

# Comparison of Lamination Iron Losses Supplied by PWM Voltages: US and European Experiences

A. Boglietti<sup>1</sup>, *IEEE Member*, A. Cavagnino<sup>1</sup>, *IEEE Member*, T. L. Mthombeni<sup>2</sup>, *IEEE Student Member*, P. Pillay<sup>2</sup>, *IEEE Fellow Member*,

<sup>1</sup>Politecnico di Torino – Dipartimento di Ingegneria Elettrica Industriale - Italy

<sup>2</sup>Department of the Electrical & Computer Engineering, Clarkson University, Potsdam, NY, USA

**Abstract** - In this paper the behavior of non-oriented laminations when excited with PWM waveforms is analyzed. The USA and the European experiences in core loss measurements with PWM waveforms are compared, highlighting the different experimental approaches and the different test benches. Parameters that characterize a PWM source (i.e. switching frequency, modulation index, modulating waveform type and switching topologies) are varied to ascertain their influence on lamination specific core losses. Although a direct numeral comparison of results was not possible, test results from the two institutions harmoniously show a consistent deterioration of lamination properties when excited with PWM supplies. The problem approach proposed by the two institutions show understanding of core loss measurement methods with non-sinusoidal excitations and can be considered a starting point for future work on a development of a standard procedure for magnetic material characterization with PWM supplies. Test benches with the respective experimental results are detailed in this paper.

## I. INTRODUCTION

A growing number of ac motors and electromechanical devices are fed through non-sinusoidal supplies. In particular, pulse width modulated (PWM) inverters can be considered a standard solution when voltage and frequency regulation is required, for process control and energy savings. The use of PWM supplies leads to a general loss increase both in the motor windings and in the magnetic laminations. It is well known that the additional copper losses in the windings are easily computed from the harmonic content, taking into account the skin effect. On the other hand the behavior of magnetic materials supplied with PWM voltages are much more complex and their dependence on induction and frequency is strongly non-linear [1]-[9]. Besides, the non-sinusoidal fluxes produced by PWM supplies, some motor operate with non-sinusoidal fluxes, which are fundamentally different in frequency, magnitude and wave shape in the different sections of the motor [10][11]. While international standards to guide lamination core loss measurements with

sinusoidal excitations have been developed, there are currently no international standards for core loss measurements with non-sinusoidal supplies. Often, electromagnetic designers try to solve the problem on the basis of their experience using corrective coefficients that do not have a generic applicability. In addition, it is important to understand how some parameters that characterize PWM voltage waveforms influence magnetic material performance deterioration. For these reasons, it is important to compare experiences and test results coming from different researchers and laboratories. A numerical comparison is not the subject of this paper, as the two test sites used different lamination materials. The aim of this paper is rather to show the repeatability of core loss measurements achieved under PWM supplies following similar methodologies, opening the possibility for an acceptable international standard.

## II. SINUSOIDAL VS. PWM SUPPLY

The mains supply is ideally a sinusoidal waveform both in single and in three phase systems. A sinusoidal supply is defined by its amplitude and frequency. It is well known that the rms value of a sinusoidal quantity is adopted as a reference in the electrical community. The PWM supply is the typical voltage source produced by inverters used in variable speed electrical machine drives. A most common method adopted for PWM waveform generation is the comparison of a modulating waveform with a carrier waveform (usually a triangular waveform). As a consequence, the PWM waveform is structured as a series of voltage pulses with different widths that are able to create a fundamental harmonic of the frequency set by the modulating waveform (the requested sinusoidal supply) plus high frequency spectra that are linked to the carrier waveform. Depending on the application, the carrier frequency can be 10 to 100 times the modulating frequency. A PWM voltage is characterized by the following parameters:

*Modulation index,  $m_a$ :*

Ratio between the modulating wave amplitude to carrier wave amplitude. Its value has to satisfy the relation  $0 \leq m_a \leq 1$  for linear control.

*DC bus voltage,  $V_{DC}$ :*

It is the average value of the DC voltage bus produced by the AC/DC rectifier.

*Modulation waveform:*

It is the waveform of the modulating waveform. (Usually a sinusoidal, but other waveforms can be used to increase the amplitude of the desired first harmonic).

