Current Measurement Issues of a High Frequency GaN Inverter in the MHz Order for Magnetic Characterization

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Abstract— Nowadays, there is a great interest in the industry for outstanding magnetic materials with low-loss properties. Moreover, with the introduction of novel Wide Bandgap devices, higher frequency operation has been demanded from these novel magnetic materials. Thereby, magnetic characterization for obtaining the iron loss behavior is essential. However, when a magnetic material is experimentally characterized, it is important to select a suitable measurement device, especially when a semiconductor inverter is powering the magnetic material and it is driven at a high switching frequency. Usually measurement devices have a good response in magnitude, but there is not a clear understanding about how their phase response at high frequencies measurements affects the characterization. Consequently, if the phase characteristics of a measurement device is not well-known, it is likely that the iron loss characterization will not be accurate. This paper studies the measurement issues when an iron loss characterization procedure is conducted. This study is carried out with the comparison of using clamp type current probes and high precision shunt resistors at high switching frequency excitations with a GANFET inverter. In addition, an experimental evaluation of iron losses at several switching frequencies is presented. As a result, the phase characteristics of several sensors was obtained, and it was possible to identify the inaccuracies that they can generate at a high frequency measurement.

Keywords—High Frequency, Gallium Nitride, Current, Measurements, Phase, Error. Sensor, Magnetics

I. INTRODUCTION

Conventionally, sinusoidal excitation has been used to evaluate magnetic properties of magnetic materials. However, with the introduction of new semiconductor materials such as gallium nitride and silicon carbide, power electronics systems have been able to be driven at higher switching frequencies without compromising the system efficiency [1].

Due to these recent advances in power electronics, it is common to drive magnetic materials in electrical motors at variable speed, inductors, reactors and transformers by high frequency excitation usually with a PWM power converter.

These converters are operated at high switching frequencies (tens and hundreds of kHz, and even several MHz) [2], [3].

Nevertheless, this high frequency operation carries complex flux-density waveforms with high-frequency components, and thereby power losses increase. In response to these high frequency demands from the power electronics applications, novel magnetic materials with low-loss performance were introduced: such as nanocrystalline and amorphous alloys, and soft magnetic composites [4]–[6]. However, these novel magnetic materials are still quite expensive in comparison to the total cost of the power electronics circuit. For instance, in most of the application, magnetic components are the biggest contributors to the volume, mass and cost of power electronics converters [7].

In this context, electrical steel laminations still provide the most cost-efficient solution for transformers, reactors, and some electrical machines [8], [9]. Consequently, accurate iron-loss characterization is required for the understanding of the loss profile of these materials at high frequency ranges.

When the magnetic characteristics of a certain material are evaluated by PWM converter excitation, the high frequency harmonics, induced by the switching properties of the converter, greatly affects the iron loss characteristics [10]–[12]. In addition, when a magnetic properties characterization procedure of a magnetic material under high frequency excitation (hundreds or thousands of kHz) is conducted, the measurement technique as well as the measurement devices become decisive to obtain an accurate measurement [13], [14].

Usually, at low switching frequencies (tens of kHz), several voltage and current measurement methods can be used. However, when the switching frequency is increased (hundreds of kHz or several MHz), several measurement methods present different phase characteristics that bring issues to the measurements and therefore to the loss characterization.

Consequently, this research proposes the evaluation of current sensors in terms of their phase characteristics for high frequency characterization of electrical steel sheets. This procedure is conducted with the comparison of wide bandwidth current probes (clamp type) and high precision shunt

resistances in order to achieve an accurate magnetic characterization.

This paper is divided as follows, first the iron loss model and the measurement procedure used to characterize the loss properties of the selected material is presented; then several current sensors are presented and characterized; after that, the issues of phase difference introduced by the measurements and its effects on the iron loss characterization are presented; finally the iron loss calculation of the presented sensors is presented.

II. METHOD

Generally speaking, in order to evaluate magnetic properties of a certain material, a ring laminated-core reactor with primary and secondary windings is used as the device under characterization[15]. The measurement setup is described in detail in [16]. The primary is supplied by a full-bridge GaNFET inverter. Specifications of the ring and the GaN inverter are given in Table I. The schematic of the measurement circuit is presented in Fig. 1. Pictures of the GaN inverter and the ring setup are shown in Fig. 2 and 3, respectively. The ring under characterization is constructed with 20 sheets of 350 μ m width each.

