Impact of aluminum casing on high-frequency transformer leakage inductance and AC resistance

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Keywords

«High frequency power converter», «Transformer», «Parasitic inductance », « Eddy current loss », «Finite element analysis»

Abstract

High-Frequency (HF) transformer is a central part of isolated HF power converters. Its parameters, in particular leakage inductance and losses, have a significant impact on the overall converter performances. With the increase of switching frequencies linked to the use of SiC and GaN based active devices, the control of the HF transformer parameters becomes essential. A HF transformer is usually designed without considering its surrounding. However, the latter can have a significant impact on the transformer's performance. In this paper, the effect of an aluminum casing surrounding the transformer is studied and quantified for two parameters: The transformer leakage inductance and the supplementary losses. The goal is to consider the casing effect in the early design stage of power converters.

Introduction

High-power density converters are a global trend in power electronics [1], [2]. Compact and more efficient converters are needed for embedded power electronics in many applications like automotive or avionics for example. In these applications, volume and weight constraints are essential. To reduce the volume and weight of power converters, increasing switching frequencies is necessary. With the emergence of wide band gap semiconductors like SiC and GaN, reaching frequencies up to MHz becomes feasible [3], [4]. These active components present low conduction and switching losses compared to Si active devices. In order to further increase efficiency, soft switching is employed to reduce the switching losses.

In isolated DC-DC converters, high-frequency (HF) transformer is a key component. It insures galvanic isolation and voltage adaptation simultaneously. With this increase of frequency, HF transformers become more and more critical. Indeed, this increase induces a rise of losses in magnetic components due to eddy current and proximity effects. As a result, the component's temperature increases and the cooling system capability needs to be adapted. In general, the converter overall efficiency is penalized [5] and the transformer parasitic elements become more critical. One of the main parameters is the leakage inductance. It has an important effect on the converter performances. In hard switching converters, a high value of leakage inductance could be a source voltage ringing, which results on additional stress and losses on semiconductors. In soft switching converters, a sufficient value of leakage inductance is necessary to discharge the capacitive energy of the switches and guaranty the soft switching condition. If its value is adequate, the use of an additional inductor can be avoided.

Thermal management is also a key element in high density power converters. Good thermal management is mandatory in order to ensure the proper function while not increasing the converter's volume too much. To that end, converter and components can be encased in aluminum container. The latter can have a non-negligible influence on the HF transformer parameters. Nevertheless, the study of the effect of the metallic parts surrounding the component is rarely performed, even if the effect of losses is mentioned in [6] for an automotive application. Therefore, in this paper, the effect of an aluminum casing on HF transformer is investigated, based on Finite Element Analysis (FEA) and measurements. The focus is on leakage inductance variation and supplementary losses induced by the casing. The goal is to highlight phenomena and their impact on the design of HF transformer in DC/DC converters.

The paper is organized as follows: In the first section, the HF transformer and the case test are described. In the second section, FEA is used to highlight and quantify the effect of the aluminum casing on the transformer's losses and leakage inductance. Finally, in the last section, measurements are performed on a prototype to validate the presented results.

High-frequency transformer and case study definition

Fig.1 presents the equivalent circuit of HF transformer. The magnetizing branch is composed from the magnetizing inductance *Lm* and core loss equivalent resistance R_c. The total leakage inductance L_{lk} and equivalent losses resistance R_{ac} are modeled on the primary side. All the elements of the equivalent circuit depend on frequency *f*. The effect of casing will be studied on these two specific parameters: L_{lk} *and* R_{ac}.