*Switching frequency,  $f_s$ :*

The frequency of the carrier waveform. The ratio of the switching frequency to the modulating waveform frequency is known as a frequency-modulating index.

*Modulation techniques:*

It is the adopted technique for the power switch command. Different modulation techniques can be used, in particular for single-phase inverters.

As a direct consequence, a PWM supply can produce the same fundamental harmonic using different PWM parameters. For example, depending on the inverter limits the same fundamental harmonic can be produced with several values of the modulation index and DC bus voltage. These PWM parameters have a direct influence on the iron losses in the laminations supplied by a PWM inverter. In this paper a complete analysis of the correlations between the lamination iron losses and the PWM parameters is carried out.

#### **A. Laboratory Test Benches**

A complete independent study has been performed in two laboratories, one in Europe, Italy at the Politecnico di Torino, and the other one in the USA, at Clarkson University, New York. A short description of the two test benches follows.

##### **a. European Test Bench**

The European test bench is based on the following devices:

- Epstein frame with 0.5 m sides loaded with 10 kg of magnetic material.
- A three-phase industrial inverter. Its control is fully analog, but some modifications have been made, in order to allow a complete separate regulation of the DC bus voltage, modulation index, switching frequency and modulating waveform.
- A single-phase transformer is connected between the inverter and the Epstein frame. This device has been introduced for decoupling the inverter from the Epstein frame with respect to any dc component or sub-harmonics. This transformer does not worsen

the voltage quality because it is used with a low level flux.

- Digital power analyzer with a voltage and current bandwidth suitable for PWM supply.
- Analog integrator connected to the Epstein secondary winding and used for obtaining the flux waveform to be visualized on a digital scope.

##### **b. USA Test Bench**

The PWM signals are generated in MATLAB SIMULINK and the DSP based dSPACE software offers a real-time interface with SIMULINK and the analog circuit. A high bandwidth linear amplifier (100 kHz) is used to excite the 25 cm Epstein frame, a standard 2 kg frame. A single-phase transformer was connected between the amplifier and the Epstein frame. A current probe and an isolated differential voltage probe were used to measure the exciting current and secondary voltage, respectively. A digital storage oscilloscope is used to monitor and store exciting current and the secondary voltage.

Although the two test benches are similar, they are not quite the same, the experimental results reported in the next sections are well comparable and show independence by the adopted measurement system. In order to develop an international standard to characterize core losses with PWM supply, a reference test bench has to be defined. The authors hope that this paper will spark a debate on defining an international standard on lamination characterization with non-sinusoidal excitations.

#### **B. Reference Magnetic Quantities**

As discussed by the authors in a previous paper [9], the use of distorted voltages require a correct choice of the magnetic quantities to be used during the comparison of results coming from different laboratories. Two magnetic quantities can be defined for a correct analysis of the iron losses. The first one is the peak flux density of the first harmonic; the second one is the peak of the flux density waveform. Both quantities can be correctly selected but each has advantages and disadvantages.

##### **a. Peak of flux density first harmonic**

This quantity is simple to measure with modern power analyzers used in PWM measurements because these instrumentations provide the first harmonic of all the measured electrical quantities. It is important to underline that this quantity matches with the traditional choice made by the electromechanical designers who use the peak of the first harmonic flux density as a main magnetic reference in the electromagnetic design.

##### **b. Peak of flux density waveform**

This quantity is usually computed using the average rectified value of the voltage source  $V_{ave}$  as shown in Eq. 1.

$$B_x = \frac{1}{4NS} \int_0^T |v(t)| dt = \frac{T}{4NS} V_{ave} \quad (1)$$

with

- N = number of secondary turns
- S = magnetic circuit cross section area
- T = period of the voltage source waveform

The average rectified value of the voltage source is not always provided by the instrumentation used in PWM measurements. In an actual machine, where saturation is to be considered, the peak flux density is a more realistic value, instead of the fundamental peak flux density harmonic.

In both laboratories the choice of the fundamental peak harmonic flux density has been done, allowing for a direct comparison of the test results.

### III. RESULTS COMPARISONS

In this section a complete analysis and comparison between the results obtained from the two laboratories is reported. In particular, the influence of PWM parameters on the iron losses is examined.