TABLE I.
SPECIFICATIONS

Ring (30H300)		GaN Inverter	
Outside diameter d_o [mm]	127	Deadtime T_d [ns]	40
Inside diameter d_i [mm]	102	DC voltage V_{dc} [V]	14.5
Height h [mm]	7	Modulation index m	0.5
Number of turns of the primary coil N_1	251	Fundamental frequency f_o [Hz]	50
Number of turns of the secondary coil N_2	251	Switching frequency f_{sw} [kHz]	5-1500

Fig. 1. Measurement circuit

Fig. 2. Inverter Setup

Fig. 3. Ring Setup

This ring is experimentally tested at different switching frequencies. During these tests, currents and voltages are measured and post-analyzed in order to find the BH curves. BH curves, composed of the magnetic flux density B and the magnetic field intensity H characteristics, are used in the evaluation to calculate the iron loss density of the material. As it is well known, the magnetic flux density B is obtained from the time integration of the induced voltage in the ring, and the magnetic field intensity H from the current that flows in the ring

Voltage in the secondary windings and current through the first windings are determined with an Oscilloscope capable of measuring with a maximum sampling frequency of 2.5 GS/s real time. With this scope, the primary-coil current is measured through a current probe (Hall effect-clamp type) and a shunt resistor (either BNC or SMD type). This probe has a wide bandwidth from DC to 100 MHz and is capable of measuring a maximum current of 30 A. In addition, high precision shunt resistors are used to measure the primary-coil current with the purpose of comparing both current sensors. The voltage of the secondary coil is measured with a differential voltage probe.

It is important to mention that a "deskewing" procedure (synchronization) of the current and voltage probes used in this study is performed before each measurement.

III. IRON LOSS MODEL

After the measurements are taken, the post-processing analysis of the data is conducted. Therefore, the magnetic field strength H_s on the surface of the iron core is calculated from the measured primary winding current i as follows:

$$H_s(t) = \frac{N_1}{l_{Fe}} i(t) \quad (1)$$

where N_1 is the number of turns of the primary winding and l_{Fe} is the magnetic length path (360 mm). Moreover, the average magnetic flux density in the core is obtained by integrating the back-electromotive force v_2 induced in the secondary winding with N_2 turns as follows:

$$B_0(t) = \frac{1}{N_2 A_{Fe}} \int v_2(t) dt \quad (2)$$

where A_{Fe} is the cross-sectional area of the laminated core (83125 mm²). The core loss density per mass unit can be obtained from different ways. In [16]–[18] the measured dynamic loop $B_0(H_s)$ during one period of the fundamental frequency f is obtained as:

$$W_{tot} = \frac{f}{\rho} \int_0^{1/f} H_s(t) \frac{dB_0(t)}{dt} dt \quad (3)$$

Nevertheless, the measured dynamic loop $B_0(H_s)$ of (3) and presented in [16]–[18] tends to suffer from numerical inaccuracies if the integration in (2) and differentiation in (3) are not consistent with each other. For instance, the results presented in [16]–[18] show a considerable variation of the calculated core losses using (3).

Having in mind the significant variation in the losses calculated with (3) and the inconsistency between each frequency, [19] proposed the use of (4) in order to avoid these variations and inconsistencies.

$$W_{tot} = \frac{N_1 f}{N_2 A_{Fe} l_{Fe} \rho} \int_0^{1/f} i(t) v_2(t) dt \quad (4)$$

where ρ is the mass density (7650 kg/m³).

In this context, although (3) and (4) are theoretically equivalent, when the losses are calculated with (4), a smaller variation is found. When both kind sensors are evaluated in the latter sections, the losses calculated with (4) are used.

The core losses in the inductor were measured at a fundamental frequency of $f = 50$ Hz and switching frequencies

ranging from $f_s = 5$ to 1500 kHz. A modulation index $m = 0.5$ was used and the DC-link voltage V_{dc} was adjusted to obtain a magnetic flux-density amplitude of 1 T in all the measurements. Depending on the switching frequency, the DC-link voltages varied around 14–20 V. For each switching frequency and each current sensor (clamp or shunt), 10 separate measurements were taken for redundancy purposes.

IV. CURRENT SENSORS

A. Current Clamp

Usually current clamps with hall-effect sensors are robust and with decent bandwidth. They have been used in several power electronics applications. However, although their magnitude characteristics are enough for high frequency measurements, their phase characteristics are usually unknown. Therefore, magnetic characterization and high frequency measurements carry a certain level of uncertainty.

In the case of this study, the selected hall-effect clamp-type probe has a wide bandwidth from DC to 100 MHz and is capable of measuring a maximum current of 30 Arms. As the iron loss characterization procedure is estimated up to 1.5 MHz of switching frequency, the bandwidth of the current clamp is enough. Nevertheless, when the phase characteristics are considered, the bandwidth is much different. Fig. 4(a) shows a sketch of the phase characteristics in terms of the switching frequency.

Here, it is important to point out that characterizing current clamps is a complex procedure that it is difficult to conduct. Although the phase difference presented in these probes is not that high, as shown in Fig. 4(a), it is considerable for high frequency measurements, especially in the MHz order. Being the most radical point here, the uncertainty of knowing exactly the phase characteristics of these sensors.

B. BNC -Shunt Resistor

On the other hand, high precision shunt resistors, usually much cheaper than complex current clamps, offer the interesting possibility to be capable of being use in characterization procedures.

