Measurements and Prediction of Iron Losses in Laminated Magnetic Cores Supplied By Ultra-High Switching Frequency PWM

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***Abstract*—The paper deals with measurements of iron losses in toroidally-wound laminated magnetic cores supplied by means of wide-bandgap-semiconductor-based power electronic converters. The study is aimed at investigating the impact of selected PWM parameters on the iron losses, through an extensive experimental measurement campaign; the magnetic core under test is supplied by pulse-width-modulated voltage waveforms with switching frequencies greater than 100 kHz and different deadtimes. This investigation is used for a critical review of an engineering method that was proposed in prior literature to predict iron losses in the presence of a distorted voltage supply.**

Keywords—PWM supply, WBG-based converters, iron loss measurements, iron loss computation,

I. Introduction

High-speed electrical machines have gained a growing interest in several industrial, automotive and aerospace applications because of their high-power density; examples include high-speed spindles (300000 r/min), air compressors and air blowers (15000 r/min), microturbines (120000 r/min), with typical fundamental frequencies exceeding 1 kHz [1]-[3]. In order to guarantee low current ripple, stable control and low losses, these electrical machines may require pulse width modulated (PWM) voltages with switching frequencies exceeding 100 kHz; otherwise, appropriate measures are needed in the design, leading to a suboptimal motor drive configuration [4].

Wide-bandgap-semiconductor (WBG) power devices (namely, silicon carbide, SiC, and gallium nitride, GaN) have very short commutation transients and can therefore be hard-switched at frequencies well above 50 kHz; consequently, three phase inverters using these switches are small, lightweight and have very high efficiencies. Hence, they represent an effective solution for the design of very robust, efficient, and compact high-speed motor drives.

Despite electrical machines are an efficient low-pass filter for high frequency harmonics, additional losses due to PWM are unavoidable, especially the iron loss, which represent a significant portion of the total losses at high rotational speeds. Consequently, an accurate prediction of core loss at both fundamental and switching frequencies becomes an important tool in electrical machine design, thermal management, and development of control strategies [5].

Several empirical models have been presented in prior literature to predict iron losses in ferromagnetic materials; some of them provide satisfactory estimates only for purely sinusoidal flux density waves and were developed based on major works by C. P. Steinmetz, H. Jordan and G. Bertotti [6], [7]. These models differ in terms of the subdivision of the overall iron losses into the three main contributions, and of their dependency on the fundamental frequency and flux density waveform.

Several models have been developed to deal with PWM supplies, but in most cases are quite and impractical for an immediate use by electrical machine designers. For this reason, the authors are looking to simple, but still accurate formulations to compute iron losses under ultra-high switching frequency PWM.

Contrary to what one might expect, iron losses in the laminated magnetic cores decrease significantly with the switching frequency [8], [9]. Even if this effect has been known since the end of the last century, it is worth investigating the effects on magnetic cores supplied by WBG inverters synthesizing PWM voltages at switching frequencies well above 50 kHz, which is presently considered a standard limit for most industrial and automotive applications. It was shown in [10] that PWM parameters such as deadtime have impact on iron losses.

The main goal of this research work is to investigate iron losses in magnetic laminations when extremely fast switching used. In particular, the paper is focused on the experimental measurement of iron losses in two toroidally-laminated cores produced with very different magnetic materials.

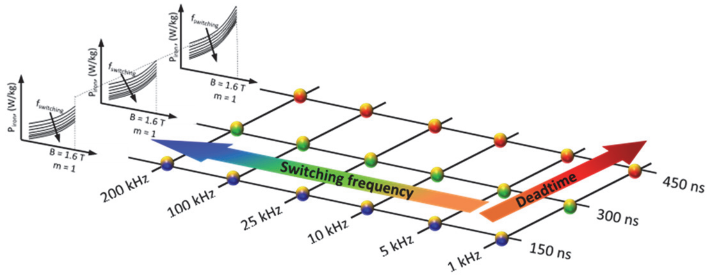


Fig. 1. Switching frequency vs. deadtime with fundamental harmonic of PWM voltage at the considered fundamental frequency of 50 Hz or 200 Hz.

TABLE I – SPECIFICATIONS OF SI-FE CORE.

Primary winding turns	*107*
Secondary winding turns	*107*
Lamination thickness, (mm)	*0.5*
Number of sheets	*40*
Radial thickness, (mm)	*40*
Weight, (kg)	*3.55*
Cross-sectional area, (mm^2)	*900*

TABLE II – SPECIFICATIONS OF COFE CORE.