The lamination magnetic characteristics used in the tests are different, but both materials are non-oriented silicon iron steels. In particular, the European lamination is a medium quality material with a thickness of 0.5 mm and a specific loss of 2.5 W/kg at 1.5 T, 50 Hz, while the USA lamination is 0.0140 inches (0.36 mm), with a specific loss of 2.86 W/kg at 1.5 T, 50 Hz. Figs. 1 and 2 show the comparison of the iron losses measured with sinusoidal and PWM supplies, from the European test site and American site, respectively.

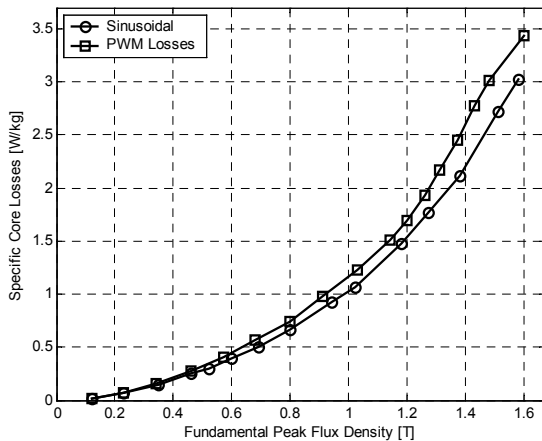


Fig. 1: European test results: Core loss increase due to non-sinusoidal supplies, with modulating wave frequency = 50 Hz,  $f_s = 1.0$  kHz and  $m_a = 0.9$

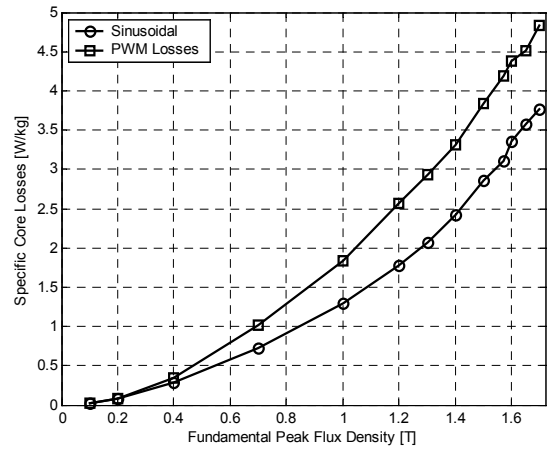


Fig. 2: USA test results: Core loss increase due to non-sinusoidal supplies, with modulating wave frequency = 50 Hz,  $f_s = 1050$  Hz and  $m_a = 0.9$

In both figures it is evident that the specific iron loss increases, although due to the different lamination characteristics, the absolute increase is not directly comparable, only a consistent trend is observed.

#### A. Modulation index

In Figs. 3 and 4, the specific iron losses comparison, using PWM supplies with different modulation indices,  $m_a$  are reported.

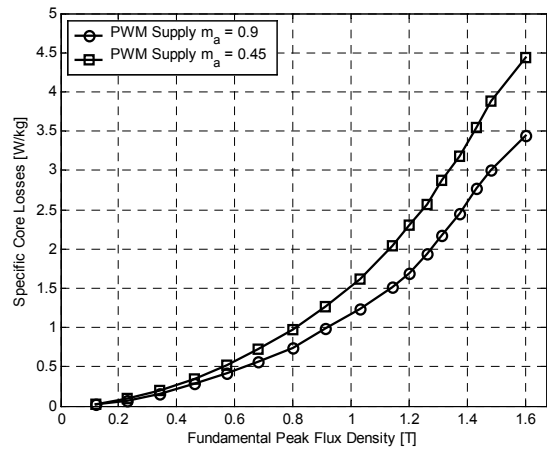


Fig. 3: European test results: Core losses with modulation index variation, with modulating wave frequency = 50 Hz and  $f_s = 1.0$  kHz

Both test results show a significant increase of the specific iron losses as the modulation index is reduced. As a direct consequence of these results, in order to avoid a consistent increase of the iron losses, a higher modulation index (close to unity) should be used in PWM inverters.

