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Harmonic Characteristic Analysis of Magnetically Saturation Controlled Reactor

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Abstract

As the operation of the magnetically saturation controlled reactor (MSCR) is based on the saturation characteristic of the core, so the harmonic characteristic of the reactor should be valued. According to the structural characteristic and working principle, the mathematical model of the reactor was derived. And the harmonic component of parameters such as current, voltage and magnetic field were systematically analyzed by the function characteristic analysis algorithm. Then, it concluded that the reactor's working current was an odd harmonic function, containing fundamental wave and odd harmonic components; controlled current and voltage were even harmonic functions, containing DC and even harmonic components; the core flux linkage, flux, magnetic field intensity and magnetic field density were just containing DC and fundamental components. The results of simulation with MATLAB confirmed the validity of analytical methods and conclusions. So the paper provided a reference to the proposition of new harmonic suppression methods and further analysis of the magnetically saturation controlled reactor.

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] and [2] have made a general and bran-new summary. The research on MSCR has been paid close attention and many achievements have been gotten, also the MSCR has been put into application [3-4]. However, 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 [5]. So, the harmonic characteristic of MSCR should be taken seriously, the existing literatures are aimed at studying the law of operating current distortion with the working condition and the way to suppress the current harmonic [6-7], but the research on harmonic component of controlled current, magnetic field density and flux is little and not very systemic, so it is difficult to understand some relevant conclusions, to 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. The harmonic constituents of physical parameters such as current, voltage and magnetic field are analyzed by function characteristic analysis algorithm. Later, the analysis and conclusions are verified and tested by the simulation.

2. Research Method

2.1. 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 ignoration of the yoke reluctance) [7]. The two windings with same total number of $N_\mathrm{A} = N_1 + N_2$ turns are wounded on each of the core as the upper and lower winding, and each winding has a tap connected with the thyristors T_1 and T_2. The tap ratio $\delta = N_2 / N_\mathrm{A}$, the upper and lower winding wounded in different magnetic core

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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 smoothly adjusted by regulating α [7].

As Figure 1 shows, the equivalent magnetic circuit length of two iron cores are equal to l, the equivalent cross-sectional area is A. R_{A} is the resistance of winding whose turns is N_{A}, similarly, $(1\text{-}\delta)R_{\mathrm{A}}$ 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 controlled current. The flux, magnetic potential, magnetic flux density and magnetic field strength of the first core are respectively ϕ_1、F_1、B_1、H_1. Relatively, the parameters of the second core are respectively ϕ_2、F_2、B_2、H_2.

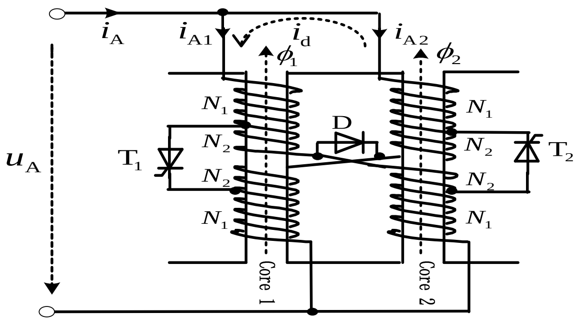


Figure 1. Structural Schematic of MSCR

2.2. Mathematical Model of MSCR

Define:

$$\begin{cases} u_1 = u_{\mathrm{A}} \\ u_2 = \dfrac{m\delta}{1-\delta} u_{\mathrm{A}} \end{cases} \tag{1}$$

$$\begin{cases} i_1 = i_{\mathrm{A}} - 2m\delta i_{\mathrm{d}} \\ i_2 = 2(1-m^2\delta) i_{\mathrm{d}} \end{cases} \tag{2}$$

Where:

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

Then, we have:

$$u_1 = R_{\mathrm{A}} i_1 + N_{\mathrm{A}} \left(\frac{d\phi_1}{dt} + \frac{d\phi_2}{dt}\right) \tag{4}$$

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

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

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

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

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

Where B_s represents the saturated magnetic flux density, the constant μ_0 is the magnetic permeability in the 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) [8].

3. Results and Simulation

3.1. Current Harmonic Characteristics

As Figure 1 shows, the two iron cores and windings of the reactor are completely symmetrical, and their working condition are mirror symmetrical in the positive and negative half cycle. So, when assume:

$$i_{A1} = i_{A1}(\omega t) \quad (9)$$

Then,

$$i_{A2} = -i_{A1}(\omega t - \pi) \quad (10)$$

When the Fourier series decomposition is done to these two formulas (9) and (10), we can get:

$$i_{A1} = I_0 + \sum_{k=2n}^{\infty} I_{mk}\sin(k\omega t + \varphi_k) + \sum_{k=2n-1}^{\infty} I_{mk}\sin(k\omega t + \varphi_k) \quad (11)$$

$$i_{A2} = -I_0 - \sum_{k=2n}^{\infty} I_{mk}\sin(k\omega t + \varphi_k) + \sum_{k=2n-1}^{\infty} I_{mk}\sin(k\omega t + \varphi_k) \quad (12)$$