Primary winding turns	*73*
Secondary winding turns	*66*
Lamination thickness, (mm)	*0.35*
Number of sheets	*90*
Radial thickness, (mm)	*14.5*
Weight, (kg)	*1.62*
Cross-sectional area, (mm^2)	*457*

Both magnetic cores are fed by a SiC H-bridge inverter, exploring a wide range of switching frequencies and deadtimes. The results are then exploited to extend the use of the analytical model presented in [11], to predict iron losses under PWM excitation at ultra-high switching frequencies.

II. METHODOLOGY

An experimentally based approach is proposed to collect the data to quantify the impact of the switching frequency and of the deadtime on the losses in laminated cores. Figure 1 shows the matrix of the values considered during the test campaign at 50 Hz and 200 Hz fundamental frequency. The results included in Section IV refer to tests carried out by using two toroidal cores. The considered magnetic cores are built with two different magnetic materials: a 0.5 mm silicon–iron (SiFe) M800-50A sheet, and the 0.35 mm cobalt–iron (CoFe) VACOFLUX 50® – see Table I and Table II, respectively. A maximum fundamental flux density in the FeSi core approximately equal to 1.6 T has been obtained (using an amplitude modulation index $m = 1$ and the proper bus voltage value), while the FeCo core sample has been loaded up to 2.2 T, both at 50 Hz and 200 Hz.

III. MEASUREMENTS SETUP

The test rig used to measure the iron losses includes a SiC H-bridge inverter supplied by a high voltage DC power supply, whose output terminals are connected to the primary winding of the toroidal core under test.

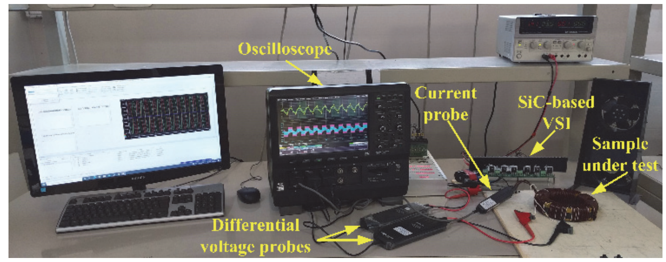


Fig. 2. Test rig for the iron loss measurements.

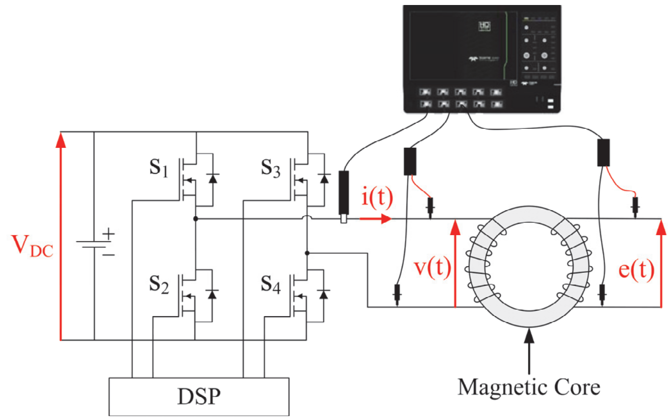


Fig. 3. Measurement layout setup.

TABLE III – TECHNICAL SPECIFICATIONS OF SIC POWER MOSFETS.

SCTW100N65G2AG	
Drain-source voltage	*650V*
Drain current (continuous) at TC = 25 °C	*100A*
Max. switching frequency (@40% I_{max})	*350kHz*
R_{dson}	*26 mΩ*

Unipolar sine-triangle PWM is used to avoid minor hysteresis loops and, consequently, further iron losses [9]. This produces voltage waveforms that are like those obtained with a three-phase inverter, with marginal differences in term of iron losses due to the different shift in the modulations of the converter legs (120 degrees, instead of 90 degrees of the H-bridge). The SiC H bridge receives via an optical fiber interface the PWM command signals generated by a DS1104 R&D controller board. Specifications of SiC devices are given in Table III, while a picture of the experimental test rig is shown in Fig. 2.

