounded in different magnetic core are cross-connected and paralleled to the grid, the freewheeling diode D is connected across the intersection of two windings. The DC control currents i_d can be regulated by switching the trigger angle α (the zero-crossing time of α is the positive zero-crossing time of u_1, its range is $0 \sim \pi$, α is zero when at full load and π when at light load). Then, the capacity of reactor can be continuously adjusted by regulating α [6].

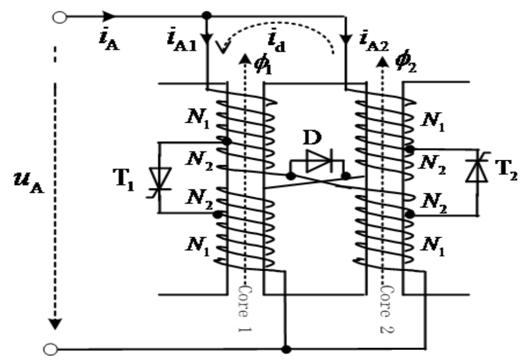

Figure 1. Schematic of MSCR

As Figure 1 shows, the equivalent magnetic circuit length of two iron cores are all l , the equivalent cross-sectional area is A . R_A is the resistance of winding whose turns is N_A , similarly, $(1-\delta)R_A$ is relative to N_1 , δR_A is relative to N_2 . The working voltage is u_A , working current is i_A , and i_d is the DC controlling current. The first core's flux, magnetic potential, magnetic flux density and magnetic field strength are respectively ϕ_1、 F_1、 B_1、 H_1. Relatively, the parameters of second core are respectively ϕ_2 、 F_2 、 B_2、 H_2.

3. Mathematical Model of MSCR

Define

$$\begin{cases} u_1 = u_A \\ u_2 = \dfrac{m\delta}{1-\delta} u_A \end{cases} \quad (1)$$

$$\begin{cases} i_1 = i_A - 2m\delta i_d \\ i_2 = 2(1 - m^2\delta) i_d \end{cases} \quad (2)$$

Where

$$m = \begin{cases} 0, & 0 \le \omega t < \alpha \\ 1, & \alpha \le \omega t < \pi \\ 0, & \pi \le \omega t < \pi + \alpha \\ -1, & \pi + \alpha \le \omega t < 2\pi \end{cases} \quad (3)$$

Then, we have

$$u_1 = R_A i_1 + N_A \left(\frac{d\phi_1}{dt} + \frac{d\phi_2}{dt}\right) \quad (4)$$

$$u_2 = \left(\frac{1 + m^2\delta}{1 - m^2\delta}\right) R_A i_2 + N_A \left(\frac{d\phi_1}{dt} - \frac{d\phi_2}{dt}\right) \quad (5)$$

$$F_1 = N_A i_1 + N_A i_2 \quad (6)$$

$$F_2 = N_A i_1 - N_A i_2 \quad (7)$$

Also, the magnetic properties of saturated core can be written as follows:

$$B = f(H) = \begin{cases} B_s, & H = 0 \\ \mu_0 H + B_s, & H > 0 \end{cases} \quad (8)$$

Where B_s represents the saturated magnetic flux density, the constant μ_0 is the magnetic permeability in air. The magnetic property of saturated iron core is symmetrical about the origin.

So, the mathematical model of MSCR can be described by formulas (4) ~ (8) [7].

4. Voltage Harmonic Characteristics

Author names and affiliations are to be centered beneath the title and printed in Times New Roman 12-point, non-boldface type. Multiple authors may be shown in a two or three-column format, with their affiliations below their respective names. Affiliations are centered below each author name, italicized, not bold. Include e-mail addresses if possible. Follow the author information by two blank lines before main text.

When formula (17) is put into (6) and (7).We can get

$$F_1(\omega t + \pi) = -F_2(\omega t) \quad (18)$$

So, we have (the magnetic field strength is equal to the effective length divided by magnetic potential)

$$H_1(\omega t + \pi) = -H_2(\omega t) \quad (19)$$

Namely, F_1 and F_2 are symmetrical in positive and negative half cycle on the horizontal axis, as well as H_1, H_2.

The magnetic property of saturated iron core is symmetrical about the origin, so we can know from (8) that *B*-*H* characteristic in which *B* as a function of *H* is an odd function which can be written as follows:

$$f(-H) = -f(H) \quad (20)$$

When put (19) into (20), we have

$$B_1(\omega t + \pi) = -B_2(\omega t) \tag{21}$$

Then, we can get (magnetic flux is equal to the flux density multiplied by effective cross-sectional area)

$$\varphi_1(\omega t + \pi) = -\varphi_2(\omega t) \tag{22}$$

Namely, B_1 and B_2 are symmetrical in positive and negative half cycle on the horizontal axis, as well as ϕ_1, ϕ_2.

