About the Evolution of the Iron Losses: From Sinusoidal to PWM Inverter Supply

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***Abstract*— The aim of this work is to present the evolution of the specific iron losses concept, in light of the introduction of the power converted supply, introduced in the 80s and currently a standard in the electrical machines' supplies. This paper deals with the evolution for the iron losses. It is focused on the main differences introduced by the power converter on the magnetic and energetic quantities, with respect to the traditional sinusoidal sources and their effects on the soft magnetic material and the related iron losses.**

Keywords—iron losses, hysteresis and eddy current losses, inverter supply

I. Introduction

Starting from the first years of the 80s, the request of speed and torque control in AC motors has been the starting point of a revolution in the use of power static converters as AC motor power supply. These AC supplies, known with the name of inverter, produce a voltage waveform completely different from the classical sinusoidal one. As a consequence, the use of static converters leads to a loss increase, both in the windings and in the magnetic core of the AC motors. The electrical machines scientific community started with detailed research focused on understanding the increase of the losses and their link with the inverter typologies. In particular, due to the complexity of the iron losses in soft magnetic material, the researchers focused their interest on the iron loss increase due to inverter supply, for better understand what happen in the soft magnetic materials, normally used in AC motors, when the magnetic flux density is produced by the classical inverter voltages. The arising problem were a shock in the physicist scientific community used to consider sinusoidal flux density only. The first papers on that issue were published in the first years of 90s [1]-[5]. In these papers, in addition to the iron loss increase analysis, the determination the reference magnetic quantities to be used, with non-sinusoidal voltage supply, was discussed as well. In this paper, the evolution of these researches focused on the iron losses due to the inverter supply will be presented and the results will be summarized.

II. Magnetic Quantities

As it is well known, the International Standards define the specific iron losses referred to the peak of the sinusoidal flux density because the voltage supply and consequently the flux density are sinusoidal waveforms in the time. Moving to inverter supply or in general to non-sinusoidal supply, the right reference magnetic quantities must be chosen in order to allow a fair comparison of the iron losses with different type of voltage supply. Using a non-sinusoidal supply, it is possible to define several flux density values to relate the magnetic and energetic quantities (for example, magnetic losses). Two flux density values seem to be the most significant:

- B_x is the peak value of the flux density waveform (valid for alternating waveform only);
- B_{fund} is the peak value of the first harmonic flux density (known if the voltage fundamental harmonic of the supply source is measurable).

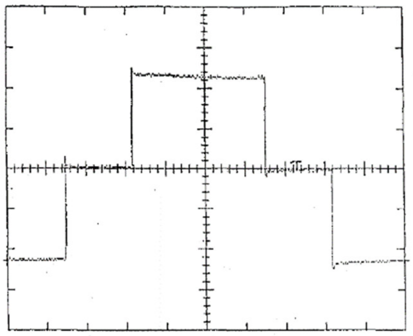
The two fluxes can be computed using the following equations:

$$B_x = \frac{1}{4}\cdot\frac{1}{N\cdot S}\int_0^T\left|v(t)\right|dt = \frac{1}{4}\cdot\frac{T}{N\cdot S}\cdot V_{ave} \qquad (1)$$

$$B_{fund} = \frac{V_{fund}}{4.44\cdot f\cdot N\cdot S} = \frac{V_{fund}\cdot T}{4.44\cdot N\cdot S} \qquad (2)$$

where V_{ave} is the average rectified value of the voltage source; V_{fund} is the fundamental harmonic RMS value of the voltage source; N is the number of turns; S is the cross-section of the magnetic circuit; T is the period of the voltage source waveform; f is the frequency of the voltage source waveform.

The voltage values in (1) and (2) can be measured using instrumentation suitable for measurements of distorted waveforms produced by static supplies. The modern power-meters or Transient Recorder and Data Acquisition System allow the measurement of these quantities in simple way and with a very high accuracy. With sinusoidal supply the two flux densities defined by (1) and (2) are identical, however using strongly distorted supply voltage the two quantities can have quite different values, preventing the correct comparison of the magnetic and energetic quantities such as the iron losses. The experimental results presented in [6] have shown that the two reference magnetic quantities lead to different values of the specific iron losses. Due to the presence of saturation phenomena, in all the practical applications concerning electromechanical devices, the peak value of the magnetic quantities is always utilized. Consequently, this value can be considered valid for inverter waveforms, too. The authors' opinion is that the fundamental flux peak density can be used as a reference magnetic quantity. In particular, this choice matches with the traditional choice made by electromagnetic and electromechanical designers who use the peak value of first harmonic flux density as main reference magnetic quantity during the design stage. It is interesting that this choice has been adopted by other researchers as well [7].