The waveforms of the primary current and the induced voltage in the sensing winding are acquired by an 8 channel, 12-bit resolution oscilloscope (LeCroy MDA810A) using 30A, 50MHz current probes (LeCroy CP030) and a 1kV, 120 MHz high voltage differential probe (LeCroy HVD3106), respectively. For an accurate computation of the active power, the sampling frequency was set to 50 MS/s and five 100 ms windows have been acquired, averaging the readings [12].

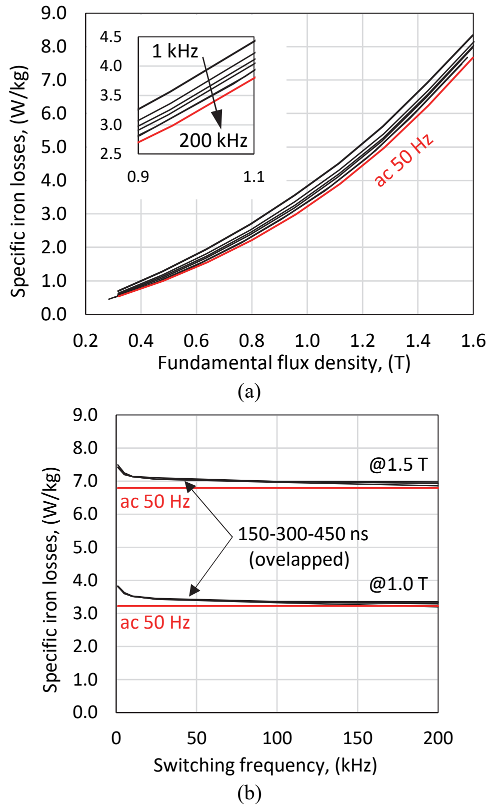


Fig. 4. The switching frequency impact on the iron losses for the FeSi core at 50 Hz: (a) deadtime = 150 ns; (b) 150, 300 and 450 ns.

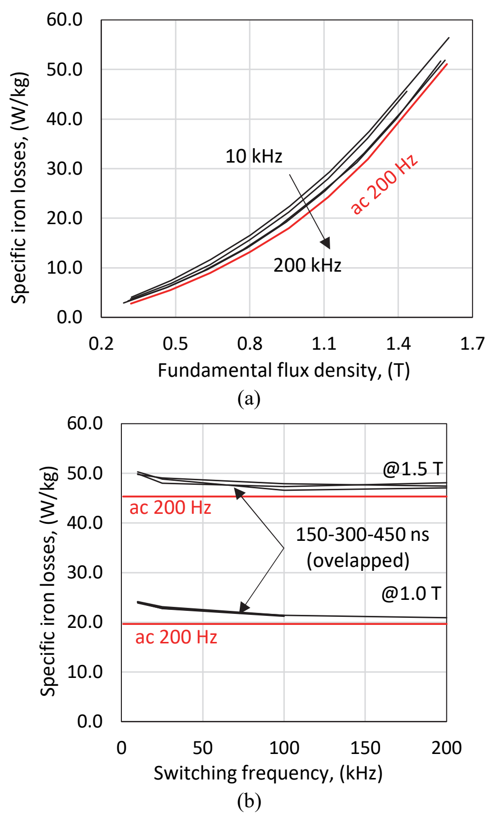


Fig. 5. The switching frequency impact on the iron losses for the FeSi core at 200 Hz: (a) deadtime = 150 ns; (b) 150, 300 and 450 ns.

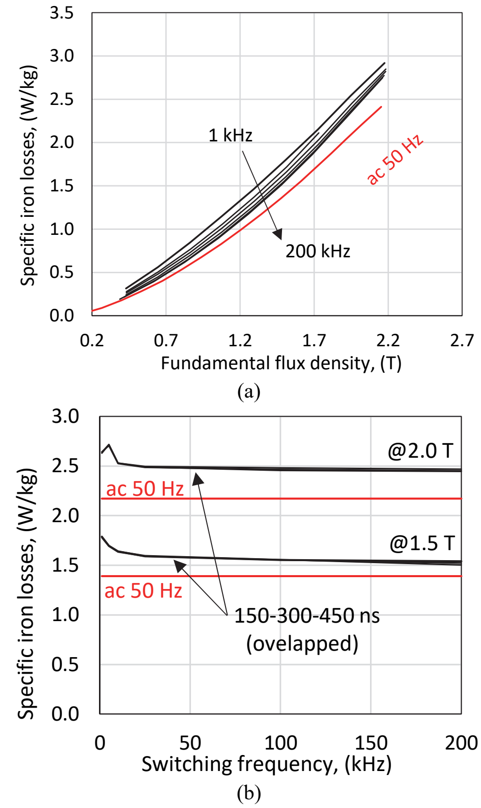


Fig. 6. The switching frequency impact on the iron losses for the FeCo core at 50 Hz: (a) deadtime = 150 ns; (b) 150, 300 and 450 ns.