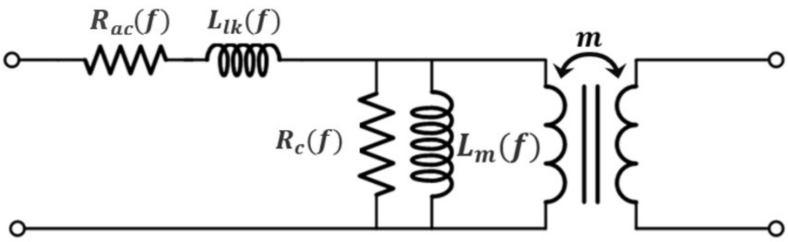
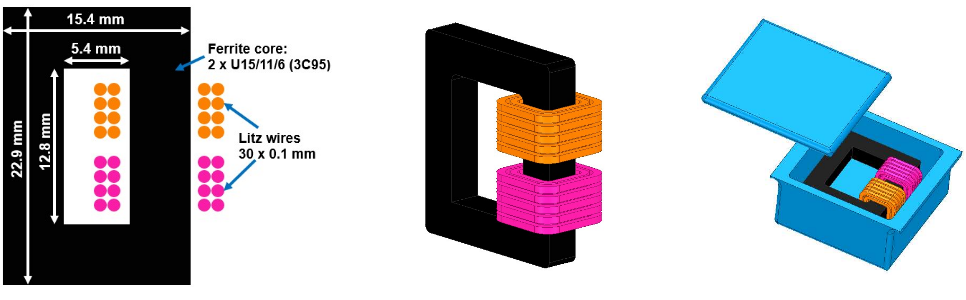


Fig. 1: HF transformer equivalent electrical circuit

For the study, a test case is defined in order to bring out and to quantify the influence of the metallic casing based on FEA and measurements. The studied case is described in Fig. 2a. A 2-winding transformer is designed based on two U-cores (U15/11/16) 3C95 material from Ferroxcube [7]. Primary and secondary windings have each 8 turns of Litz wires with 30 strands of 0.1 mm diameter. A view of the 3D geometry is shown in Fig. 2b. In Fig. 2c, the transformer is put into an aluminum casing. Three casing thickness are considered: 1.5, 2 and 3 mm, with 1 mm margin space between the transformer and the casing's internal faces for each case.



(a) (b) (c)

Fig. 2: Case study: (a) 2D view of the transformer, (b) 3D geometry, (c) Transformer inside the aluminum casing

Finite element study of the casing effect

In this section, the FEA based methodology that is performed to analyze the impact of casing is first introduced. Then, the main results are presented and analyzed.

FEA Methodology

As presented in Fig. 2b, the transformer presents a 3D shape that cannot be easily simplified, especially for the leakage flux that follow multiple directions path inside and outside the transformer window. Then, in order to avoid complex 3D FEA with Liz wires, double 2D finite element studies are preferred [8], [9]. A couple of 2D simulations is then needed to reproduce the 3D effects as shown in Fig. 3a. The first simulation is done in the XZ cut plane, containing winding part covered by the core (*i.e.* the transformer window). This is referred as XZ simulation throughout the paper. The second one is done in the YZ cut plane, representing the part of winding outside the window (*i.e.* the end winding). This is referred as YZ simulation in the next parts. The two simulations are combined to compute the global leakage inductance and the lobalwinding resistance. The same analysis is also completed with the aluminum casing (Fig. 3b).

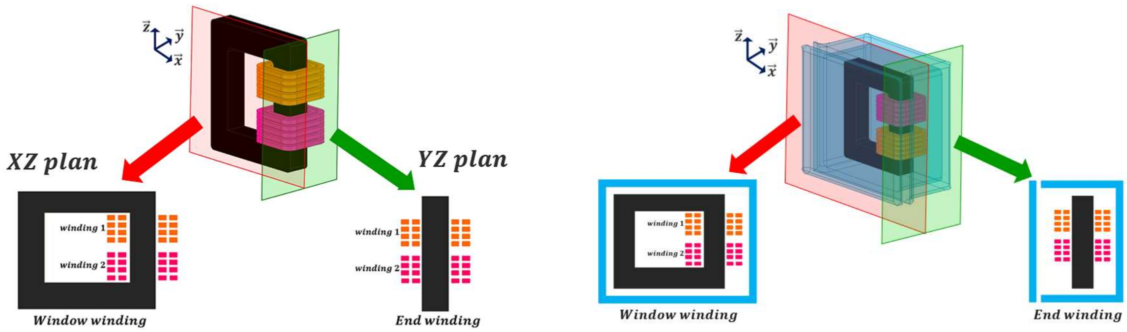


Fig. 3: Double 2D finite element simulations: (a) without casing, (b) with casing

FEA is performed under Ansys Maxwell Software [10] for several frequencies between 20 Hz and 1 MHz. For these simulations, the geometry of the Litz wires (Fig. 4) is detailed and the 30 strands of every Litz conductor are modeled. Finally, the mesh size is adapted to accurately model HF effects in conductors and casing.