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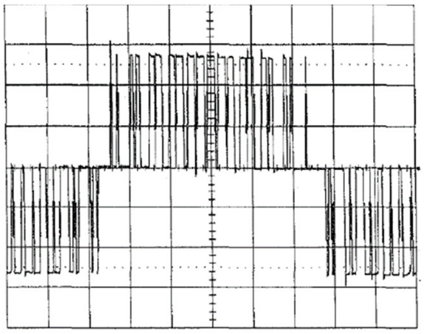


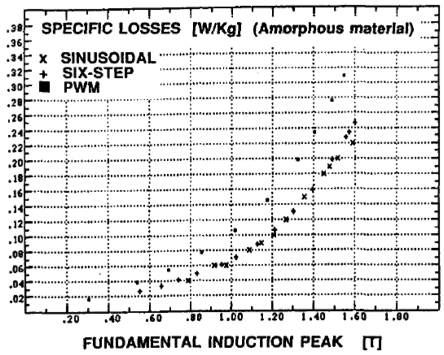
b)

Fig. 1. Voltage waveforms [6]: a) six-step, b) PWM.

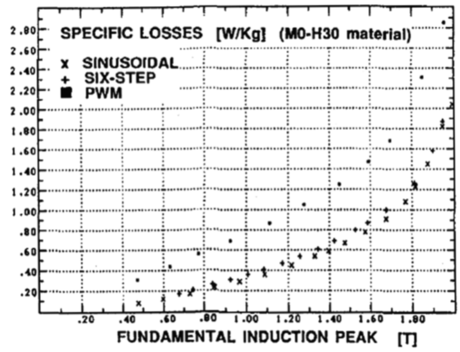
III. Inverter Typologies

Before talking about the iron losses with inverter supply, it is important to define the inverter typologies used to supply AC motors in electrical drives. From the historic point of view, the first inverter used in electrical drives was the square wave or six-step inverter. Fig. 1a shows the three phase line voltage produced by a six-step inverter. This inverter does not require high switching performances and the classical power BJT components could be used without critical problems. The harmonics components of the output line voltage are due to all the odd harmonics with the exception of the third harmonic and its odd multipliers (3, 9, 15, ...). The main drawback of the six-step inverter was the production of significant torque ripple, due to the presence of low order harmonics torque, not always acceptable by the mechanical load. Currently this inverter is still used when a very high output frequency is requested, or a very high output power is demanded. The evolution of the power electronic led to new power switches ever more performing in terms of voltage, current and switching frequency. Currently, modern power components based on IGBT, SiC, and GaN technologies can work with switching frequencies of tens and tens kHz. This evolution allowed the introduction of a new inverter typology based on the pulse width modulation or PWM inverter, solving the drawback of the six-step inverter. In fact, the PWM inverters harmonic content is only due to high frequency harmonics which are produced by the modulation technique. Fig. 1b shows the classical line voltage produced by a PWM supply.

Comparing six-step and PWM inverter, it is important to highlight the following points. A six-step inverter output waveform is completely defined by its voltage amplitude and fundamental output frequency. On the contrary, a PWM inverter output waveform depends on several parameters, such as the modulation waveform, the switching frequency f_s, the modulation index m, etc. For this reason, the influence of the PWM inverter parameters on the iron losses increment must be considered.



a)



b)

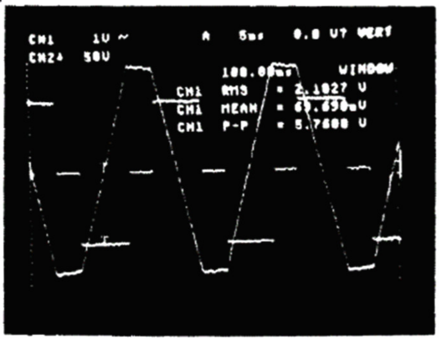
Fig. 2. Specific iron losses with sinusoidal, six-step and PWM supply [1]: a) amorphous material, b) high-quality grain-oriented material.

A proposal for defining a standard methodology for measuring iron losses with PWM supply was presented for the first time in [8] and [9].

IV. Experimental results

Based on the previous considerations, experimental results were obtained on wound toroidal cores realized with different magnetic material typologies. The first analysis was focused on a comparison of the specific iron losses with sinusoidal, six-step and PWM inverters. In Fig. 2, the results obtained on amorphous a) and grain-oriented magnetic materials b) are shown. The results put in evidence that the specific iron loss differences between sinusoidal and six-step supply can be considered negligible and consequently, the magnetic materials energetic behavior is not worsened by six-step inverter supply. In fact, despite the distorted voltage waveform, the flux inside the core does not present high harmonic contents, as shown in Fig. 3a. On the other contrary, the increase of the specific iron losses with PWM supply is well evident. With an increase of 42% in the amorphous material sample and about 100% in the grain-oriented steel one related to the sinusoidal supply. The PWM supply requires a detailed analysis to understand the reason for this increase. Fig. 3b shows the flux inside the core and the current with PWM supply. The flux is very similar to that with sinusoidal supply with a small ripple due to the modulation. On the other hand, the absorbed current is not sinusoidal, and several spikes are distributed all over the waveform.

