A comparative study of the effect of different converter topologies on the iron loss of nonoriented electrical steel

A. Salem[1,2], A. Abdallh[1,3], F. De Belie[1], L. Dupré[1] and J. Melkebeek[1]

[1]Department of Electrical Energy, Systems & Automation, Ghent University, Belgium
[2]Electrical Power & Machines Department, Helwan University, Egypt
[3]Electrical Power & Machines Department, Cairo University, Egypt

***Abstract*—In this paper, a comparative study of the effect of different converter topologies on the iron loss of nonoriented electrical steel is presented. Three converter topologies are considered in this investigation; namely: two-level, three-level, and five-level power converters. Moreover, the effect of the carrier frequency on both the iron loss and converter loss is introduced. The experimental results show a dramatic increase of the iron loss for the two-level converter, especially for low levels of the carrier frequency. Furthermore, the increase of the iron loss is negligible for the multilevel converter topologies. Specifically, the use of the five-level converter, even at a low value of the carrier frequency, results in lower iron losses than the three-level converter at a relatively higher carrier frequency.**

***Index Terms*—Iron loss, magnetic material, multilevel converters, pulse width modulation.**

I. Introduction

POWER converters, with a pulse width modulation (PWM), are widely used nowadays in industrial applications, due to their flexibility and efficiency for controlling electromagnetic devices (EMDs), such as rotating electrical machines [1]. Classically, a two-level converter is used in the drive system of EMDs. However, this type of converters produces high harmonic contents in their output voltage, which consequently affects the iron loss of the core magnetic material of EMDs [2], [3]. Recently, other configurations for the circuit of power converters have been introduced, such as three-level and five-level converters, and successfully applied for a wide range of EMDs [4]. The performance of these types of multilevel converters seems to be much better than the classical two-level converter.

In fact, the effect of the two-level converter on the iron loss of the magnetic material was intensively studied in literature. Generally, the iron loss models for distorted waveform excitation including minor hysteresis loops were presented in [5], [6]. Specifically, a generic iron loss model under PWM supply voltage was presented in [7]. Recently, the effect of different converter circuit parameters on the iron loss of laminated steel was studied in [2], [3]. The aforementioned research studies were performed for a traditional full bridge single phase converter. However, to the best of the authors' knowledge, the behavior of the iron loss under multilevel converters including PWM has not been fully investigated yet. Therefore, in this paper, we present a comprehensive comparison of the iron loss dependence on different converter topologies.

This study is performed for the single phase circuit of the different converter schemes. The advanced multilevel converter topologies of the three-level (T-type) and the five-level (dual-T-type) converter are selected to perform this comparative study [4], [9]. These advanced multilevel converters, as well as the two-level converter, are compared to the standard sinusoidal excitation system.

II. Experimental setup

The different converter topologies are tested with a fully and uniformly wound magnetic ring core with two windings; an excitation winding and a measurement winding, see Fig. 1. The magnetic field strength and magnetic induction are obtained using Ampere's law and Faraday's law, respectively. The standard ring core measurements are chosen, rather than the Epstein and single sheet tester measurements, in order to decrease the measurement error caused by the parasitic air gaps in the later standard measurement techniques [8]. The ring core specimen is constructed using the spark erosion cutting technique from M530/50A nonoriented electrical steel sheets. The ring core consists of 20 laminations with 45 mm and 55 mm, internal and external radii, respectively.

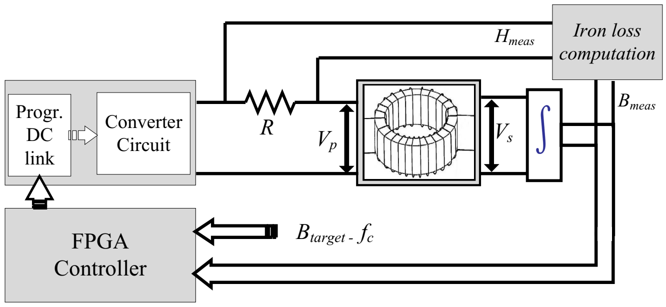

Fig. 1. Overall schematic diagram for a single-line diagram the proposed system.