Where n is the positive integer, I_0 is the DC component, I_{mk} and φ_k are separately represent amplitude and initial phase of the k th-degree harmonics. From (11) and (12), we can get:

$$i_d = \frac{i_{A1} - i_{A2}}{2} = I_0 + \sum_{k=2n}^{\infty} I_{mk}\sin(k\omega t + \varphi_k) \quad (13)$$

$$i_A = i_{A1} + i_{A2} = 2\sum_{k=2n-1}^{\infty} I_{mk}\sin(k\omega t + \varphi_k) \quad (14)$$

From (13) and (14), we knows that the controlled current i_d is an even harmonic function, containing only DC and even harmonic components; working current i_A is an odd harmonic function, containing only fundamental wave and odd harmonic components.

Then, we can get:

$$\begin{cases} i_{\mathrm{d}}(\omega t+\pi)=i_{\mathrm{d}}(\omega t) \\ i_{\mathrm{A}}(\omega t+\pi)=-i_{\mathrm{A}}(\omega t) \end{cases} \tag{15}$$

From formula (3):

$$m(\omega t+\pi)=-m(\omega t) \tag{16}$$

Namely, *m* is an odd harmonic function.

When formulas (15) and (16) are put into (2), we can get:

$$\begin{cases} i_1(\omega t+\pi)=-i_1(\omega t) \\ i_2(\omega t+\pi)=i_2(\omega t) \end{cases} \tag{17}$$

So, i_1 is odd harmonic function, i_2 is an even harmonic function. Then, only odd harmonic is contained in i_1; only DC and even harmonic components are contained in i_2.

Actually, the tap ratio δ is always ranged from 0.015 to 0.05, which is far from 1.0 [8], so the working current i_1 in equivalent circuit can be equaled to reactor's operating current i_{A}, and controlled current i_2 is twice the actual controlled current, so the harmonic components of i_1 is same to i_{A} ,and i_2 is same to i_{d} too.

3.2. Voltage Harmonic Characteristics

When formula (17) is put into (6) and (7), we can get:

$$F_1(\omega t+\pi)=-F_2(\omega t) \tag{18}$$

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

$$H_1(\omega t+\pi)=-H_2(\omega t) \tag{19}$$

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

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

$$f(-H)=-f(H) \tag{20}$$

When put formula (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)

$$\phi_1(\omega t+\pi)=-\phi_2(\omega t) \tag{22}$$

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 $u_{\mathrm{A}} = U_{\mathrm{Am}} \sin \omega t$, for 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:

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

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

3.3. Magnetic Field Harmonic Characteristics

Knowing from formula (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 derivation which is same to formula (13) and (14), we can get:

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

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

For u_1 just contains fundamental wave, i_1 contains only odd harmonic, so we can know from formula (4) that the odd EMF induced by $(\phi_1 + \phi_2)$ can be balanced by the resistance $R_{\mathrm{A}} i_{\mathrm{A}}$.

However, $R_{\mathrm{A}} i_{\mathrm{A}}$ can be neglected when compared with $N_{\mathrm{A}} (\frac{d\phi_1}{dt} + \frac{d\phi_2}{dt})$ in formula (4), so $(\phi_1 + \phi_2)$ contains only fundamental wave, both u_2 and i_2 contain only DC and even harmonic components. From formula (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 in $(\phi_1 - \phi_2)$.

So, we have:

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

Where $\phi_{1\mathrm{m}} = \frac{U_{\mathrm{Am}}}{2\omega N_{\mathrm{A}}}$, 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:

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

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

Also, we can get:

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

Where $B_{1\mathrm{m}} = \dfrac{U_{\mathrm{Am}}}{2\omega N_{\mathrm{A}} S}$, and B_0 is the DC flux component.

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

3.4. Simulation Based on MATLAB

According to the mathematical model, a simulation model of MSCR based on MATLAB is shown in Figure 2 [8].