In order to have a fair comparison, Fig. 3c shows the same quantities with a sinusoidal supply with the same magnetic stress conditions. The comparison between the two cases leads to conclude that the spikes are not linked to the core flux changes. In fact, similar, spikes are not present in the flux waveform. Therefore, the spikes can be due only to the eddy currents effects inside the magnetic material.



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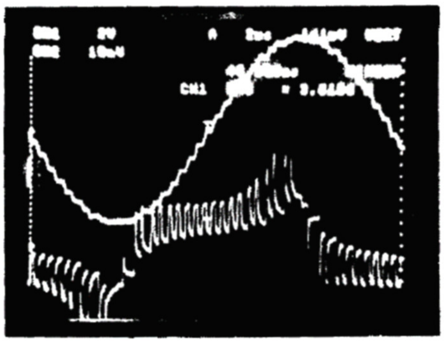

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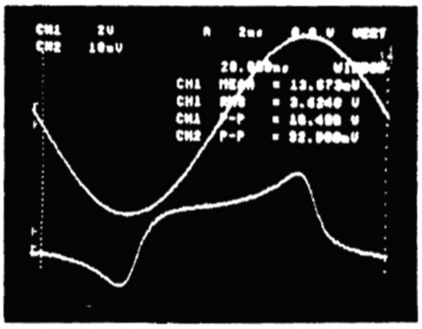

c)

Fig. 3. Core flux and voltage [1]: a) six-step supply, b) PWM supply, c) sinusoidal supply.

Furthermore, it is possible to conclude that the heavy iron loss increase in the case of PWM supply has to be attributed only to the eddy-current-loss increment inside the iron core. As a final remark, in order to confirm this statement, the iron-loss increase in the amorphous material core is reduced with respect to the iron loss increase in the high-quality grain-oriented steel. As previously discussed, the effects of the PWM inverter characteristics on the iron losses, have been subsequently analyzed. To corroborate the importance of the topic, parallel researches have been developed both in Europe and in USA as summarized in [11] leading to very similar results.

A. Modulation Index "m"

In a PWM inverter, the amplitude of the output voltage can be changed thank the variation of the modulation "*m*". The modulation index m is defined as the ratio between the amplitude of the modulating waveform and carrier waveforms. The variation of the modulation index allows to change the duty cycle of each pulse getting a modification of the amplitude of the output first harmonic voltage.

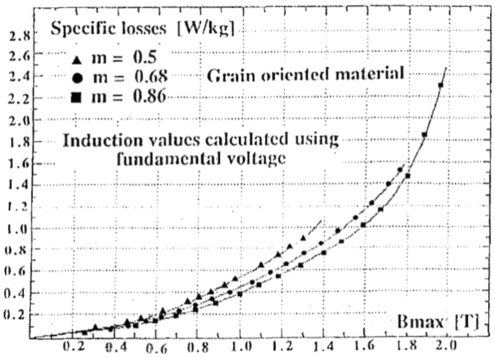

Fig. 4. Specific iron losses versus different modulation index "*m*" [10].

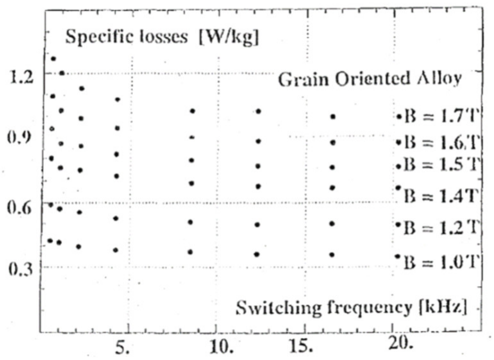

Fig. 5. Specific iron losses versus different switching frequency "f_s" [10].

For better understand how the modulation index works, a modulation index equal to zero produces output pulses with a duty cycle equal to 50% corresponding to an output voltage equal to zero, but at the same time since the output pulses are produced and they stress the load both from the electrical and magnetic point of view. As shown in Fig 4, the modulation index "m" influences in heavy way the specific losses [10]. A reduction of the modulation index corresponds to an increase of the specific iron losses. Since the iron losses will be dependent on the modulation index, lower iron losses can be obtained producing the same fundamental voltage with higher modulation index. This solution can be implemented in electrical drives for fluid processing as discussed in [12] where a detail description of the requested power converter is reported.