First, the iron loss measurements are carried out under the standard sinusoidal excitation, in which the supply voltage is controlled in such a way to generate the target 'sinusoidal' magnetic induction waveform. These measurements are referred to as the reference data.

For the sake of comparison, the same ring core is tested under the PWM supply voltage generated by the aforementioned converter circuits. The schematic diagram of the entire experimental setup system is shown in Fig. 1. It consists of a magnetic ring core connected to the considered converter through a power resistance. The converters are controlled by means of a carrier based pulse width modulation (CBPWM) with a constant modulation index M_d and variable DC link to achieve the required magnetic induction. A fixed higher modulation index will result in lower harmonic contents in the supply voltage waveform. Moreover, the DC input supply voltage of the converter is controlled iteratively based on the difference between the fundamental component of the measured magnetic induction waveform and the target 'sinusoidal'

The authors gratefully acknowledge the financial support of the Erasmus Welcome program, the Special Research Fund (BOF) of Ghent University, and the Interuniversity Attraction Pole Program (IUAP) P7/02. Corresponding author: A. Abdallh (e-mail: ahmed.abdallh@ieee.org)

one, with the maximum allowable difference of 0.1%. In this study, the per unit reference waveform, with the DC link voltage being the base value, which is required to generate the desired magnetic flux density in the magnetic core, is sampled by three different values of the carrier frequencies, i.e. 1, 2.5 and 5 kHz. The CBPWM technique is implemented on a Field Programmable Gate Array (FPGA) digital controller.

A. Converter topologies and principle of operations

The circuit configuration of the utilized power converter has the flexibly to work in different converter modes. It is designed to work as two-level, T-type three-level, or dual-T-type five-level converter. Fig. 2 shows the single phase circuits for the considered power converters, in which the discrete power electronic Metal Oxide Field Effect Transistors (MOSFETs), with a code number of IXKR-40N60C, are used.

In general, for all converter types, the system operation is based on generating the appropriate reference voltage waveform that corresponds to the desired 'sinusoidal' magnetic induction, i.e. B_{target}. Initially, the FPGA compares a proposed reference voltage, in per-unit of the DC link voltage, to the carrier sawtooth waveform in order to produce the proper pulses for each converter type. The FPGA is connected to a programmable DC power supply which controls the DC link voltage of the converter. This process is repeated iteratively till reaching the required criterion, i.e. the permissable error between the fundamental component of the measured magnetic induction and the target 'sinusoidal' one is less than 0.1%.

As it is inferred from their names, the main difference between the multilevel converters and the two-level converter is the number of levels in the output voltage waveform. The multilevel converters contain much more levels that enhance the accuracy of tracking the sinusoidal waveform, and consequently reduce the harmonic contents in the output waveform. An example for the comparison between carrier and modulation waveforms, for the five-level converter, is shown in Fig. 3. The carrier waveforms with a carrier frequency of 5 kHz are compared to a sampled reference per-unit voltage for a magnetic induction of 1.5 T are shown in Fig. 3(a), while Fig. 3(b) depicts the converter phase voltage for this specific case. This figure clarifies that the phase voltage tracks the reference voltage with a gain of the DC link voltage, i.e. 35 V in this case. Additionally, Fig. 3(c) shows a good correspondence between the target 'sinusoidal' and measured magnetic induction.

The current and voltage waveforms are monitored and saved using a high-resolution LeCory 314-A oscilloscope. These waveforms are also interfaced to a computer with 100,000 samples per cycle. The control scheme of the converter, that generates the supply voltage corresponding to the desired magnetic induction waveform, is performed in Virtex-II Pro Development FPGA system. This digital controller is preferred here as it performs parallel computations and shares resources resulting in a high amount of operations each clock cycle. For more information related to the converters circuit configuration and the control schemes, see [4].