Fig. 4: Litz wire detailed model

The leakage inductance L_{lk} is computed from magnetic energy W_{mag} in short-circuit condition (compensated Amper-turns) and primary current I_{rms} as expressed by equation (1):

$$L_{lk} = \frac{2W_{mag}}{I_{rms}^2} \tag{1}$$

The equivalent R_{ac} resistance is computed from losses P_{losses} in windings and metallic casing (2):

$$R_{ac} = \frac{P_{losses}}{I_{rms}^2} \tag{2}$$

The magnetic energy W_{mag} and losses P_{losses} are deduced by adding the two 2D simulation results (per length unit) weighted by the corresponding mean length as expressed in (3) and (4):

$$L_{lk} = l_{XZ} \cdot L_{lk\_XZ} + l_{YZ} \cdot L_{lk\_YZ} \tag{3}$$

$$R_{ac} = l_{XZ} \cdot R_{ac\_XZ} + l_{YZ} \cdot R_{ac\_YZ} \tag{4}$$

where l_{XZ} and l_{YZ} are the simulations length in the two configurations recalled in Fig.5a. The two simulations length are linked to the core section and the winding thickness as illustrated in Fig.5b. Their values are 10.25mm and 9mm, respectively.

(a) (b)

Fig. 5: Simulations in XZ and YZ plans: (a) simulation configurations, (b) Simulation lengths

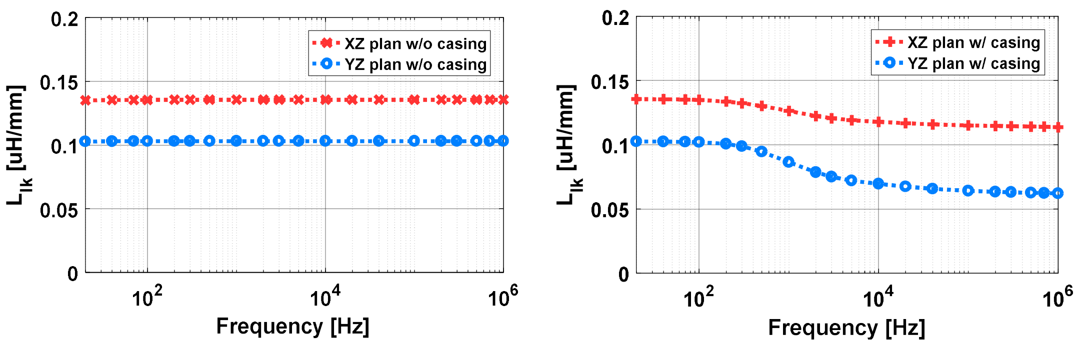
The relative variation of the leakage inductance (5) and winding resistance (6) after adding the casing is computed for every simulated frequency in order to quantify the impact of the metallic casing with the frequency.

$$L_{lk\_variation}(f) = \frac{|L_{lk\_Casing}(f) - L_{lk\_WO\_Casing}(f)|}{L_{lk\_WO\_Casing}(f)} \tag{5}$$

$$R_{ac\_variation}(f) = \frac{|R_{ac\_Casing}(f) - R_{ac\_WO\_Casing}(f)|}{R_{ac\_WO\_Casing}(f)} \tag{6}$$