B. Switching Frequency "f_s"

Even if at first glance, the switching frequency might seem an inverter parameter that strongly influence the iron losses, the experimental results have shown that this is not true. As shown in Fig. 5, the switching frequency does not influence the iron losses (for the usual thickness of industrial iron sheets) if frequencies higher than 3-4 kHz are employed. Considering that nowadays the inverters have switching frequencies higher than 5 kHz, the iron losses can be considered invariant with the switching frequency [13].

C. Modulation Waveform

In order to increase the output first harmonics, PWM inverters use different modulation waveforms or different modulation techniques. With reference to analog modulation techniques, sinusoidal, sinusoidal plus third harmonic or plus triangular waveform, space-vector are the most used modulation waveforms.

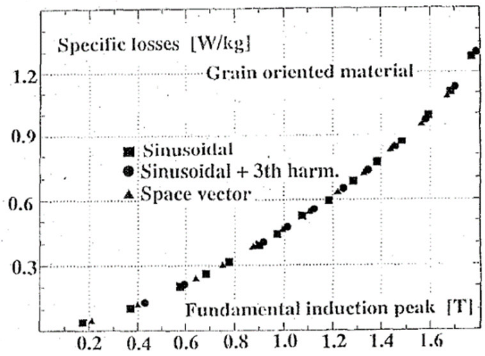

Fig. 6. Specific iron losses versus different modulating waveforms [9].

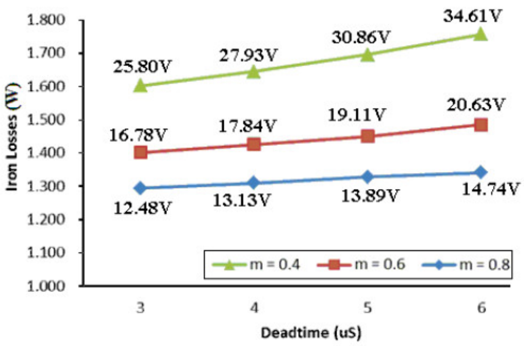

Fig. 7. Specific iron losses versus different dead-time [14].

In digital modulation techniques, the equivalent waveform can be led back to the same analogue waveforms. Experimental results show that modulation waveform does not influence the specific losses, as shown in Fig. 6. As a consequence, the modulation technique can be considered invariant with respect to the iron losses.

D. Dead-Time

To avoid the short circuit, across the DC bus of the inverter, a short delay called dead-time is introduced between the upper and lower switching signals of each leg. Therefore, both the switches of the inverter leg are off during the deadtime intervals. The influence of the dead-time on the iron losses, have been analyzed in more recent time in [14]. Fig. 7 shows that at constant modulation index the iron losses increases with the dead-time increase.

V. AC Motor Assessment

In the previous sections, the effects on magnetic materials due to inverter supply have been analyzed using toroidal samples. In order to verify the validity of the obtained results, the effects of inverter supply have been analyzed on induction motors as well [15]. It is well known that the measurements of the iron losses in induction motor requires an approach based on the balance of the loss contribution when the motor is working in no-load conditions as defined by equation (3) and used by the International Standards.

$$P_{no-load} = P_{iron} + P_{cu-sta} + P_{cu-rot} + P_{mech} \tag{3}$$

In (3), $P_{no\text{-}load}$ is the total no-load input power; P_{iron} are the iron losses; $P_{cu\text{-}sta}$ are the stator windings copper losses; $P_{cu\text{-}rot}$ are the rotor windings copper losses; P_{mech} are the mechanical losses.

In order to increase the accuracy in the determination of the iron losses a specific induction motor prototype has been realized. In particular, to overcome the problems related to mechanical and rotor copper losses the authors proposed an unconventional test bench, composed by a common induction motor stator with three phase windings and a slotless rotor instead of the standard one [16]. The used test bench is shown in Fig. 8.

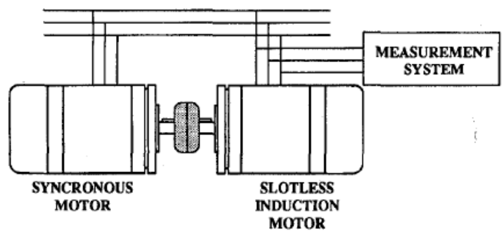

Fig. 8. Test bench for induction motor iron losses determination [16].

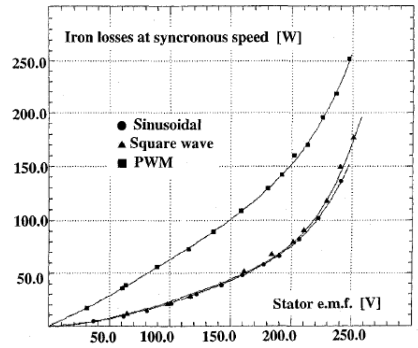

Fig. 9. Induction motor iron losses [16]: comparison with sinusoidal, six-step and PWM inverters.