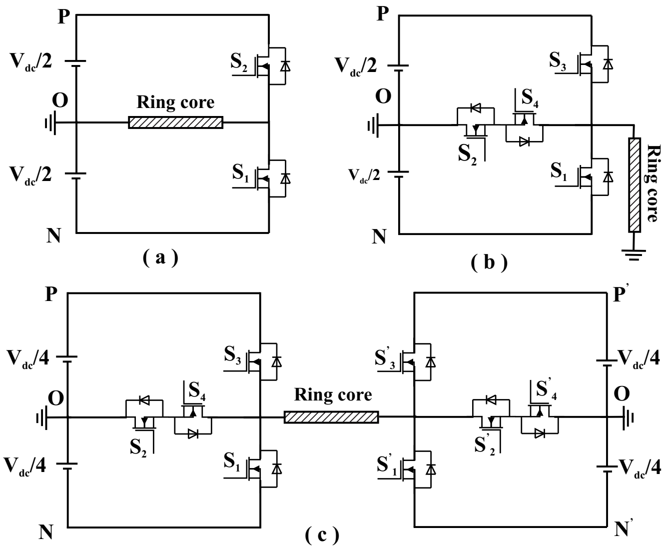

Fig. 2. The single phase circuit of (a) the two-level converter, (b) the T-type three-level converter, and (c) the dual-T-type five-level converter.

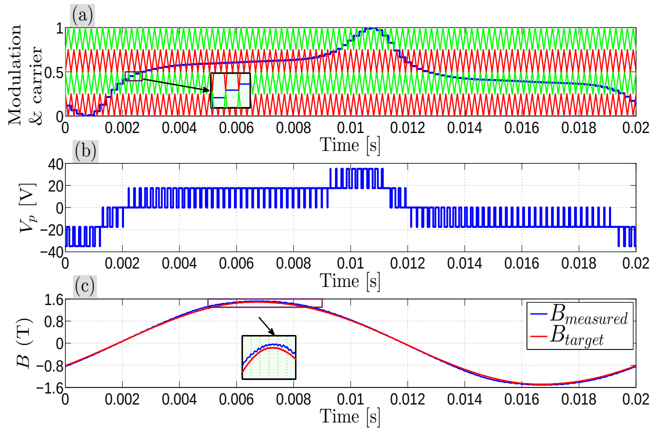

Fig. 3. (a) A comparison between modulation and carrier waveforms, at $f_c =$ 5 kHz, 1.5 T. (b) Single phase of the five-level (dual-T-type) converter output voltage. (c) A comparison between target and measured magnetic induction.

III. Results and Discussion

The test is performed for the aforementioned converter topologies at a wide range of the magnetic induction, i.e. from 0.25 T to 1.5 T. In addition, different values of the carrier frequency are tested, i.e. at 1, 2.5, and 5 kHz, in order to study their effects on both iron core and converter losses.

In the following, the iron loss per unit mass P, in (W/kg), is computed based on the magnetic energy dissipated W, in (Joule/m^3), within the magnetic material. The energy dissipated, at each magnetic induction level, is obtained as the area confined by the corresponding hysteresis loop:

$$W = \oint H(B)\mathrm{d}B, \quad P = f \cdot W \cdot \gamma^{-1} \tag{1}$$

with f and γ being the fundamental power frequency in the measurements, and the mass density of the electrical steel, which is assumed here $\gamma = 7650$ kg/m^3.

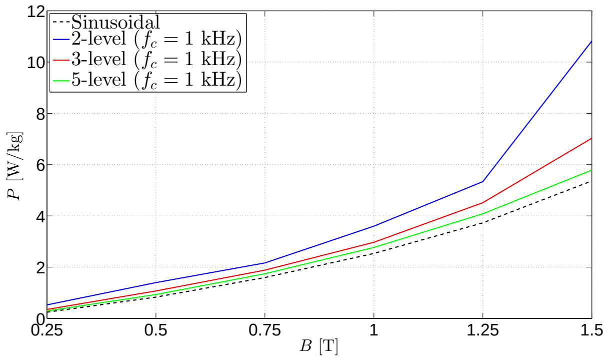

Fig. 4. The measured iron loss for the three considered converters at $f_c = 1$ kHz compared to the sinusoidal excitation at 50 Hz.

