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Losses analysis of soft magnetic ring core under sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) excitations

Hezhe Gao,¹ Yongjian Li,^{1,a} Shanming Wang,⁴ Jianguo Zhu,²
Qingxin Yang,^{1,3} Changgeng Zhang,¹ and Jingsong Li⁴

¹State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin 300130, China

²School of Electrical Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

³Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology, Tianjin Polytechnic University, Tianjin 300387, China

⁴State Key Laboratory of Control and Simulation of Power System and Generation Equipments, Tsinghua University, Beijing 100084, China

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Practical core losses in electrical machines differ significantly from those experimental results using the standardized measurement method, i.e. Epstein Frame method. In order to obtain a better approximation of the losses in an electrical machine, a simulation method considering sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) waveforms is proposed. The influence of the pulse width modulation (PWM) parameters on the harmonic components in SPWM and SVPWM is discussed by fast Fourier transform (FFT). Three-level SPWM and SVPWM are analyzed and compared both by simulation and experiment. The core losses of several ring samples magnetized by SPWM, SVPWM and sinusoidal alternating current (AC) are obtained. In addition, the temperature rise of the samples under SPWM, sinusoidal excitation are analyzed and compared. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.5007762>

I. INTRODUCTION

Modern AC drives are usually fed with voltage source inverters (VSI) with PWM schemes,¹ which can cause extra core losses due to the presence of harmonic components. Optimization of system efficiency is a challenge for magnetic material producers, motor designers and consumers to optimize the performance of machine cores under completed magnetization condition.² Since core losses account for a large percentage of the total motor losses, predicting core losses caused by PWM voltage is very important in the stage of motors design and during analysis for realizing high efficiency and high performance.³ The extra core losses increase the temperature of the machines and reduce the efficiency and the lifetime. SPWM and SVPWM are two widely-used PWM patterns. Continuously increasing use of converters for the supply of electric machines introduces the necessity to study core losses under non-sinusoidal excitation conditions.⁴ Usually, manufacturers of electrical steel specify the magnetic properties for single frequencies without any harmonic components in the flux density as it is required in the Epstein frame measurement standard.⁵ In order to take the influence of inverter supply into account, measurements with SPWM and SVPWM voltage excitations are carried out with the ring core method.

^aCorresponding Author is Yongjian Li. Electronic mail: liyongjian@hebut.edu.cn.

II. HARMONIC ANALYSIS OF OUTPUT VOLTAGE WITH SVPWM AND SPWM EXCITATIONS

The general principle of SPWM is that an isosceles triangle carrier wave is compared with a sinusoidal modulating wave, and the points of intersection determine the switching point of power devices. SVPWM scheme has a different consideration that combines inverter and motor to obtain a round magnetic field. And this paper takes the three-level SPWM as an example to represent multi-level SPWM for analysis.

First, we define some parameters to facilitate analysis.

f_r : modulation wave frequency

U_r : amplitude of modulation wave

f_c : carrier wave frequency

U_c : amplitude of carrier wave

U_{11m} : fundamental amplitude of line voltage

U_d : DC link voltage

the modulation ratio can be defined $M_{SPWM}=U_r/U_c$, $M_{SVPWM}=U_{11m}/U_d$, carrier wave ratio $N=f_c/f_r$.

FFT is a commonly used tool to compare several PWM schemes against each other. This paper takes FFT as a tool to analyze the effect of modulation parameters of SPWM on harmonics of output voltage and compares the harmonics of SPWM and SVPWM under same modulation parameters.

It is found that the harmonic components of the output voltage decreased significantly with the increase of the modulation ratio, and harmonic components decreases with the increase of carrier wave ratio, but it is not obvious. So, the modulation ratio has a greater impact on harmonics than the carrier wave ratio, SVPWM has less harmonic components than SPWM and has higher DC voltage utilization under the same modulation parameters. The output voltage of PWM methods contain the components of fundamental frequency (f), carrier wave frequency ($N*f$), m times carrier wave frequency ($m*N*f$) and its nearby frequencies $[(m*N+n)*f]$.