The rotor was realized as a laminated cylinder composed of magnetic sheets taken out from the motor production line before the operation of rotor slots cutting. The obtained structure has the same outer diameter and is composed of the same material as that of a standard induction motor rotor. If such an experimental device is supplied, the rotor is not able to start and to rotate by itself, but it has to be put into rotation by connecting it mechanically to an external motor. In order to keep the rotor at the synchronous speed, a synchronous motor with the same poles pair of the test device stator windings was employed. If the two machines are supplied at the same frequency, both rotors are forced to rotate at synchronous speed; thus, a no-load test, at synchronous speed, can be performed. Using the proposed test bench, the mechanical losses and the Joule rotor losses are zero, and the iron losses item can be computed as:

$$P_{iron} = P_{no-load} - P_{cu-sta} \tag{4}$$

Tests with sinusoidal and inverter supply have been performed, following the same criteria used for the toroidal samples. The obtained results are shown in the following figures. Fig. 9 shows the comparison of the iron losses with sinusoidal, six-step and PWM inverter supply. Fig. 10 presents the variation of the iron losses depending on the modulation indexes. Fig. 11 shows the variation of the iron losses with the switching frequency, while Fig. 12 shows the variation of the iron losses depending on the modulation waveform.

The analysis of the results shown in the previous figures confirms the results obtained on the toroidal sample. In particular, the modulation index plays an important role on the motor iron losses.

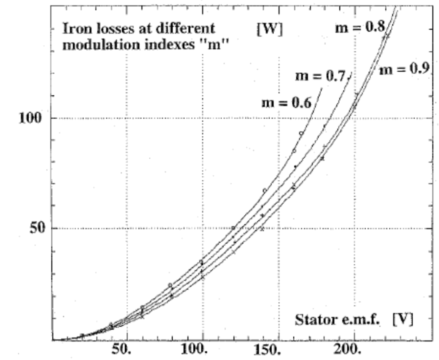

Fig. 10. Induction motor iron losses at different modulation indexes [15].

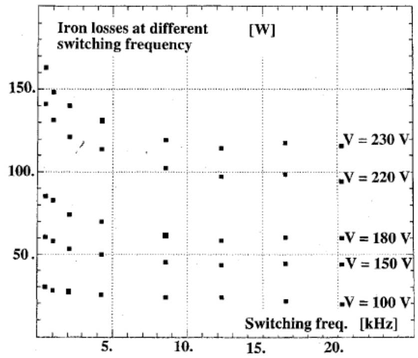

Fig. 11. Induction motor iron losses at different switching frequencies [15].

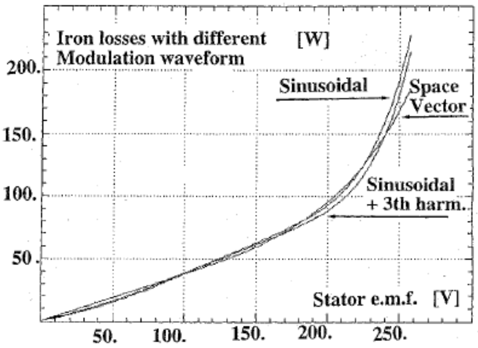

Fig. 12. Induction motor iron losses at different modulating waveforms [15].

As a consequence, in order to reduce the iron losses, it is better to operate with the highest allowed modulation index. In particular, for applications where the energetic performances are important in comparison with the dynamic ones, the use of inverters with fixed and high modulation index and variable DC bus voltage can be considered as a suitable solution [12]. The switching frequency is not so important from the iron losses point of view. In particular, with the switching frequency increase, a small reduction of the core losses can be obtained. The modulation function waveform is not an important factor in the increase in iron loss.

VI. Prediction of the Iron Losses with Inverter Supply

The analysis of the effects of the inverter supply on the iron losses is still a popular research topic, taking into account other phenomena such as the hysteresis minor loops that introduce an increase of the hysteresis losses. It is interesting to underline that the results confirmed those obtained in the previous decade [17]-[19]. In the 90s, the focus of the

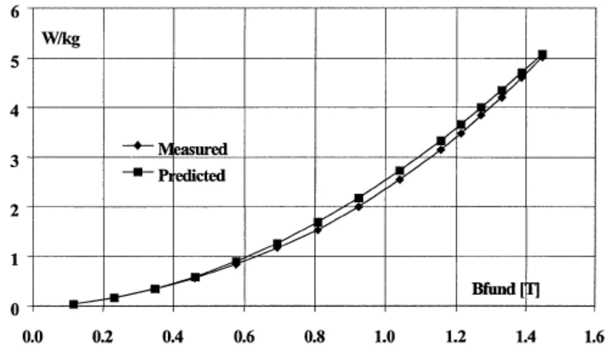

Fig. 13. Comparison between the measured and the predicted PWM losses for 5.7 W/kg 0.5 mm lamination.