A. Iron loss dependence on the converter type

Fig. 4 shows the iron loss values versus the values of the fundamental component of the magnetic induction for the three studied converters, at $f_c = 1$ kHz, compared to the sinusoidal excitation measurements. Generally speaking, the use of PWM results in higher iron losses compared to the sinusoidal excitation. It is clear from this figure that the increase of the iron loss for the multilevel converters is lower than the ones for the two-level converter. The five-level converter gives the lowest iron loss among the three converters at a given frequency and magnetic induction.

B. Hysteresis loops

Furthermore, the $B-H$ hysteresis loop at 1.5 T for the PWM converter supply is compared with the sinusoidal one for 2.5 kHz carrier frequency, see Fig. 5. The latter figure clarifies the existence of the minor loop, which increases the iron loss compared to the sinusoidal reference excitation. Again, the five-level converter has the less minor loops.

C. Effect of carrier frequency

Fig. 6 shows the effect of the carrier frequency on the iron loss measurements for the considered converter topologies compared to the sinusoidal excitation measurements. It is clear from these results that the increase of the iron losses for the multilevel converters is lower than the ones for the two-level converter. In the traditional two-level converter, the iron loss is appreciably decreased with increasing the carrier frequency, especially at high values of the magnetic induction. Similar trend is observed, with a less pronounced effect, in the three-level converter. However, a negligible effect of the carrier frequency on the iron loss is noticed in the five-level converter.

In order to quantify the increase of the iron loss, we define the increase rate η as [2]:

$$\eta = P_{\text{PWM}}/P_{\text{sine}} \tag{2}$$

with P_{PWM} and P_{sine} being the iron loss at the PWM excitation and the one at the sinusoidal excitation, respectively. Fig. 7(a) illustrates the values of the increase rate η of the iron loss for the three studied converters at different values of the carrier frequency at 1.5 T and 50 Hz.

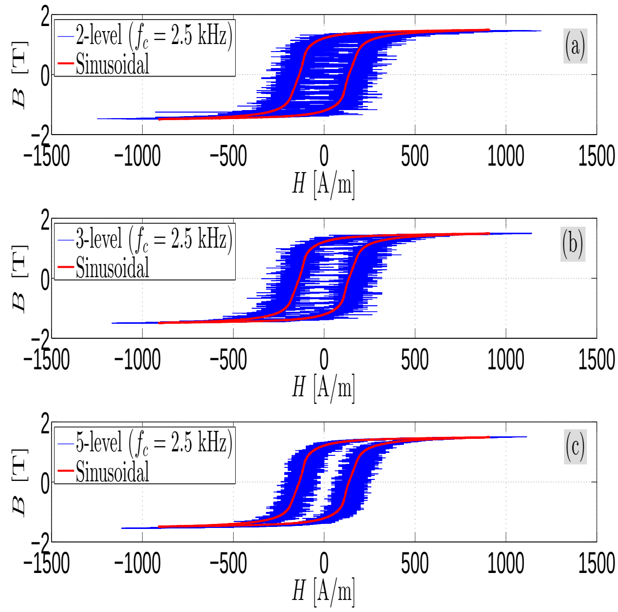

Fig. 5. Hysteresis loops for the 2-level (a), 3-level (b) and 5-level (c) converter topologies, at $f_c = 2.5$ kHz carrier frequency, compared to the sinusoidal excitation at 1.5 T, 50 Hz. Less minor loops are clear in 5-level converter.