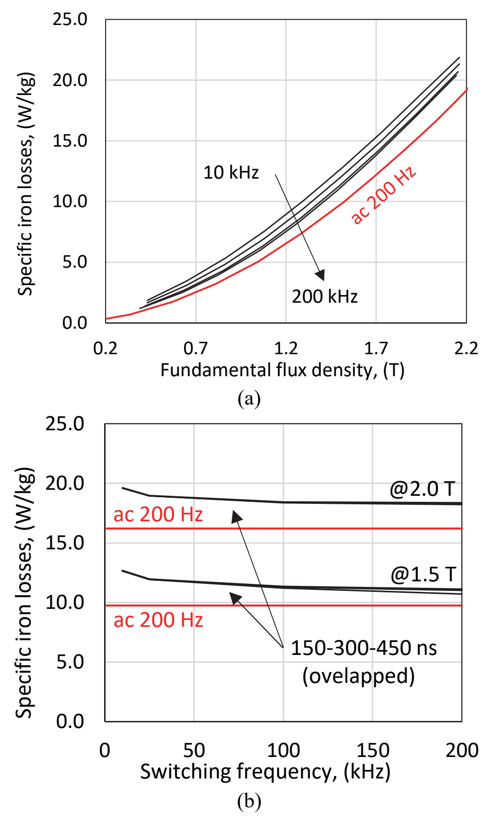
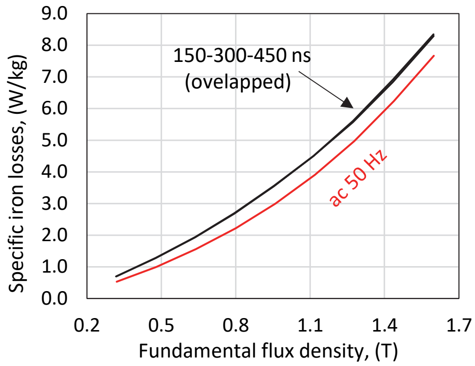
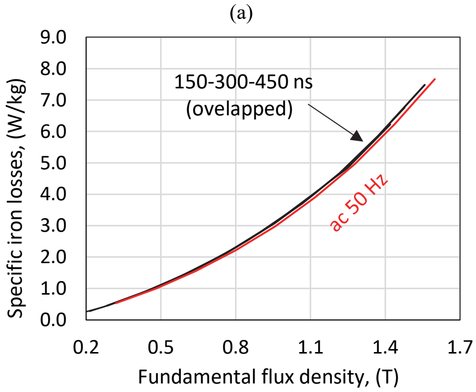


Fig. 7. The switching frequency impact on the iron losses for the FeCo core at 200 Hz: (a) deadtime = 150 ns; (b) 150, 300 and 450 ns.

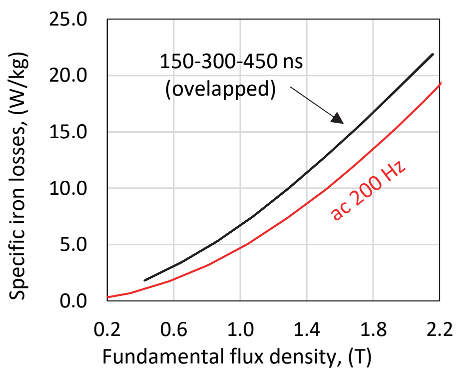


(a)

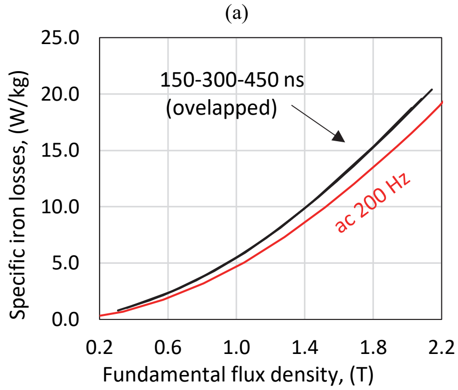


(b)

Fig. 8. Effects of 150 ns, 300 ns and 450 ns deadtimes on the iron losses of the FeSi for 1 kHz (a) and 200 kHz (b) switching frequencies for a fundamental frequency of 50 Hz.