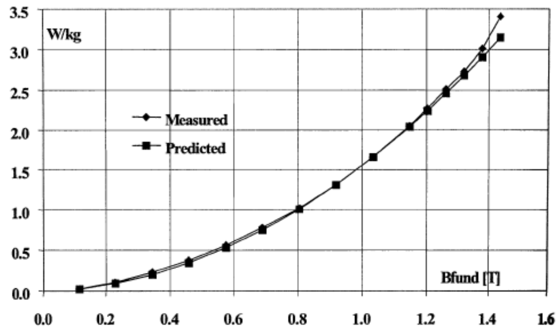

Fig. 14. Comparison between the measured and the predicted PWM losses for 2.7 W/kg 0.35 mm lamination.

researchers moved to the prediction of the iron with inverter supply [20]-[28]. The proposed approaches started from the iron loss model proposed by Bertotti in 1985 [29]. In [23] and [24], the authors proposed a method based on separating the iron losses in the hysteresis and the eddy currents contribution modified on the base of voltage distortion coefficients. An arbitrary alternate supply voltage can be characterized by means of the following two parameters:

$$\eta = \frac{V_{av}}{V_{av,fund}} \qquad (5)$$

$$\chi = \frac{V_{rms}}{V_{rms,fund}} \qquad (6)$$

where V_{av} is the mean value of the rectified voltage; $V_{av,fund}$ is the mean value of the rectified fundamental voltage; V_{rms} is the voltage RMS value; $V_{rms,fund}$ is the RMS value of the fundamental voltage. This way, the iron losses P_{ir} with an arbitrary waveform can be written as:

$$P_{ir} = \eta^{x} \cdot P_{h,sin} + \chi^{2} \cdot P_{ec,sin} \qquad (7)$$

where $P_{h,sin}$ and $P_{ec,sin}$ are the hysteresis and eddy-current losses with sinusoidal supply, respectively.

It is noted that (7) requires the separation of the iron losses into two contributions, hysteresis and eddy currents, which usually are not reported on the magnetic material data sheets. If the separation between hysteresis and eddy-current losses and the supply voltage characteristics are known, the iron losses with any kind of voltage supply can be predicted. As an example, Fig. 13 shows the comparison between the measured and the predicted iron losses when a PWM supply having a switching frequency of 1 kHz, a modulation index of 0.45 and a fundamental frequency of 50 Hz is applied on a laminated toroidal sample with 5.3 W/kg and a thickness of 0.5 mm. Conversely, Fig. 14 shows the comparison between the measured and the predicted iron losses when a PWM supply

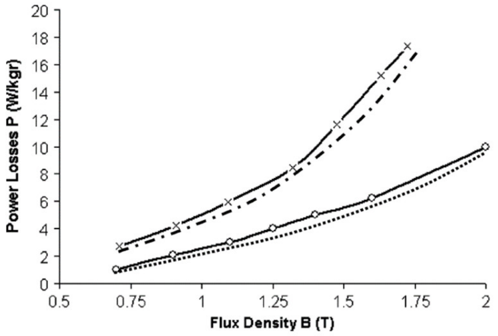

Fig. 15. Comparison of measured and simulated iron losses in non-oriented grain iron laminations of 0.5 mm width for a fundamental frequency of 50 Hz [3]: x------x measured under PWM excitation at switching frequency of 5 kHz, -.-.-.-.- simulated under PWM excitation at switching frequency of 5 kHz, o------o measured under sinusoidal excitation, -------- simulated under sinusoidal excitation.

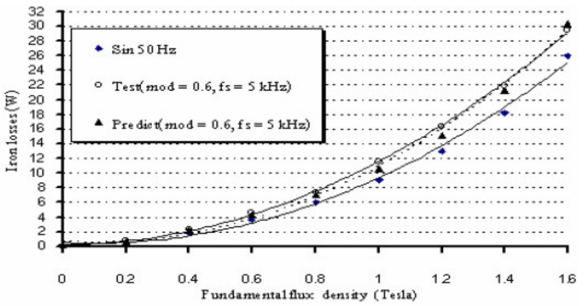

Fig. 16. Predicted and measured iron losses of a single-phase inductor with PWM inverter supply, fundamental frequency of 50 Hz, modulation index of 0.6, and switching frequency of 5 kHz [31].

having a switching frequency of 1 kHz, a modulation index of 0.45 and a fundamental frequency of 50 Hz is applied on a laminated toroidal sample with 2.7 W/kg and a thickness of 0.35 mm.