In the recent years, three-level inversion has been achieved by using cascaded retrofit of two two-level inverters.⁶ The pole voltage of the cascaded inverter configuration can output three voltage levels viz. 0, $+V_{DC}/2$ or $+V_{DC}$.⁶ V_{DC} is the voltage of DC power.

Two types of three-level SPWM are studied in this paper, which are three-level SPWM of “synclastic carrier wave” and three-level SPWM of “adverse carrier wave”, respectively. FFT has been used to analyze these two kinds of three-level SPWM. The “adverse carrier wave” type has higher harmonic content than that of “synclastic carrier wave” type. Meanwhile, the harmonic content of three-level SPWM is reduced than the two-level SPWM obviously under the same parameter.

III. MEASUREMENT SETUP

In this paper, three ring core samples made of different materials as electrical steel sheet, soft magnetic composite (SMC) and nanocrystalline, are measured and compared. The primary coil of the sample is excited by a power amplifier which gets the signals from a signal generator. For the calculation of the **B-H** loops, the current of the primary coil and the voltage of the secondary coil are measured with the oscilloscope. The data in the oscilloscope is processed with MATLAB, and the final **B-H** loops are plotted.

IV. MEASUREMENT RESULTS

Based on the core losses separation model,⁷ the core losses are composed of hysteresis loss and eddy current loss, which is divided into classical eddy current loss and anomalous loss. The specific core losses P_{Fe} (in [W/kg]) can be determined:

$$P_{Fe} = f \frac{A_{BH}}{\rho_{Fe}} \quad (1)$$

where, f is the fundamental frequency of the voltage source on the primary side, A_{BH} is the area of the **B-H** loops and ρ_{Fe} is the specific mass density of the considered ring core material.

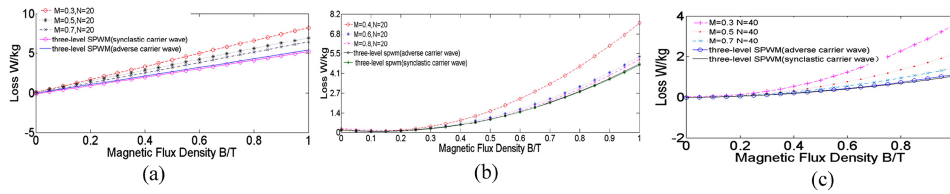


FIG. 1. Core losses of the three ring samples under different modulation ratios and level numbers: (a) SMC at 50Hz (b) nanocrystalline at 2 kHz and (c) electrical steel sheet at 50Hz.

The magnetic path length can be calculated as follows:

$$l_{m,\log} = \frac{d_0 - d_i}{\ln(d_0/d_i)} \quad (2)$$

where, d_0 is outer diameter of the ring core and d_i is inner diameter of the ring core.

Hysteresis loops of the electrical steel sheet ring core under SPWM and sinusoidal excitation are plotted with MATLAB. It is found that due to the existence of harmonic content in SPWM, when the harmonic content increases to some degree, minor loop will appear.

Electrical steel sheet and SMC are suitable for working at the low frequency, but nanocrystalline works at the relatively high frequency, thus, this article selects the two kinds of different frequencies.

Fig. 1 shows the influence of different modulation ratios and the level numbers on the core losses of the three ring samples.

Be noted that for SPWM, core losses decrease with increasing of modulation ratio. And the reason is that at a higher modulation ratio the amplitudes of harmonic components become relatively low. Moreover, the core losses of the samples under the three-level SPWM have significant decrease compared to the two-level SPWM.

Fig. 2 shows the influence of different carrier ratios on the core losses of the samples.

It can be seen that with the carrier ratio increasing, the core losses of the three samples decrease, but it is not obvious. However, the switching losses are also going up with the carrier ratio increasing, so a suitable value of N should be chosen in the application.