(a)



(b)

Fig. 9. Effects of 150 ns, 300 ns and 450 ns deadtimes on the iron losses of the FeCo for 10 kHz (a) and 200 kHz (b) switching frequencies for a fundamental frequency of 200 Hz.

IV. Selected Measurements Results

For a fundamental frequency of 200 Hz, the lowest switching frequency used in the tests was limited to 10 kHz. Therefore, looking at the matrix shown in Fig. 1, four experimental test campaigns have been carried out:

- FeSi core tested at 50 Hz and B_{max} =1.6 T: deadtime = 150-300-450 ns, $f_{switching}$ = 1-200kHz – see Fig. 4;
- FeSi core tested at 200 Hz and B_{max} = 1.6 T: deadtime = 150-300-450 ns, $f_{switching}$ = 10-200kHz – see Fig. 5;
- FeCo core tested at 50 Hz and B_{max} = 2.2 T: deadtime =
- 150-300-450 ns, $f_{switching}$ = 1-200kHz – see Fig. 6;
- FeCo core tested at 200 Hz and B_{max} = 2.2 T: deadtime = 150-300-450 ns, $f_{switching}$ = 10-200 kHz – see Fig. 7.

Figures 4-7 shows in detail the impact of the switching frequency on the specific iron losses for the two considered cores. In particular, the iron losses monotonically decrease as the switching frequency increases. These results are in good agreement with those presented in literature [8], [9]. In the explored flux density range, for the FeSi core the iron losses for switching frequency exceeding 100 kHz have been found practically constant and slightly larger than the ac iron losses both at 50 Hz and 200 Hz – see Fig. 4 and Fig. 5. The same general conclusion can be drawn also for the cobalt-iron material, but with some differences. In fact, the '*distance*' between the trends under PWM supply remains quite '*far*' from the *ac* 50 Hz and 200 Hz curves, especially for high flux density values, as shown in Fig. 6 and Fig. 7.

As clearly proven by Fig. 8 and Fig. 9, the test results don't highlight any significant dependence of the specific losses with deadtime, since all the three black trends are perfectly overlapped. For switching frequencies greater than 100 kHz, this finding does not match with the findings of [10], although it must be stated that a different magnetic material, geometrical dimensions of the toroid, fundamental frequency and WBG technology were used.

V. Challenges in the Iron Loss predictions

Generally speaking, the prediction of iron losses under arbitrarily distorted waveform is a real challenge. In the past, a simple 'engineering' method was proposed and validated with the inverter technology available at the time and suitable for switching frequencies of 1 - 5 kHz and deadtime in the order of 10 microseconds, [11]. In the absence of minor hysteresis loops, the iron loss under PWM can be theoretically computed knowing the hysteresis losses $P_{hystesis_{sin}}$ and eddy current losses $P_{eddy\ current_{sin}}$ with sinusoidal supply at the same fundamental frequency by using (1), where ν is the Steinmetz coefficient of magnetic material and 'avg' indicates the average rectified value of the alternate voltage E induced in the secondary winding.

$$P_{iron_{PWM}} = \alpha^{\nu} P_{hystesis_{sin}} + \beta^2 P_{eddy\ current_{sin}}$$

$$\alpha = \frac{E_{avg,PWM}}{E_{avg,fundamental}} \qquad \beta = \frac{E_{rms,PWM}}{E_{rms,fundamental}} \qquad (1)$$