Double 2D FEA Analysis

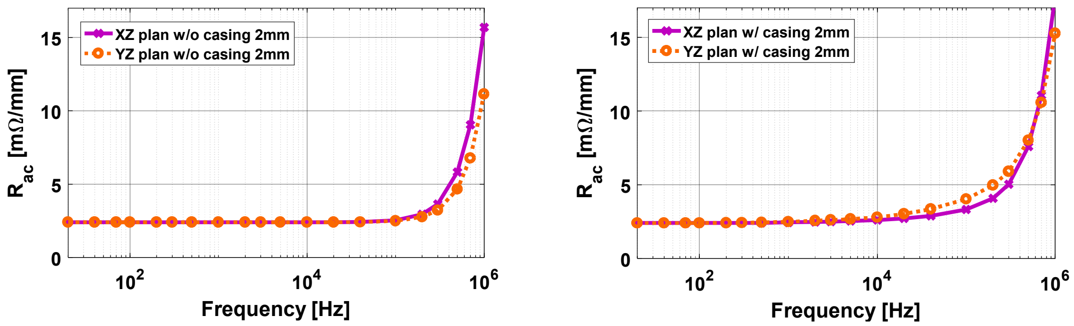
Fig. 6a and Fig. 6b presents the leakage inductance for the simulations in XZ and YZ plans without and with casing, respectively. Without casing (Fig. 6a), the XZ plan simulation has higher inductance compared to YZ plan. From Fig. 5b, it could be noticed that the variation due to the casing effect is more significant in YZ plan.



(a) (b)

Fig. 6: Leakage inductance per unit length for XZ and YZ plans: (a) without casing, (b) with casing

Regarding AC resistance (*i.e.* losses) without casing, the XZ plan simulation has also a higher resistance compared to the YZ plan (Fig. 7a). Adding the casing has more influence on the YZ plan. Then, it becomes close to the XZ plan resistance, especially in HF (Fig.7b).

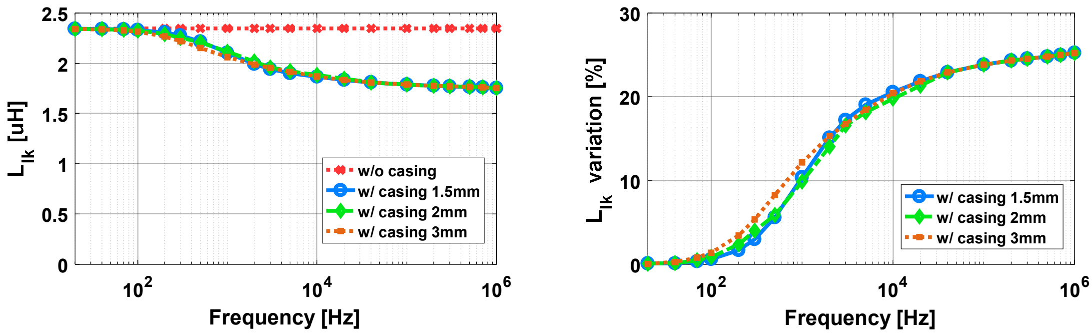


(a) (b)

Fig. 7: AC resistance per length unit for XZ and YZ plans: (a) without casing, (b) with casing

L_{lk} and R_{ac} global analysis

From the simulation results and the mean lengths (3) (4), the leakage inductance evolution with frequency is plotted in Fig. 8a, with and without casing. The variation of the leakage inductance obtained for the 3 casing thicknesses is shown in Fig. 8b. It could be noticed that the leakage inductance without casing is very stable with frequency thanks to Litz wire. It significantly drops when the transformer is encased. Indeed, its value is reduced by more than 20% compared to the case without casing. The variation starts from 10 kHz and the leakage value decreases as the frequency increases. The casing impact is then non-negligible on the leakage inductance parameter. From these results one can say that the casing thickness influence is negligible.



(a) (b)

Fig. 8: Leakage inductance vs frequency: (a) values with and without casing, (b) variation (%) after adding the casing

These results on the leakage inductance can be explained by the shielding effect of the aluminum casing in HF. Indeed, in low frequency (LF), the effect of the casing is not significative and the leakage flux pass through it as shown by the flux density distribution in Fig. 9b. Fig. 9a recalls the simulation geometry showing the transformer elements and the casing. In LF, the leakage energy has the same value and is stored in the same space with or without the casing. For higher frequencies, currents are induced in the aluminum casing due to the leakage flux. These currents create an opposite magnetic field. As a consequence, the magnetic energy is only stored in the space inside the casing (Fig. 9c). The magnetic energy is then reduced and so the leakage inductance.