Define the working voltage $u_A = U_{Am}\sin\omega t$, m is an odd harmonic function, we can know that u_2 is an even harmonic function from the second expression of formula (1), and it can be written as

$$\begin{cases} u_1 = U_{Am}\sin\omega t \\ u_2 = U_{20} + \sum_{k=2n}^{+\infty} U_{2mk}\sin(k\omega t + \varphi_k) \end{cases} \tag{23}$$

Only the fundamental contained in u_1, DC and even harmonic components contained in u_2.

5. Magnetic Field Harmonic Characteristics

Knowing from (10) and (22), the core flux ϕ_1 and ϕ_2 are mirror symmetrical in positive and negative half cycle, as well as i_{A1} and i_{A2}. By using the similar formula derivation of (13) and (14), we can get

$$\phi_1 - \phi_2 = 2\phi_0 + 2\sum_{k=2n}^{\infty} \phi_{mk}\sin(k\omega t + \varphi_k) \tag{24}$$

$$\phi_1 + \phi_2 = 2\sum_{k=2n-1}^{\infty} \phi_{mk}\sin(k\omega t + \varphi_k) \tag{25}$$

For u_1 just contains fundamental, i_1 contains only odd harmonic, so we can know from (4) that the odd EMF induced by $(\phi_1 + \phi_2)$ can be balanced by the resistance $R_A i_A$. However, $R_A i_A$ can be neglected when compared with $N_A(\frac{d\phi_1}{dt} + \frac{d\phi_2}{dt})$ in formula (4), so $(\phi_1 + \phi_2)$ contains only fundamental, both u_2 and i_2 contain only DC and even harmonic components. From (5), EMF generated by $(\phi_1 - \phi_2)$ contains a little amount of even harmonic which can be neglected. Then, only DC component will be contained.

So, we have

$$\begin{cases} \phi_1 = \phi_0 - \phi_{1m}\cos\omega t \\ \phi_2 = -\phi_0 - \phi_{1m}\cos\omega t \end{cases} \tag{26}$$

Where $\phi_{1m} = \frac{U_{Am}}{2\omega N_A}$ and ϕ_0 is the DC flux component.

According to the relationship of flux linkage, flux density and magnetic flux, the flux linkage and flux density can be written as follows:

$$\begin{cases} \psi_1 = \psi_0 - \psi_{1m} \cos \omega t \\ \psi_2 = -\psi_0 - \psi_{1m} \cos \omega t \end{cases} \tag{27}$$

Where $\psi_{1m} = \frac{U_{Am}}{\omega}$, and ψ_0 is the DC flux component.

Also, we can get

$$\begin{cases} B_1 = B_0 - B_{1m} \cos \omega t \\ B_2 = -B_0 - B_{1m} \cos \omega t \end{cases} \tag{28}$$

Where $B_{1m} = \frac{U_{Am}}{2\omega N_A S}$, and B_0 is the DC flux component.

It can be concluded from (26) ~ (28) that iron magnetic field parameters contain only DC and fundamental components.

6. Simulation using MATLAB/Simulink

A simulation model in MATLAB/Simulink for TCR is shown in Figure 2. The model is based on the mathematical model [8].

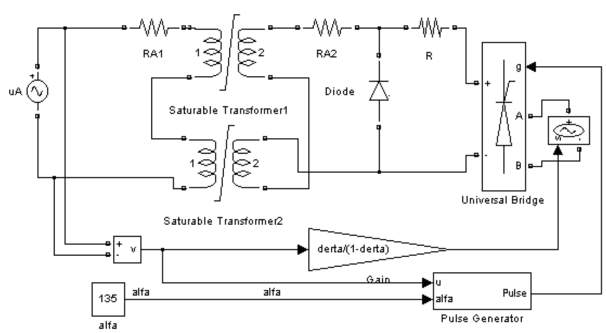

Figure 2. Simulation Model of MSCR

The related parameters are given as follows:

The rated capacity $S_{AN} = 60.044\text{MVA}$, the rated voltage $U_{AN} = 500/\sqrt{3}\ \text{kV}$, the frequency $f_N = 50$ HZ, the winding resistance, $R_A = 40\Omega$, and the tap ratio $\delta = 0.0474$.

As Figure 3 shows, the simulation waveforms are gotten when the trigger angle is 135 degrees. Clearly, Figure 3 shows that the working current just contains fundamental and odd current harmonic components; Figure 4 shows that the controlling current only contains fundamental and even current harmonic components; Figure 5 shows that the controlling voltage just contains DC and even current harmonic components; Figure 6 and Figure 7 shows that the iron flux contains only DC and fundamental components, and DC component of iron core 1 and core 2 are equal in magnitude but opposite in sign. So results of simulation are consistent with the theoretical derivation above. But what should be noted is that these simulation results are gotten under the condition that the trigger angle is 135 degrees, but it is sure that the harmonic constituents are remain unchanged when the trigger angle changed.