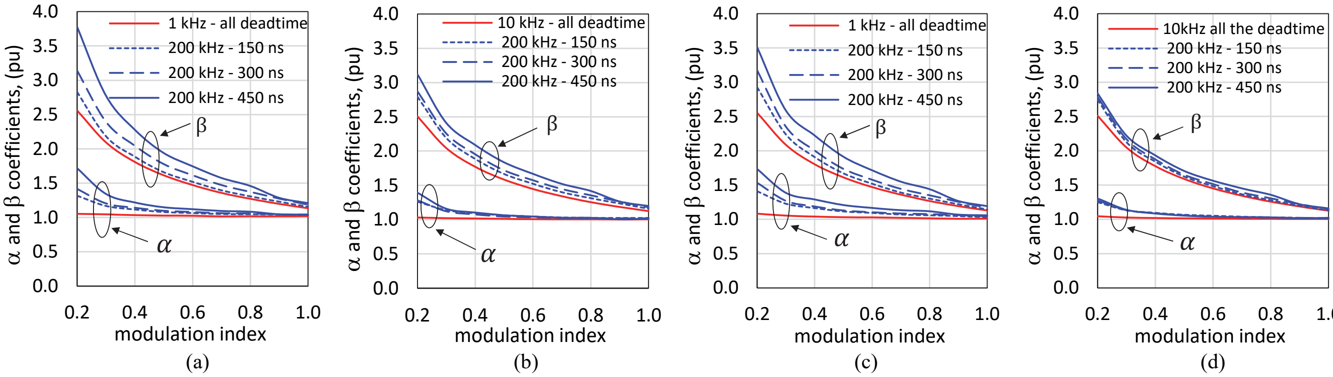


Fig. 10. PWM waveform coefficients for the FeSi material @ 50 Hz (a), FeSi material @ 200 Hz (b), FeCo material @ 50 Hz (c) and FeCo material @ 200 Hz (d).

TABLE IV – MATERIAL COEFFICIENTS FOR THE SINUSOIDAL LOSS MODEL (2)

Coefficient	*FeSi material*	*FeCo material*
k_h	0.0516	0.0115
v	1.716	1.451
k_{ec}	0.00026	0.000062

The coefficients α and β were introduced in [11] to keep into account the effects of distortion of the PWM waveform with respect to its fundamental component, in an 'equivalent' way. The specificity of the method (1) is that the iron losses under PWM supply can be estimated starting from '*simple*' measurements of the PWM voltage waveform characteristics and the knowledge of the losses in sinusoidal supply. The iron losses under sinusoidal supply must be separated in their basic Steinmetz's components in accordance to (2): the hysteresis losses and the '*global*' eddy currents (sum of the classical eddy current losses and of Bertotti's excess losses). Adopting the Steinmetz formulation and performing measurements at variable frequency and flux density levels, the hysteresis coefficients (k_h, v) and the eddy current coefficient (k_{ec}) can be easily determined, for example applying a least square fitting of the specific iron losses expressed in watt per kilogram [11], [13].

$$P_{iron_{sin}} = P_{hysteresis_{sin}} + P_{eddy\ current_{sin}}$$
$$P_{hysteresis_{sin}} = k_h \cdot f \cdot B^v; \quad P_{eddy\ curent_{sin}} = k_{ec} \cdot f^2 \cdot B^2 \qquad (2)$$

In the present study, the loss separation under sinusoidal supply has been done performing measurements in the range 20-100 Hz and 0.3-1.6 T for the FeSi toroidal core, while the cobalt-iron sample was tested at 50, 100 and 200 Hz and 0.4-2.3 T. The material coefficients are reported in Table IV.

The α and β coefficients to be used in (1) can be directly measured during the tests; these coefficients are reported in Fig. 10 for the four test campaigns previously listed. The red trends in this figure refer to the lowest switching frequency used in the tests and are practically identical to their theoretical values for a sine-triangle PWM voltage waveform. It is interesting to observe that the spread of the α and β values mainly depend on the fundamental frequency and only secondarily on the switching frequency.

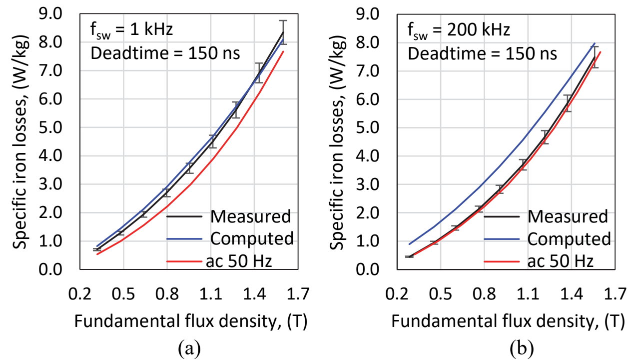


Fig. 11. Iron loss prediction for the FeSi core at the fundamental frequency of 50 Hz for switching frequencies of 1 kHz (a) and 200 kHz (b).