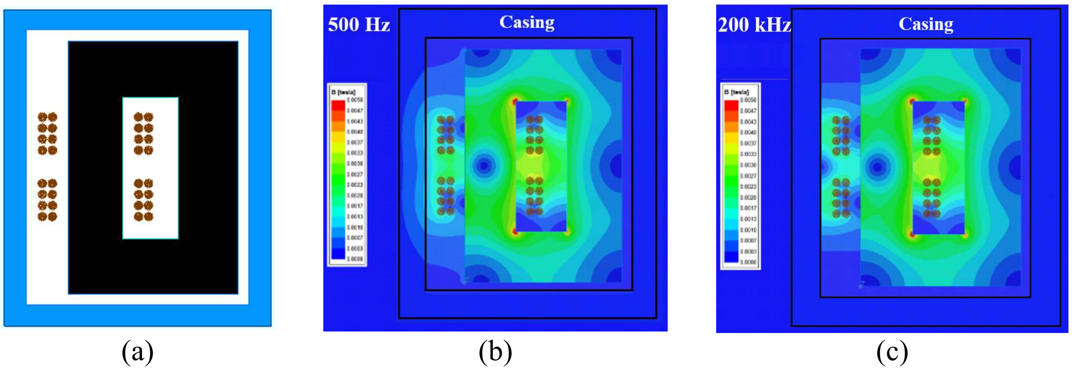


Fig. 9: FEA Simulations: (a) XZ cut plane simulation geometry (window winding) with casing, (b) flux density at 500Hz, (c) flux density at 200kHz

In order to explain the weakness impact of the casing thickness, the skin depth of aluminum is expressed with (7) and plotted for the three-casing thickness (Fig. 10):

$$\delta_{Al} = \frac{1}{\sqrt{\pi \cdot \mu_0 \cdot \sigma_{Al} \cdot f}} \tag{7}$$

where μ_0 is the air permeability $4\pi \cdot 10^{-7}\ H/m$, σ_{Al} is the aluminum electrical conductivity $38 \cdot 10^6\ S$ and f is the frequency.

From 3kHz, the three-casing thickness are greater than aluminum skin depth (Fig. 10). Then, the induced currents have the same distribution for all the casing. As a consequence, from this frequency, the three casing have the same behavior. In LF, the induced currents are negligeable, so the three casing can be assimilated to an air box from electromagnetic point of view.

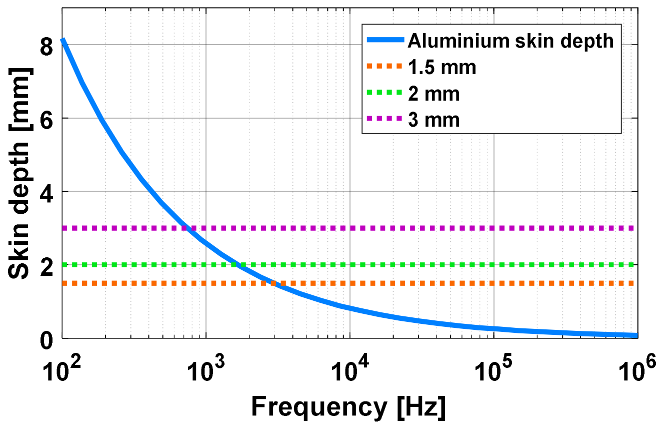
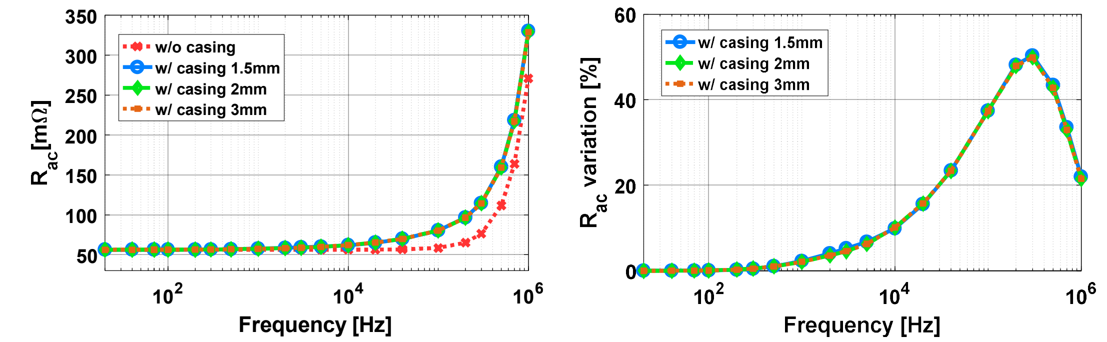