More recently novel approaches have been proposed with excellent result [30]-[33]. In Fig. 15, the simulated and measured iron losses with flux density for both sinusoidal and PWM excitation at fundamental frequency of 50 Hz and switching frequency of 5 kHz in non-oriented laminations of width 0.5 mm is presented [30]. Fig.16 shows the results on an inductor built with unknown magnetic material with lamination thickness equaling to 0.5 mm. The iron loss comparison has been done for modulation index m of 0.6 and switching frequency f_s of 5 kHz [31]. More recent research contributions investigating iron losses for higher switching frequencies are reported in the literature [34], providing results consistent with the new inverter technologies using wide bandgap devices (e.g., SiC, GaN). It should be considered that the ongoing increase in the switching frequencies will probably reduce the PWM losses even more, leading to overall iron losses very close to those obtained with a sinusoidal supply.

VII. Conclusion

In this paper an overview on the iron losses evolution has been based on a historical approach highlighting the first original contributions dated first years of the 90s. The question is: Is this topic still hot in the new millennium? The answer is yes, and the researchers are still focused on both the effects of the inverter supply and the prediction of the iron with the inverter supply. The overview on the iron loss concept has been presented taking into account their evolution starting from the classical sinusoidal waveform to the PWM inverter supply and it has put in evidence that the most modern results, obtained with modern instrumentation and approaches still confirm the oldest ones.

References

[1] A. Boglietti, P. Ferraris, M. Lazzari, F. Profumo, Iron losses in magnetic materials with six-step and PWM inverter supply (induction motors), IEEE Trans. on Magnetics, Year: 1991, Volume: 27, Issue: 6.

[2] M. Amar. R. Kaczmarek. F. Protat. "Magnetic Losses in PWM Voltage Excitation Schemes", Conf.Rec.- ICEM'94, September 1994, Paris (France), p.536-541.

[3] H.P. Nele, E. Nipp," if Contribution to the Calculation of Harmonic Iron Losses of Inverter Fed Induction Motors", Conf.Rec. ICEM'94, September 1994, Paris (France), pp.698-703.

[4] K. Damraz, F. Marthouret, J.P. Masson, "Iron Losses Prediction in Various Waveforms Excitations", Conf.Rec. ICEM'94, September 1994, Paris (France), pp.542-547.

[5] A. J. Moses and N. Tutkun, "Investigation of Power Loss in Wound Toroidal Cores under PWM Excitation," IEEE Trans. on Magnetics, vol. 33, no. 5, pp. 3763-3765, 1997.

[6] A. Boglietti, M. Lazzari, M. Pastorelli, "About the choice of the reference magnetic quantity in presence of non sinusoidal waveforms", IEEE Transactions on Magnetics, Year: 1997, Volume: 33, Issue: 5.

[7] O. Walti, J.P. Swan, " A Simplified Approach for Characterization of Soft Magnetic Material under PWM. Excitation" Con. Rec. ICEM96, Vol. 2, 10-12 Sept. 1996, Vigo (Spain), pp. 514- 517.

[8] A. Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "Iron loss measurements with inverter supply: a first discussion to define a standard methodology", IEEE Transactions on Magnetics, Year: 1995, Volume: 31, Issue: 6

[9] 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, Year: 1997, Volume: 33, Issue: 5.

[10] A. Boglietti, P. Ferraris, M. Lazzari, M. Pastorelli, "Influence of modulation techniques on iron losses with single phase DC/AC converters", IEEE Transactions on Magnetics, Year: 1996, Volume: 32, Issue: 5.

[11] A. Boglietti, A. Cavagnino, T.L. Mthombeni, P. Pillay, "Comparison of lamination iron losses supplied by PWM voltages: US and European experiences", IEEE International Conference on Electric Machines and Drives, 2005, Year: 2005

[12] A. Boglietti, A. Cavagnino, M. Lazzari, M. Pastorelli, "Electrical drives to increase the fluid processing efficiency", Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting, Year: 2001.

[13] A. 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, Year: 1995, Volume: 31, Issue: 6.

[14] S. M. Dehghan, K. Fujisaki, "Impact of dead-time on iron losses in inverter-fed magnetic materials", IEEE Energy Conversion Congress and Exposition, Denver, 15-19 September 2013.

[15] 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, Year: 1996, Volume: 32, Issue: 5.

[16] A. Boglietti, P. Ferraris, M. Lazzari, "Induction motor iron losses measurement with a static converter supply using a slotless rotor test bench", IEEE Transactions on Magnetics, Year: 1994, Volume: 30, Issue: 6.

[17] Zhi-Cheng Sun, Jian-Xin Shen, Meng-Jia Jin, He Hao, "Research of the Influence of Different PWM Inverters on the Iron Losses for Induction Motors", 7th International Conference on Electrical Machines and Systems (ICEMS), October. 22-25, 2014, Hangzhou, China.