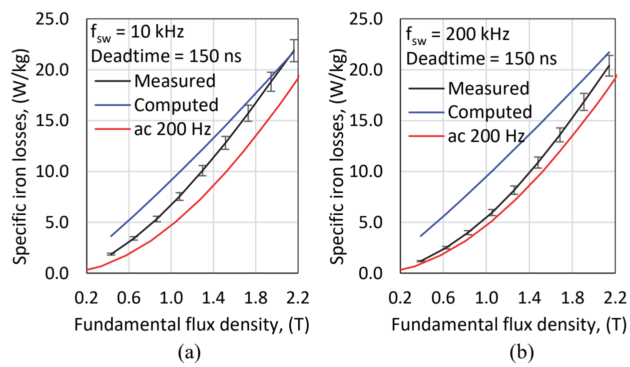


Fig. 12. Iron loss prediction for the FeCo core at the fundamental frequency of 200 Hz for switching frequencies of 10 kHz (a) and 200 kHz (b).

Additionally, the α and β coefficients also depend on the amplitude modulation index and on the deadtime. These coefficients have been used to predict iron losses under PWM supply by using (1). Due to space limitations and considering that the comparative results are similar for all fundamental/switching frequency combinations, only four plots of the computed iron losses are reported in the paper. Figure 11 and Fig.12 show what happens for the FeSi and FeCo cores for various values of the fundamental and switching frequencies. In these figures the errors bars are set at ±5%. Since $P_{hysteresis_{sin}}$ and $P_{eddy\ current_{sin}}$ are invariant with respect to the PWM characteristics, for a fixed fundamental flux density, it possible to conclude that (1) can be reasonably used only for switching frequency smaller than 5 kHz, approximately.

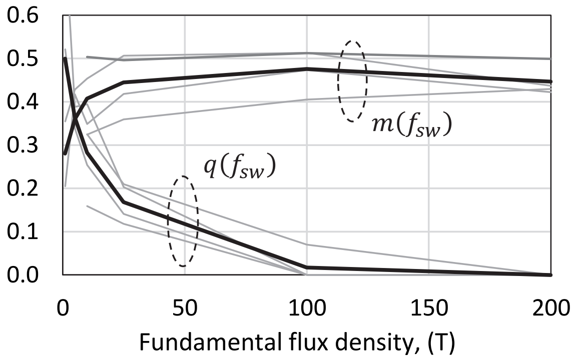


Fig. 13. The $m(f_{sw})$ and $q(f_{sw})$ parameters of model (4): the black trends are the averages of the gray ones.

A. Iron loss comupution under WBG inverter supply

It should be remarked that method (1) is theoretically correct as long as there are no minor loops in the hysteresis cycle and the impact of the skin effect in the magnetic laminations is reasonably negligible. However, the above results show that (1) is not suitable to predict the iron losses when a high switching frequency is used because α and β are greater than one and the specific iron losses decrease as the switching frequency increases. Nonetheless, by pursuing an engineering approach and being aware that the issue lies in the eddy current loss formulation at high frequency, the authors propose to adapt the previous model as shown in (3), where f_{sw} is the switching frequency and B_{fund} is the fundamental flux density in the core. Note that α is always very close to one, at high flux density values.

$$P_{iron_{PWM}} = \alpha^{\nu} P_{hystesis_{sin}} + \\ +k\left(f_{sw}, B_{fund}\right) \cdot \beta^2 P_{eddy\ current_{sin}} \tag{3}$$

To find the unknown coefficient $k\left(f_{sw}, B_{fund}\right)$, a least square fitting of (3) was applied to nullify the differences between estimates and measurements. This approach highlights, for each switching frequency, a linear trend of k with respect to the flux density. In other words, the authors propose the following equation for k, where the dependence with the switching frequency is confined only to the $m(f_{sw})$ and $q(f_{sw})$ parameters:

$$k\left(f_{sw}, B_{fund}\right) = m(f_{sw}) \cdot B_{fund} + q(f_{sw}) \tag{4}$$

Once again, the least squares fitting has been applied to the measured values, but this time considering the constraint (4). For all four test campaigns, the values of the $m(f_{sw})$ and $q(f_{sw})$ parameters are shown in Fig. 13 as gray curves, one for each material type and fundamental frequency value. In the same figure, the black continuous lines show the average trend of the parameters as a function of the switching frequency. For $f_{sw} = 200$ Hz an average m value equal to 0.45 has been determined.

The very interesting finding of the proposed modified model (3) is that, for switching frequency higher than 100 kHz, both m and q are practically constant.