Fig. 10: Aluminum skin depth with frequency

Regarding losses, winding resistance equivalent resistance R_{ac} evolution with frequency is shown in Fig. 11a and its relative variation due to metallic casing in Fig.11b. The presence of the aluminum casing has caused a significant increase on the transformer winding resistance that can exceed 20% for frequencies upper than 100kHz. Above 500 kHz, the effect of the casing is less significant because losses are dominated by the proximity losses of the Litz wires.



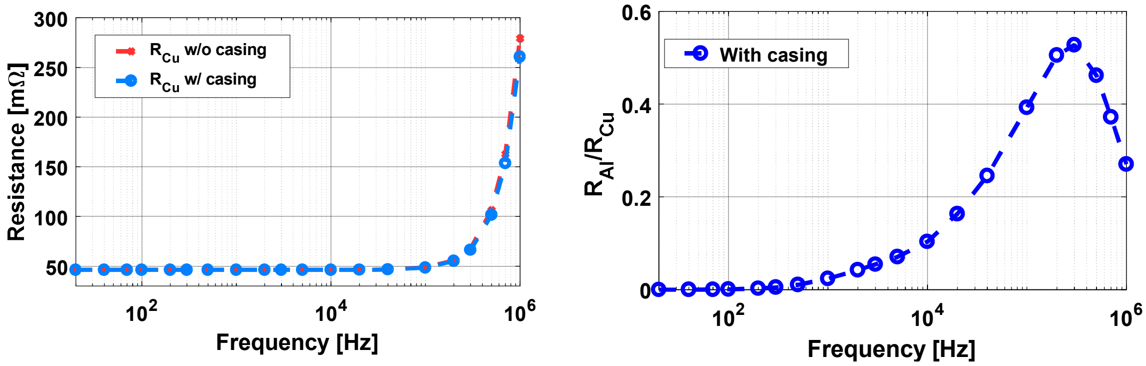
(a) (b)

Fig. 11: Winding resistance vs frequency: (a) values with and without casing, (b) relative variation (%) after adding the casing

In order to determine the origin of the AC resistance increase, the latter is split into two parts (8): R_{Cu} represents the copper losses in the transformer due to the Litz windings and R_{Al} represents the induced losses in the aluminum casing. The total resistance R_{ac} is then the sum of the two introduced resistances (8).

$$R_{ac} = R_{Cu} + R_{Al} \tag{8}$$

Fig. 12a presents the winding copper loss equivalent resistance with and without casing. It can be noticed that the copper losses are not affected by the casing. Hence, the equivalent resistance that increases when the transformer is encased is only due to the induced losses in the casing. To compare the winding copper losses and the induced losses in the casing, the ratio between the resistances linked to each part $\frac{R_{AL}}{R_{Cu}}$ is plotted in Fig.12b. The induced losses in the aluminum casing exceeds 40% of the total copper losses in the frequency range between 100kHz and 500kHz. Those losses are significant and must be evacuated by the thermal management system. Moreover, it impacts negatively the efficiency of the power conversion.