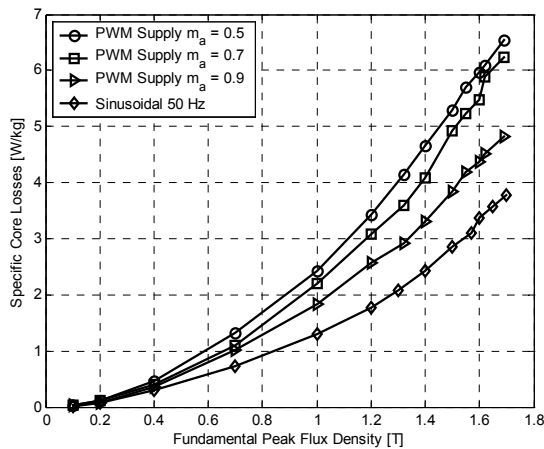


Fig. 4: USA test results: Core losses with modulation index variation with modulating wave frequency = 50 Hz and  $f_s = 1050$  Hz

### B. Switching frequency

The effect of the switching frequency on the specific iron losses has been analyzed too, with experimental results reported in Figs. 5 and 6, for several flux density values. Comparing the two Figures, a decrease in core losses is seen when the switching frequency is increased. Increasing the switching frequency not only reduces core losses, it also reduces the acoustic noise in the machine. It is evident that for switching frequencies higher than 4 – 5 kHz the iron losses are constant with the switching frequency. In these publications, [4] and [10], the authors have provided a detailed explanation of this behaviour. However, switching losses in the inverter increase with an increase in the switching frequency. This concern is nullified by the fact that modern IGBTs are optimized to operate at switching frequencies greater than 5 kHz; hence the best condition for minimal iron losses is naturally imposed from the switching frequency point of view.

### C. Modulation techniques

In this section the correlation between core losses and the inverter modulation technique adopted is discussed. In a two-level modulation (also called bipolar), the voltage is always switched between  $+V_{dc}$  and  $-V_{dc}$ , as shown in Fig. 7. On the contrary, in a three-level modulation (also called unipolar), the voltage is switched from between  $+V_{dc}$  and zero during the positive half wave and between zero and  $-V_{dc}$  during the negative half wave as shown in Fig. 8. The unipolar and bipolar switching schemes can only be adopted in a single-phase inverter since a three-phase inverter produces a three-level waveform for both the line-to-line voltage and the phase voltage.

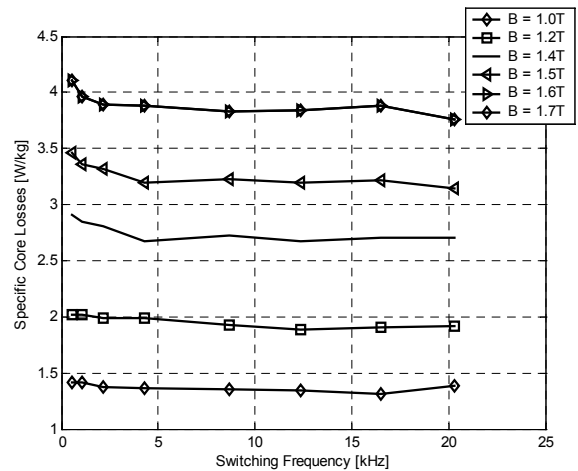


Fig. 5: European test results: Effect of varying the switching frequency with modulating signal frequency = 50 Hz

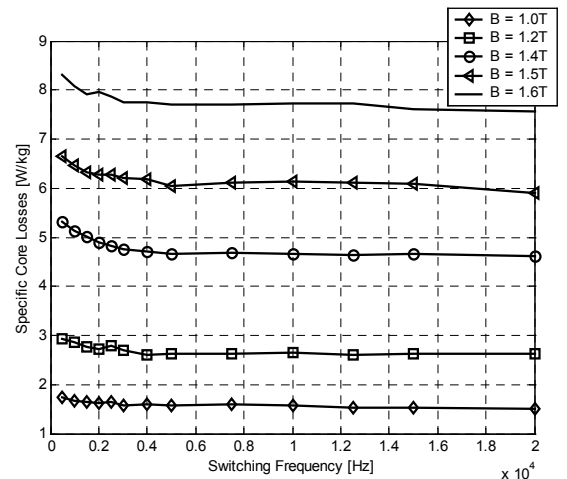


Fig. 6: USA test results: Effect of varying the switching frequency with a modulating signal frequency = 50 Hz