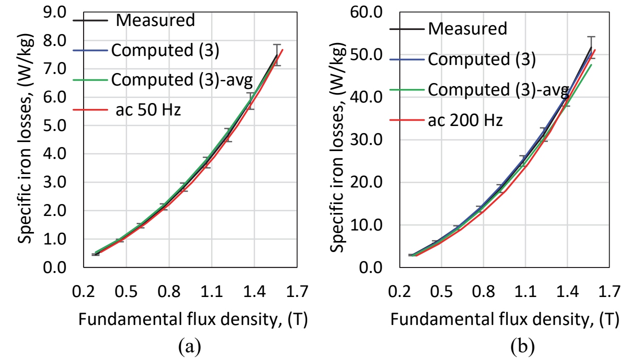


Fig. 14. Iron loss prediction for the FeSi core at the fundamental frequency of 50 Hz (a) and 200 Hz (b) for a switching frequency equal to 200 kHz.

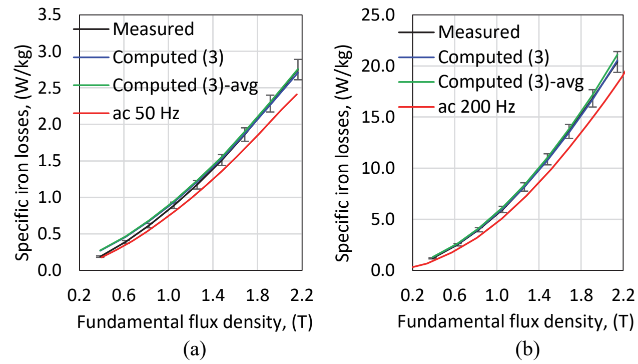


Fig. 15. Iron loss prediction for the FeCo core at the fundamental frequency of 50 Hz (a) and 200 Hz (b) for a switching frequency equal to 200 kHz.

In particular, $m(f_{sw}) \approx$ 0.4-0.5 and $q(f_{sw}) \approx$ 0, independently of the magnetic material grade and fundamental frequency.

Figure 14 and Fig. 15 show the results obtained by using (3) for the maximum switching frequency of 200 kHz for the four considered test campaigns, both considering the specific $m(f_{sw})$ and the $m_{avg} = 0.45$. In the figure legends, the latter approach is indicated as model '*(3)-avg*'.

Looking at the above two figures, it is evident that (4) achieves a perfect match between the measured and the computed specific iron losses: in fact, the black and blue curves are perfectly overlapped. This happens for all fundamental and switching frequencies considered in the tests. Furthermore, also the specific iron losses estimated using the '*average*' model provide very accurate results in the whole flux density range.

Even if m_{avg} depends on the switching frequency, the possibility of using a constant value for switching frequencies above 100 kHz is extremely intriguing considering that the tested magnetic core samples have very different characteristics in term of magnetic material quality, thickness, saturation level and so on. Unfortunately, this is not enough to generalize the finding for any type of magnetic lamination. Consequently, further investigations are ongoing to extend the presented analyses to higher fundamental and switching frequency values, also expanding the case series to other magnetic materials. The attention will be focused on laminations used to produce very high-speed motors, where the use of WBG-based PWM is more and more relevant to reach fundamental frequencies up to some kHz.

VI. Conclusion

The main aim of this study is to investigate the iron losses of laminated magnetic cores under WBG-based PWM supply. A low grade and a very performing magnetic material have been considered to give more generality to the study, as well as different values of the fundamental frequency The conducted experimental test campaigns confirm that the specific iron losses decrease with the increase of the switching frequency. However, contrary to other published findings, the authors didn't observe a significant impact of the deadtime on the iron losses, even if different WBG technology and maximum switching frequency have been used.

In the second part of the paper, a previously published engineering approach to predict the iron losses under PWM has been re-adapted accounting for the ultra-high switching frequency case. In particular, the skin effect impact on the eddy current loss contribution has been modeled by introducing a coefficient that is a linear function of the flux density, with a slope and *y*-intercept depending on the switching frequency only. The parameters of the linear trends have been determined by means of a least square fitting of the measured losses. For the considered SiC PWM inverter and magnetic materials, it was found that a constant value for the slope of the linear function can be used above 100 kHz switching frequency. However, the research is at an initial stage and the possibility to define some '*magic*' numbers to accurately predict the iron losses under ultra-high switching frequency is still under investigation.

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