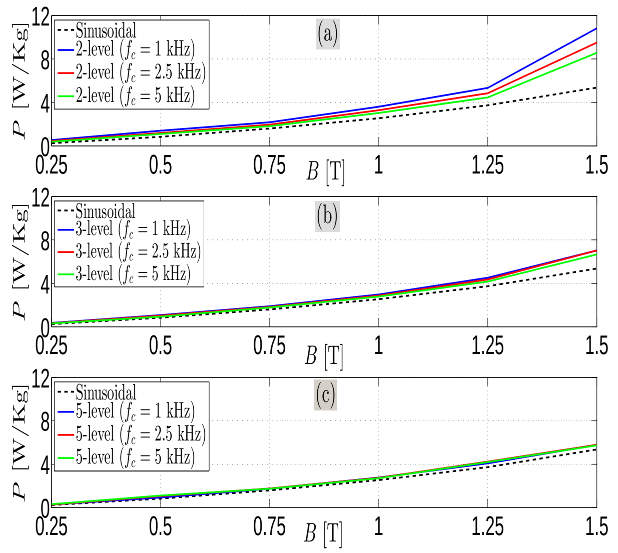

Fig. 6. The measured iron loss for the 2-level (a), 3-level (b) and 5-level (c) converter topologies at different values of the carrier frequency (f_c) compared to the sinusoidal excitation at 50 Hz.

The results shown in Fig. 7(a) clarify the superiority of the five-level over the other converter configurations. For example, the iron loss in the five-level converter even at a low value of the carrier frequency, i.e. 1 kHz, is considerably less than the corresponding iron loss for the three-level converter at a high value of the carrier frequency, i.e. 5 kHz.

D. Loss separation

It is well known that the energy losses in electrical steels are commonly evaluated based on the principle of loss separation [10]. Following this principle, the total iron loss P_{total} of a magnetic material can be decomposed into hysteresis loss P_{hys}

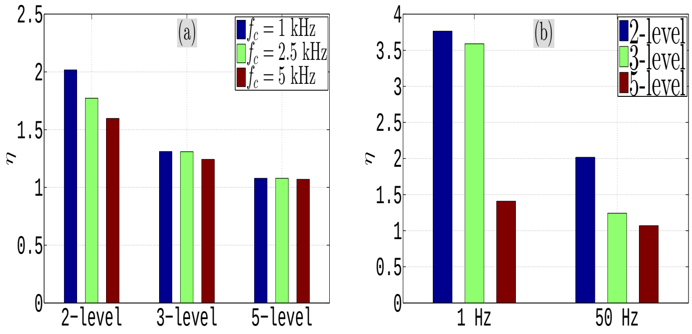

Fig. 7. (a) The increase rate η of the iron loss for the different considered converter topologies at 1.5 T and 50 Hz. (b) The increase rate η of the iron loss, at 1.5 T and 1 kHz carrier frequency, for the different considered converter topologies at 1 Hz and 50 Hz.

and dynamic loss P_{dyn}, which is the summation of the classical eddy current loss P_{edd} and excess loss P_{exc}:

$$P_{total} = P_{hys} + P_{dyn}. \quad (3)$$

In this section, we aim at finding out the dominant loss component that is most influenced by the PWM. To this end, the measurements are repeated at a considerable low frequency, i.e. 1 Hz, in order to have a negligible presence of eddy current effects in the magnetic core. Therefore, it is reasonable to assume that the measured loss in this specific case consists of only the hysteresis component. However, the 50 Hz measurements represent the total loss including the hysteresis and dynamic components. Fig. 7(b) shows the increase rate η of the iron loss, at 1.5 T and 1 kHz carrier frequency, for the three converters at 1 Hz and 50 Hz. It is obvious from this figure that the rate of rise in the hysteresis loss is larger than the rate of rise in the total loss. This result clarifies that the hysteresis loss is the dominant loss component that is most affected by the PWM than the dynamic loss.

E. Converter losses

Although the results mentioned in previous sections show a great reduction of the iron loss when the multi-level converters are used, it is expected that an extra power loss is dissipated in the converter. In practice, the converter 'switching' loss is a carrier frequency dependent; the higher the carrier frequency, the higher the converter loss. Therefore, it is essential to estimate the converter losses in order to check their effects on the total loss of the system. The converter losses are measured, as being the difference between converter input and output power, for the different carrier frequencies and for different values of the magnetic induction at 50 Hz power frequency.