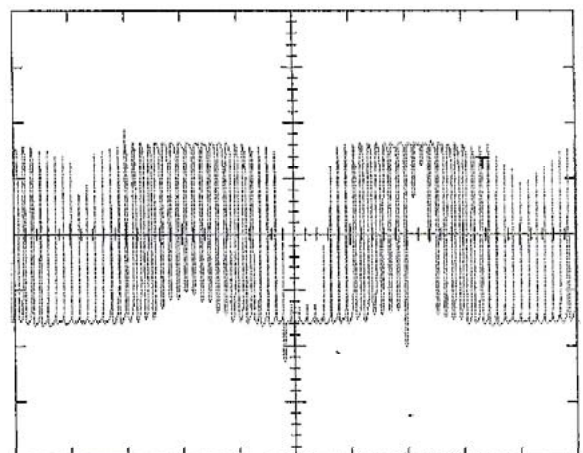


Fig. 7: Output voltage with bipolar modulation technique

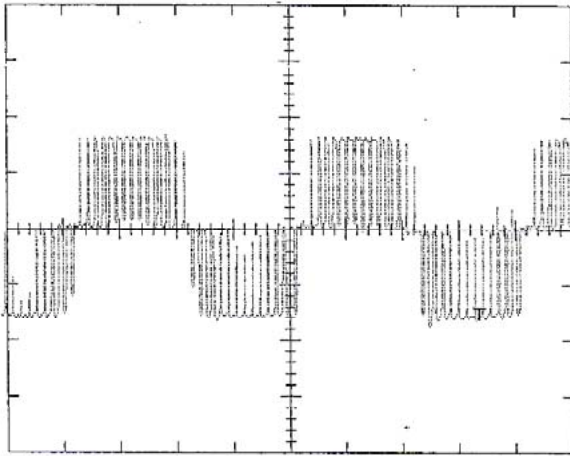


Fig. 8: Output voltage with unipolar modulation technique.

Figs. 9 and 10 compare the specific iron losses for different modulation technique, from both European and American laboratories. Both figures show a consistent increase of the specific iron losses with a bipolar modulation with respect to unipolar modulation. The main reasons of this consistent loss increase are linked to the different time evolution in the flux density waveform. In Figs. 11 and 12, flux density waveforms for the two modulation techniques are reported.

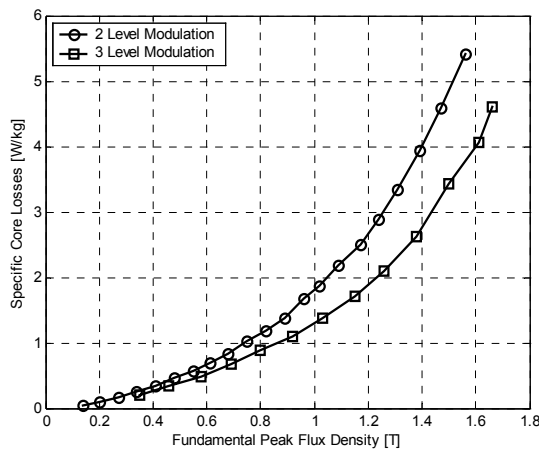


Fig. 9: European test results: Core loss comparison due to bipolar and unipolar PWM schemes, with modulating wave frequency = 50 Hz and  $f_s = 1.72$  kHz

In the bipolar modulation, the flux density derivate changes sign, as indicated by the circle. A direct consequence of this behavior is the presence of minor loops in the hysteresis circle with a hysteresis loss increase. On the contrary, with the unipolar technique the flux density slope does not change sign; in fact, when the applied voltage is zero the flux density is constant as evident in Fig. 12. As a consequence, the hysteresis losses do not increase. It must be noted that the flux density waveforms reported in Figs. 11 and 12 have been obtained by integrating the Epstein frame

secondary winding voltage using an analog integrator connected to the frame terminals.