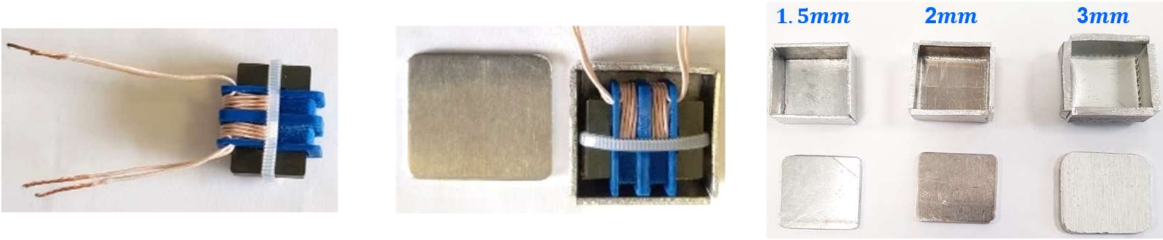


(a) (b)

Fig. 12: Resistance vs frequency: (a) winding resistance with and without casing, (b) ratio between casing losses (aluminum) and copper losses

Measurements and experimental validation

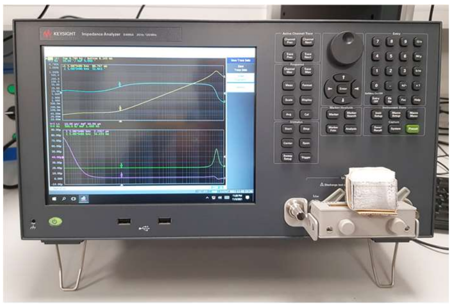
A prototype of the defined test case (Fig. 2) has been manufactured in order to validate the FEA results and the L_{lk} and R_{ac} variations. The prototype without and with casing is shown in Fig. 13a and Fig.13b. In addition, three aluminum casings with 1.5mm, 2mm and 3mm thickness respectively, have been manufactured (Fig. 13c).

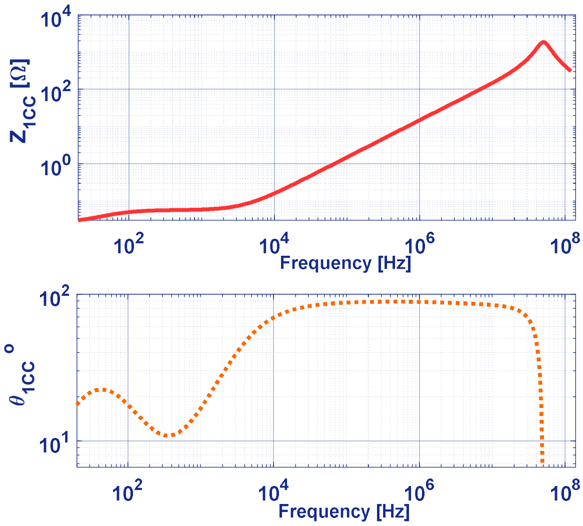


(a) (b) (c)

Fig. 13: Prototype: (a) without casing, (b) with casing, (c) manufactured casings

The transformer characterization is performed using Keysight E4990A high precision impedance analyzer [11] (Fig. 14a). The transformer equivalent leakage inductance and equivalent resistance have been extracted from the impedance Z_{1CC} and phase θ_{1cc} measurements, when the transformer secondary is short-circuited. As an example, Fig. 14b shows the impedance Z_{1CC} and the phase θ_{1cc} of the prototype without casing.



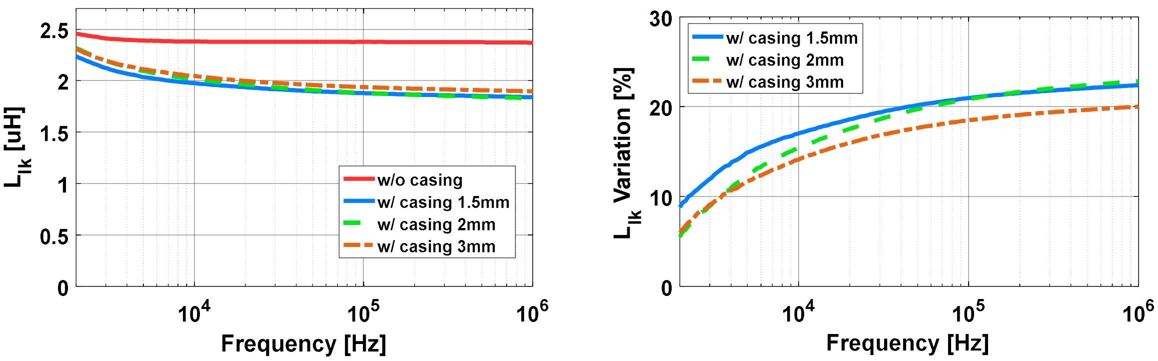


(a) (b)