Table I indicates the iron and converter loss, in (W), for the three converters at 1 kHz carrier frequency and 1.5 T. The results shown in this table clarify that the increase of the converter losses between the different converters are significantly lower than the reduction of the iron loss between the converters. For example, at 1.5 T and 1 kHz carrier frequency, the difference between the five-level and two-level converter losses is around 0.03 W, while a reduction of approximately 1.2 W is gained when the five-level is implemented instead of the two-level converter. Similar results are expected, with different values, for a higher rating of EMDs. These results indicate the effectiveness of using multi-level converters.

TABLE I
THE IRON AND CONVERTER LOSS IN (W) FOR THE TWO-LEVEL (2L), THREE-LEVEL (3L) AND FIVE-LEVEL (5L) CONVERTERS AT 1 KHZ CARRIER FREQUENCY, 1.5 T, 50 HZ.

Converter type	Loss [W]	
	Iron loss	Converter loss
2L	2.6007	0.0269
3L	1.6896	0.0311
5L	1.3911	0.0569

IV. CONCLUSION

In conclusion, a comprehensive comparison among different circuit configurations of power converters was presented in this paper. Three converter topologies were studied, at different carrier frequencies. The iron loss is appreciably decreased for the multilevel converters, i.e. T-type three-level and dual-T-type five-level, compared to the traditional two-level converter. The iron losses for 5-level converters can be assumed independent to the carrier frequency in the frequency range 1 kHz - 5 kHz, while in 2-level converters an increase could be noticed in the losses for higher carrier frequencies. Moreover, we showed that the hysteresis loss is the iron loss component that is most affected by the PWM. Furthermore, the increase of the converter losses, at multilevel converters, are negligible compared to the decrease in the iron loss. Finally, this presented study shows the advantage of using a more complex configuration of the converter power circuit that results in a lower iron loss. This study is of a great importance for understanding the iron loss in rotating electrical machines drive systems.

REFERENCES

[1] A. Boglietti and A. Cavagnino, "Iron loss prediction with PWM supply: An overview of proposed methods from an engineering application point of view," *Electric Power Systems Research*, vol. 80, pp. 1121-1127, 2010.

[2] H. Kaihara, *et al.*, "Effect of Carrier Frequency and Circuit Resistance on Iron Loss of Electrical Steel Sheet Under Single-Phase Full-Bridge PWM Inverter Excitation," *IEEE Transactions on Magnetics*, vol. 48, pp. 3454-3457, 2012.

[3] M. Kawabe, *et al.*, "Behavior of Minor Loop and Iron Loss Under Constant Voltage Type PWM Inverter Excitation," *IEEE Transactions on Magnetics*, vol. 48, pp. 3458-3461, 2012.

[4] A. Salem, *et al.*, "Evaluation of a dual-T-type converter supplying an open-end winding induction machine," Proceeding of 39th Annual Conference of the IEEE Industrial Electronics Society (IECON), Vienna, Austria, November 10-13, pp. 749-754, 2013.

[5] E. Barbisio, *et al.*, "Predicting loss in magnetic steels under arbitrary induction waveform and with minor hysteresis loops," *IEEE Trans. Magn.*, vol. 40, pp. 18101819, 2004.

[6] W. Roshen, "A practical, accurate and very general core loss model for nonsinusoidal waveforms," *IEEE Trans. Power Electron.*, vol.22, pp. 3040, 2007.

[7] M. Popescu, *et al.*, "A General Model for Estimating the Laminated Steel Losses Under PWM Voltage Supply," *IEEE Transactions on Industry Applications*, vol. 46, pp. 1389-1396, 2010.

[8] IEEE Standard 393-1991. "IEEE standard for test procedures for magnetic cores". Institute of Electrical and Electronics Engineers, 1992.

[9] M. Schweizer and J. Kolar, "Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications," *IEEE Transactions on Power Electronics*, vol. 28, pp. 899-907, 2013.

[10] G. Bertotti, "General properties of power losses in soft ferromagnetic materials," *IEEE Trans. Magn.*, vol. 24, pp. 621–630, 1988.