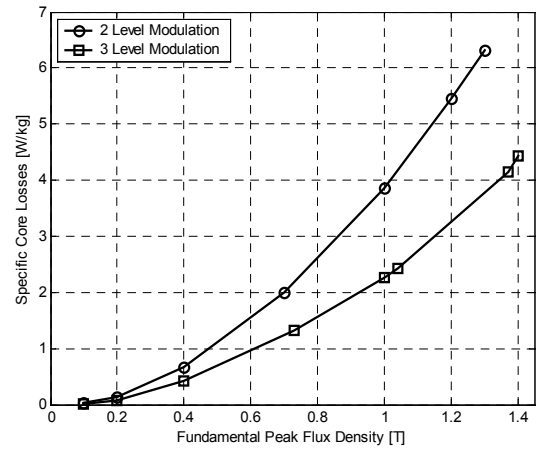


Fig. 10: USA test results: Core loss comparison due to bipolar and unipolar PWM schemes, with modulating wave frequency = 50 Hz and  $f_s = 1.0$  kHz

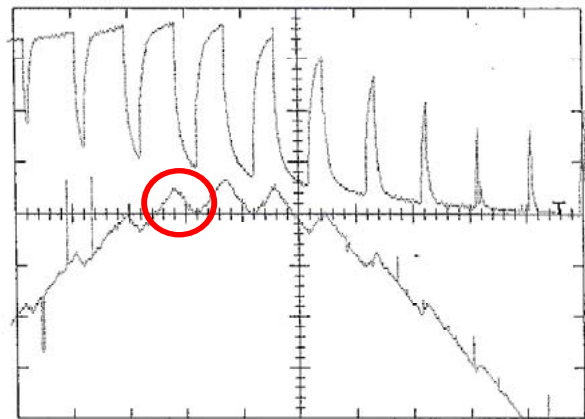


Fig. 11 Two level modulation technique; upper trace: absorbed current, lower trace: flux density

#### D. Modulation waveform

Tests with three types of modulation waveforms have been performed to find any correlation between this parameter and the specific iron losses. A pure sinusoidal, a sinusoidal plus third harmonic and a space vector waveform have been used. The results are summarized in Fig. 13 where it is evident that the specific iron losses do not depend on the modulation waveform used. As a consequence, this PWM inverter parameter can be neglected in iron loss considerations.

#### IV. GENERAL CONSIDERATIONS

Based on the results reported here, the following general remarks can be made:

- Experimental results presented in this paper confirm the deterioration of magnetic qualities in laminations when excited with PWM supplies, compared to when excited with sinusoidal supplies.

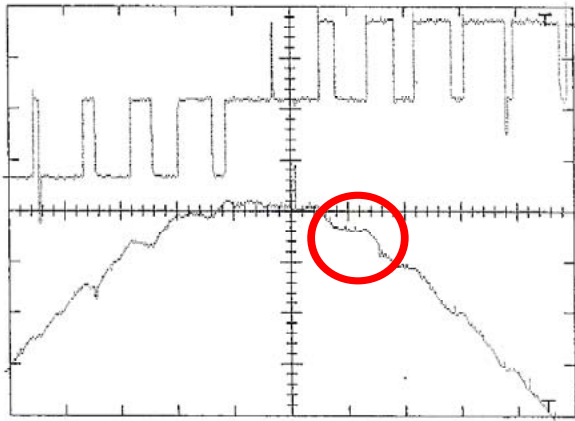


Fig. 12: Three level modulation technique; upper trace: induced voltage on the secondary winding; lower trace: flux density

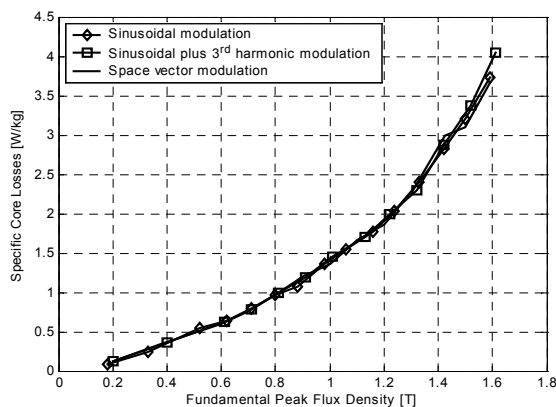


Fig. 13: Specific iron losses variation with the modulating waveform at 50 Hz with a switching frequency = 8.57 kHz

- Qualitatively, the two institutions obtained a similar core loss trend; confirming the understanding of core loss measurements techniques with non-sinusoidal waveforms. Thus, demonstrating that core losses measurements with non-sinusoidal excitations can be standardized,
- For the first time, a direct international comparison of core loss analysis has been done, which had not been done before.