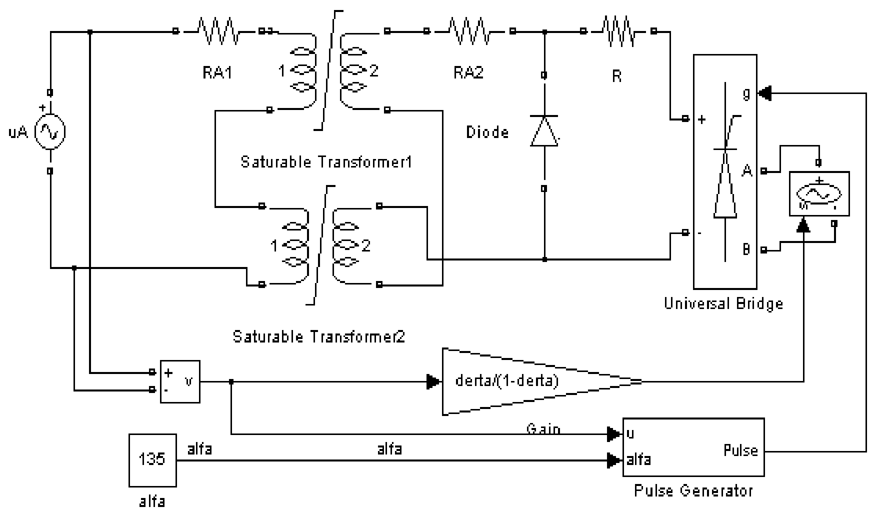
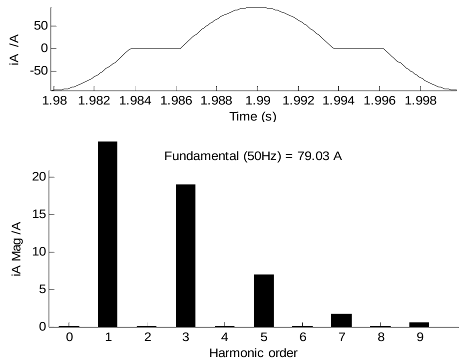


Figure 2. Simulation Model of MSCR

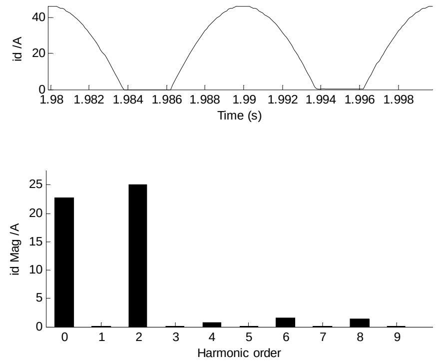
The related parameters are given as follows:

The rated capacity $S_{\mathrm{AN}} = 60.044\mathrm{MVA}$, the rated voltage $U_{\mathrm{AN}} = 500/\sqrt{3}\ \mathrm{kV}$, the frequency $f_{\mathrm{N}} = 50$ HZ, the winding resistance $R_{\mathrm{A}} = 40\Omega$, and the tap ratio δ=0.0474.

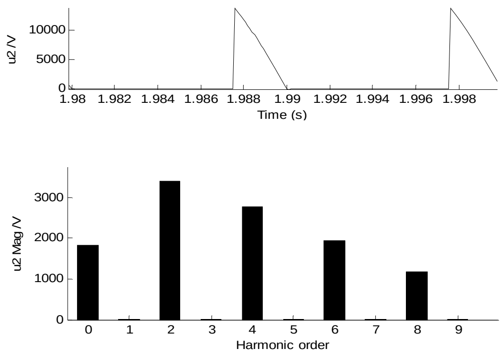
The simulation waveforms shown as Figure 3 are gotten when the trigger angle is 135 degrees. Clearly, Figure 3(a) shows that the working current just contains fundamental wave and odd current harmonic components; Figure 3(b) shows that the controlled current contains only fundamental wave and even current harmonic components; Figure 3(c) shows that the controlled voltage just contains DC and even current harmonic components; Figure 3(d) 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 the results of simulation are consistent with the theoretical derivation. 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.



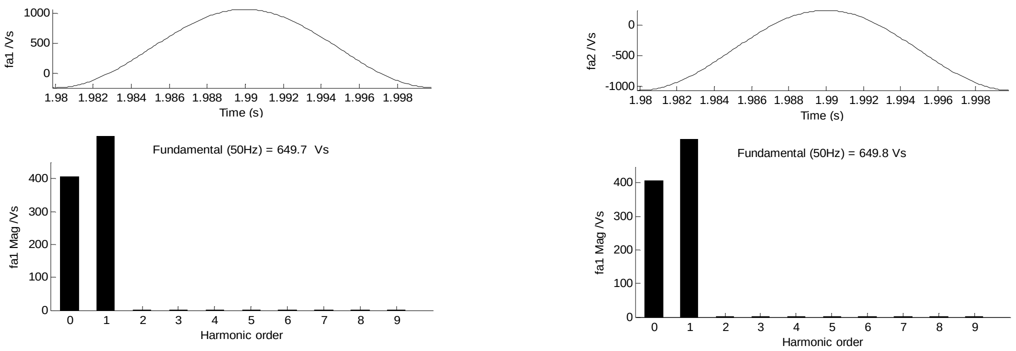
(a) Steady waveform and amplitude-frequency diagram of working current



(b) Steady waveform and amplitude-frequency diagram of controlled current i_d



(c) Steady waveform and amplitude-frequency diagram of controlled voltage u_2



(d) Steady waveform and amplitude-frequency diagram of iron core1 flux ψ_1, core2 flux ψ_2

Figure 3. Simulation Waveforms

4. Conclusion

The paper systematically analyzed harmonic constitution of working current, controlled current and magnetic field parameters of MSCR, then it concludes that the working current is an odd harmonic function, containing fundamental wave and odd harmonic; controlled 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. The theoretical analysis and conclusions are verified to be correct by the simulation based on MATLAB.

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