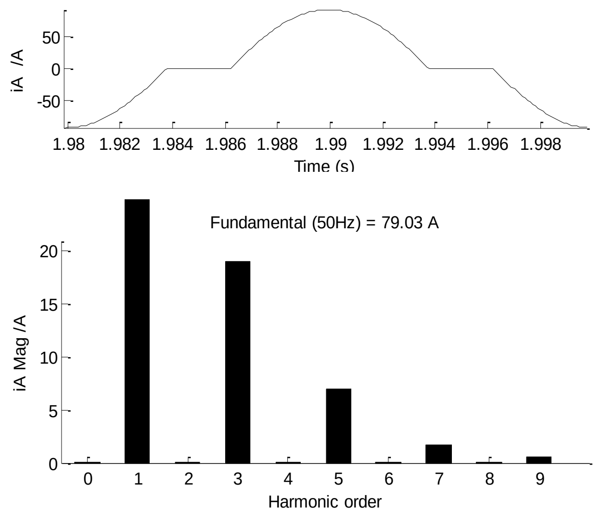

Figure 3. Steady Waveform and Amplitude-frequency Diagram of Working Current

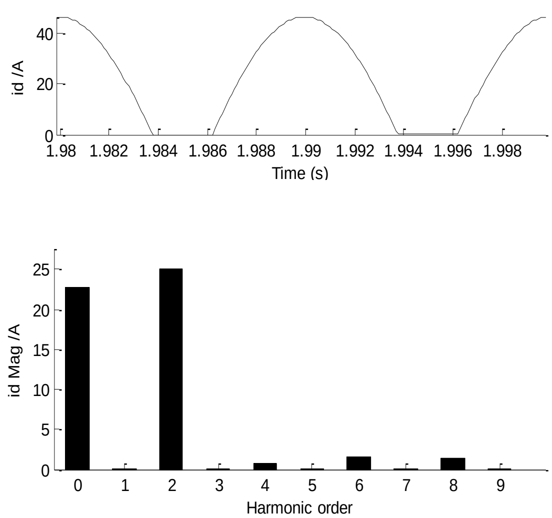

Figure 4. Steady Waveform and Amplitude-frequency Diagram of Controlling Current i_d

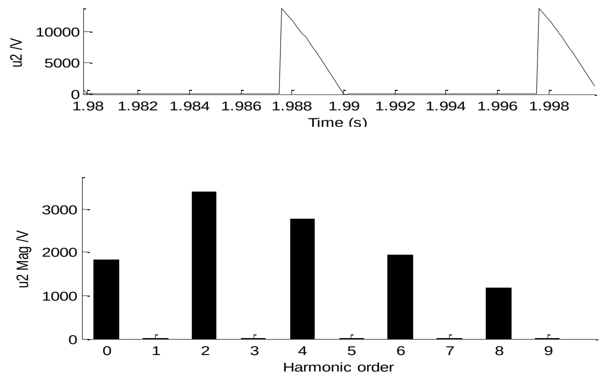

Figure 5. Steady Waveform and Amplitude-frequency Diagram of Controlling Voltage u_2

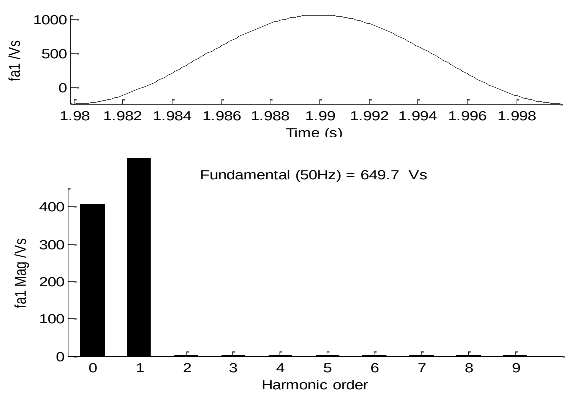

Figure 6. Steady Waveform and Amplitude-frequency Diagram of Iron Core1 Flux ψ_1

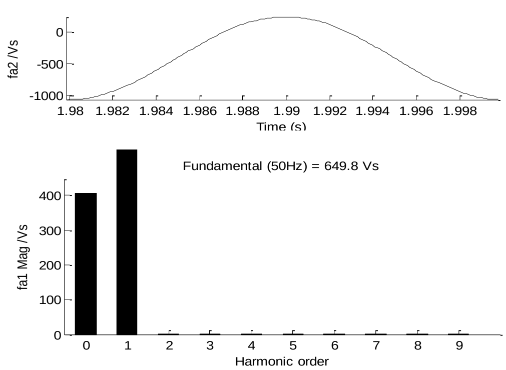

Figure 7. Steady Waveform and amplitude-frequency Diagram of Iron Core2 Flux ψ_2

7. Conclusion

This paper systematically analyzed harmonic constitution of MSCR's working current, controlling current and magnetic field parameters, then it concludes that the working current is an odd harmonic function, containing fundamental and odd harmonic; controlling current and voltage are even harmonic function, containing DC and even harmonic components; core flux, magnetic field intensity, magnetic field density are just containing DC and fundamental components. And the analysis and conclusions are verified to be correct by the simulation based on MATLAB.

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