## V. CONCLUSIONS

This paper presented lamination core loss results with PWM supplies measured at two institutions, in two different countries (the USA and Italy in Europe) using different equipment. Although a direct numerical comparison cannot be done, because of the different magnetic materials used, the observed trends from the two different test setups agree. They both show lamination core loss increase with PWM supplies. Similar trends in core losses with variation of PWM parameters were observed. Consequently, the proposed methodologies for laminations characterization with PWM

supplies can assume a general validity. In particular, it is the authors' opinion that current industrial practice on laminations characterization with sinusoidal supplies is not sufficient when electromagnetic devices have to optimize for use with PWM supplies. Although other authors have individually studied PWM core loss increases [13] and [14], this is the first time that results obtained from different laboratories, by different researchers are compared together with such a consistent agreement. It is hoped that this will lead to a development of the much-needed standard to characterize laminations with non-sinusoidal excitations.

## REFERENCES

- [1] A. Boglietti, P. Ferraris, M. Lazzari, F. Profumo, "Iron losses in magnetic materials with Six-Step and PWM inverter supply," *IEEE Transactions on Magnetics*, vol 27, no. 6, pp. 5334-5336, Nov. 1991.
- [2] A. Boglietti, P. Ferraris, M. Lazzari, F. Profumo, "Energetic behavior of soft magnetic materials fed by inverter supply," *IEEE-Transactions on Industry Applications*, vol. 30, no. 6, pp. 1580-1587, Nov./Dec. 1994.
- [3] A. Boglietti, P. Ferraris, M. Lazzari, F. Profumo, "Effects of different modulation index on the iron losses in soft magnetic material supplied by PWM inverter," *IEEE Transactions on Magnetics*, vol. 29, no. 6, pp. 3234-3236, Nov. 1993.
- [4] Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "Change of the iron losses with the switching supply frequency in soft magnetic materials supplied by PWM inverter," *IEEE Transactions on Magnetics*, vol. 31, pp. 4250-4252, no. 6, Nov. 1995.
- [5] A. Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "Iron losses measurements with inverter supply: a first discussion to define a standard methodology", *IEEE Transactions on Magnetics*, vol. 31, no. 6, pp. 4006-4008, Nov. 1995.
- [6] A. Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "About the possibility of defining a standard method for iron loss measurement in soft magnetic materials with inverter supply," *IEEE Transactions on Industry Applications*, vol.33 no. 5, pp. 1283-1288, Sept./Oct. 1997
- [7] A. Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "Influence of the inverter characteristics on the iron losses in PWM inverter fed induction motors," *IEEE Transactions on Industry Applications*, vol. 32, no. 5, pp. 1190-1194, Sep. 1996
- [8] A. Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "Influence of modulation techniques on iron losses with single phase DC/AC converter," *IEEE Transactions on Magnetics*, vol. 32, no. 5, pp. 4884-4886, Sep. 1996.
- [9] A. Boglietti, M. Lazzari, M. Pastorelli, "About the choice of the reference magnetic quantity in presence of non sinusoidal waveforms," *IEEE Transactions on Magnetics*, vol. 33, no. 5, pp. 4002-4004, Sep. 1997.
- [10] T. L. Mthombeni, P. Pillay and A. S Naidu, "Lamination core loss measurements in machines operating with PWM or non-sinusoidal excitation", *IEEE International Electric Machines and Drives Conference*, Wisconsin, Madison, June 1-4, 2003.
- [11] T. L. Mthombeni and P. Pillay, "Core losses in motor laminations exposed to high frequency or non-sinusoidal excitation", *IEEE IAS Annual Meeting*, Salt Lake City, Utah, October 12-16, 2003.
- [12] R. Katmarek, M. Amar, F. Protat, "Iron loss under PWM voltage supply on Epseti frame in an induction motor core" *IEEE Trans. Mag.* Vol. 32, NO 1, pp.189-194, 1996.
- [13] R. Katmarek, M. Amar, F. Protat, "Prediction of power losses in silicon iron sheets under PWM voltage supply", *Journal of magnetism and magnetic materials*, 1995, N° 133, pp. 140-143.
- [14] C. A. Hernandez-Aramburo, T.C. Green, A.C. Smith, "Assessment of power losses of an inverter driven induction machine with its experimental validation", *IEEE-IAS 2002 Annual Meeting* 13-18 October 2002, Pittsburgh, USA.