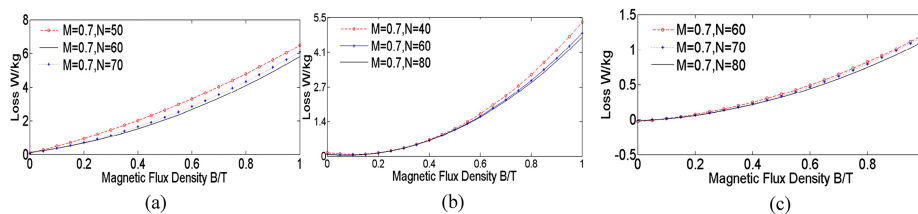


FIG. 2. Core losses of the three ring samples under different carrier ratios: (a) SMC at 50Hz (b) nanocrystalline at 2 kHz and (c) electrical steel sheet at 50Hz.

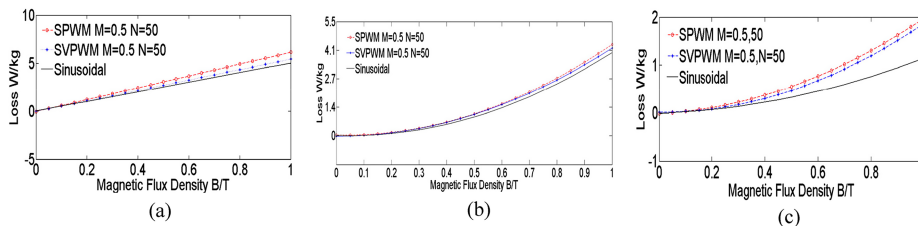


FIG. 3. Core losses of the three ring samples under SPWM, SVPWM and sinusoidal excitations: (a) SMC at 50Hz (b) nanocrystalline at 2 kHz and (c) electrical steel sheet at 50Hz.

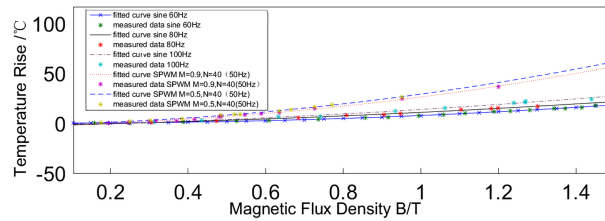


FIG. 4. Temperature rise of electrical steel sheet ring core under SPWM and sinusoidal excitations.

Fig. 3 shows the influence on the core losses of the three samples under SPWM, SVPWM and sinusoidal excitations.

It can be seen from Fig. 3 that core losses of the three samples under SVPWM excitation are all smaller than that of SPWM excitation. Furthermore, the core losses of the samples under sinusoidal excitation are minimal because there are no harmonic contents in the sinusoidal excitation.

V. TESTING RESULTS OF TEMPERATURE RISE

The presence of harmonics will cause additional loss, temperature rise and vibration. And the additional temperature rise can lead to local heating and affects the operation of motors, which will damage the insulation of the motors and reduce the lifetime.

A K-type thermocouple is attached to the inner surface of the electrical steel sheet ring core, and the temperature can be detected by a multi-meter with high precision. Depending on that, the temperature rise of the ring core within one minute can be calculated. When the next experiment is carried out, the temperature of the ring core should be kept close to room temperature. Fig. 4 shows the temperature rise of the ring core under the sinusoidal excitation at different frequencies and SPWM excitation.

It can be seen from Fig. 4 that the temperature rise of ring core is obvious and increased with excitation frequency under sinusoidal excitation. The temperature rise of the ring core with SPWM excitation is higher than that of sinusoidal excitation, and the smaller modulation ratio of the SPWM, the higher the temperature rise of the ring core.

VI. CONCLUSION

The influence of PWM supply parameters on the core losses of soft magnetic ring core is presented in this paper. The modulation parameters play important roles according to the core losses analysis. Be noted that with the increasing of modulation ratio (M) and carrier ratio (N), the core losses of samples all decrease, but the carrier wave ratio has smaller effect on core losses than that of modulation ratio. In terms of material losses, SVPWM has fewer harmonics than SPWM in the same modulation parameters, and lower core losses than SPWM excitation under same flux density. Meanwhile, the temperature rise and core losses characteristics of material samples are analyzed, which can provide reference for improving the efficiency of electrical equipments.

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