[18] M. Oka, H. Kiyotake, M. Enokizono, and D. Wakabayashi, "Iron Loss Measurements under PWM Excitation for Ring Cores Made of Ultrathin Electrical Steel Sheets for a Stator Core",International Conference on Electrical Machines (ICEM) 2020, 23rd-26th August 2020, Gothenburg Sweden.

[19] T. Shimizu1, K. Kakazu1, K. Takano, H. Ishii, "Loss evaluation of AC filter inductor core on a PWM Converter", 8th International

Conference on Power Electronics - ECCE Asia May 30-June 3, 2011, The Shilla Jeju, Korea.

[20] F. Fiorillo, A. Novikov, "An Improved Approach to Power Losses in Magnetic Laminations under Nonsinusoidal Waveform', IEEF Transactions on Magnetics, Vol 26, N05, Sept. 1990, pag. 621.

[21] R. Kaczmarek, M. Amar, and F. Protat, “Prediction of power losses in silicon iron sheets under PWM, voltage supply,” J. Magn. Magn. Mater., vol. 133, pp. 140–143, 1995.

[22] R. Kaczmarek, M. Amar, and F. Protat, “A general formula for prediction of iron losses under nonsinusoidal supply voltage waveform,” IEEE Trans. Magn., vol. 31, pp. 2505–2509, Sept. 1995.

[23] A. Boglietti, M. Lazzari, M. Pastorelli, “Iron losses prediction with PWM inverter supply using steel producer data sheets”, IAS '97. Conference Record of the 1997 IEEE Industry Applications Conference Thirty-Second IAS Annual Meeting, Year: 1997.

[24] A. Boglietti, A. Cavagnino, M. Lazzari, M. Pastorelli, “Predicting iron losses in soft magnetic materials with arbitrary voltage supply: an engineering approach”, IEEE Transactions on [21] Magnetics, Year: 2003, Volume: 39, Issue: 2.

[25] A. Cavagnino, A. Boglietti, “Iron Loss Prediction with PWM Supply: An Overview of Proposed Methods from an Engineering Application Point of View”, 2007 IEEE Industry Applications Annual Meeting, Year: 2007.

[26] Zbigniew Gmyrek, Aldo Boglietti, Andrea Cavagnino,“Iron Loss Prediction With PWM Supply Using Low- and High-Frequency Measurements: Analysis and Results Comparison”, IEEE Transactions on Industrial Electronics, Year: 2008, Volume: 55, Issue: 4.

[27] M. Kawabe, T. Nomiyama, A. Shiozaki, H. Kaihara, N. Takahashi, M. Nakano, “Behavior of Minor Loop and Iron Loss Under Constant Voltage Type PWM Inverter Excitation”, IEEE Transactions on Magnetics, Year: 2012, Volume: 48, Issue: 11.

[28] Hiroaki Matsumori, Toshihisa Shimizu, Takashi Kosaka, Nobuyuki Matsui, “Iron loss calculation under PWM inverter switching for SiFe steel materials”, 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Year: 2019.

[29] G. Bertotti, “Physical interpretation of eddy current losses in ferromagnetic materials. I. Theoretical considerations,” J. Appl. Phys., vol. 57, pp.110–2117, Mar. 1985.

[30] C. Patsios, E. Tsampouris, Minos. Beniakar, P. Rovolis, A. G. Kladas, “Dynamic Finite Element Hysteresis Model for Iron Loss Calculation in Non-Oriented Grain Iron Laminations Under PWM Excitation”, IEEE Transactions on Magnetics, Year: 2011,Volume: 47, Issue: 5.

[31] Siriwich Tadsuan, Chanwit Tangsiriworakul, “Design and comparison of iron losses mathematical model with single phase and three phase PWM inverter supply”, 2008 IEEE International Conference on Industrial Technology, Year: 2008.

[32] D. Cittanti *et al.*, "PWM-Induced Losses in Electrical Machines: An Impedance-Based Estimation Method," 2021 24th International Conference on Electrical Machines and Systems (ICEMS), Gyeongju, Korea, Republic of, 2021, pp. 548-553.

[33] S. Rubino et al., "Impedance-Based Estimation Method of PWM-Induced Losses for Traction Motors," 2023 IEEE International Electric Machines & Drives Conference (IEMDC), San Francisco, CA, USA, 2023, pp. 1-6.

[34] I. Sirotić, M. Kovačić and S. Stipetić, "Methodology and Measurement Setup for Determining PWM Contribution to Iron Loss in Laminated Ferromagnetic Materials," in *IEEE Transactions on Industry Applications*, vol. 57, no. 5, pp. 4796-4804, Sept.-Oct. 2021.

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