In this case, the selected shunt resistors are high accuracy shunts with a bandwidth up to 2 GHz, a maximum rise-time of 30ns and a maximum power of 3W. Nevertheless, although the magnitude characteristics of these shunts are relatively good until certain hundreds of kHz, the phase characteristics are quite deficient at high frequencies. Fig. 4(b) shows the phase characteristics of two shunt resistors with difference resistances.

Fig 4(b) was obtained with a high precision impedance analyzer using its function of frequency sweep. Here, it is evident the phase difference between the current clamp and the shunts. However, shunt resistances are easy to characterize using a good impedance analyzer, and hall-effect current clamps are much more difficult to characterize. Consequently, designing and implementing an additional phase compensator circuits for correction of the measurements can be relatively easy when the phase characteristics are well known.

C. SMD -Shunt Resistor

For comparison purposes, and as BNC resistors tend to be much more expensive than regular SMD resistors, high precision SMD resistors were chosen as well for this comparison.

Fig 4(c) shows the phase characteristics of the selected resistor. It is possible to see that the resistance of the selected SMD resistor is higher than the BNC types. However, the phase characteristics were relatively better than the ones presented in Fig. 4(b), although the magnitude characteristics are compromised as the bandwidth of these resistors is not as high as the ones presented before.

Nevertheless, if the magnitude and phase characteristics are well known a measurement procedure can be conducted with a good accuracy adding the respectively corrections.

(a) Current Probe

(b) Shunt Resistance – BNC type

(c) Shunt Resistance – SMD type

Fig. 4. Phase Characteristics of several sensors

V. MEASUREMENT ISSUES

From the results presented before, and the previous experiences presented in [16]–[19], some conclusions can be already presented.

High frequency characterization presents several challenges when the MHz order is achieved. Every component in the circuit and specially the measurement devices are phase-error sources.

As it was presented in [18], sampling frequency of the scope/measuring device as well as its sampling rate are also an error source as the BH loops cannot be constructed properly and thereby the iron loss calculation is not accurate.

Parasitic components in the voltage measurements are also an error-source as current flow generates voltage drops and thereby measurements are affected. Therefore, always Bcoils are recommended in order to avoid these issues. Moreover, parasitic components in the measurement devices themselves should be properly characterized for a post-processing correction.

Regarding the phase mismatch or discrepancy Δd , defined as phase angle difference between the measured and the real waveform. Therefore, there is a capacitive or inductive effect in the measurement with a lagging or leading effect. This effect tends to increase when the switching frequency increases as Fig 4 shows. Fig 5 shows a representation of the effect of this phase difference when the switching frequency increases.

Fig. 5. Phase difference between measurements in frequency domain

This difference is usually generated by the parasitics inside the sensors, mismatch between probes, and scope's sampling resolution [20]

VI. EXPERIMENTAL RESULTS

Fig. 6 shows the iron losses when the current probe and the shunt resistance are used, in the case of the experimental circuit presented in Fig. 1. Fig. 6 also presents the conventional iron loss case of sinusoidal 50Hz excitation.

For the case of the sinusoidal excitation, a linear amplifier was used. In fact, the iron loss value obtained by this procedure at 50 Hz is quite close to the one presented by Nippon Steel & Sumitomo Metal Corporation in the datasheet of the selected material [15].

Fig. 6. Iron Losses (Current Probe Clamp Type vs. Shunt Resistance)

The iron losses measured and calculated from the method presented in this paper are aligned with the ones presented in [19] and [21]. Where it is stated that iron losses tend to increase at not a fast rate at high frequency ranges. This is possible despite the fact that the higher the switching frequency of the inverter, the closer the inverter output current signal to a sinusoidal signal. The model presented in [19] offers a better understanding of this phenomenon.

Moreover, it is interesting how close the measurements of the fundamental frequency with both sensors are. This proves that both techniques are good for really low frequency applications.

Nevertheless, when both sensors are evaluated at high frequency orders, the difference tends to increase with the frequency increment. Here, it is possible to see the effect of the phase-error that is injected by the sensor.

Still the clamp sensor offers a better solution, but unfortunately, it is difficult to find the real reference to evaluate the sensors when the phase characteristics are unknown. On the other hand, with a simple sweep of a shunt resistor is possible to implement a phase compensator and obtain a reference for the measurement.

CONCLUSION

In this paper, the influence and issues of the current sensor on the magnetic characterization of an electrical steel core was explored. This study was conducted through the variation of switching frequency and several sensors on the iron loss characteristics of a ring excited with a GaN FET inverter and operated at high frequency switching.

It was found that a suitable measurement equipment is important when a high frequency procedure is conducted. Specifically, the A/D converter must have a high sampling frequency and the voltage and current detectors must have a wide bandwidth response with good magnitude and phase characteristics.

Especially, the performance of current clamps and shunt resistors was compared. Both type of sensors are phase-error sources that affect the measurements and therefore the magnetic characterization.

Shunt resistances are easy to characterize using a good impedance analyzer, and hall-effect current clamps are much more difficult to characterize. Consequently, designing and implementing an additional phase compensator circuits for correction of the measurements can be relatively easy when the phase characteristics are well known.

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