Fig. 14: Characterization: (a) Keysight E4990A impedance analyzer, (b) measured impedance and phase with short-circuited secondary

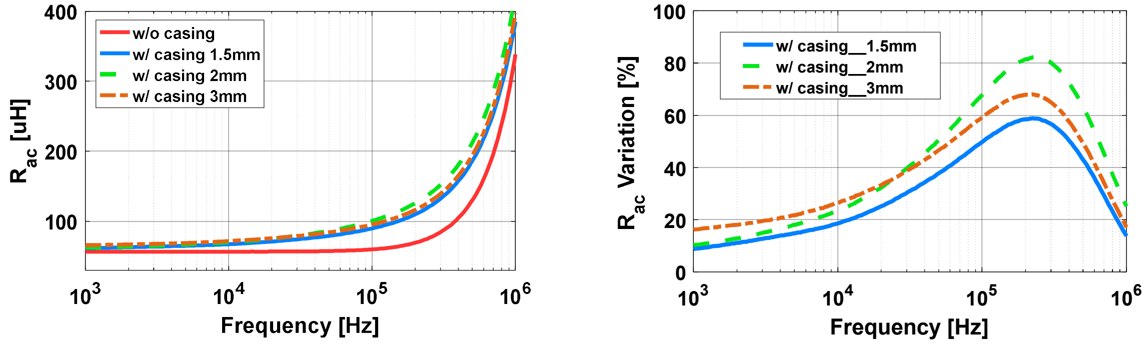
Measurements are performed on the transformer prototype without casing and with the three presented casings (Fig. 13c). The measured leakage inductances are plotted between 10 kHz and 1 MHz in Fig. 15a. Those measurements confirm the results of the simulations. The leakage inductance significantly decreases with frequency when the transformer is put in a casing. Its variation (Fig. 15b) exceeds 20% for the operating frequencies of HF converters.

The winding resistance is strongly increased with the aluminum casing as shown in Fig. 16a. Its variation (Fig.16b) is also consistent with FEA results. As expected, the effect of the casing thickness is not significant. The small difference between the three casings is due to the manufacturing tolerance and the geometrical disparities between the 3 casing prototypes.



(a) (b)

Fig. 15: Measured leakage inductance: (a) value without and with casing, (b) variation after adding the casing

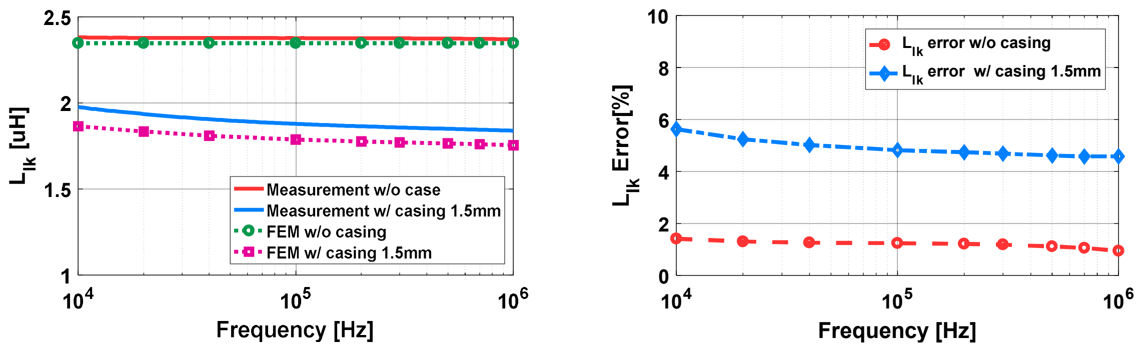


(a) (b)

Fig. 16: Measured winding resistance: (a) value without and with casing, (b) variation after adding the casing

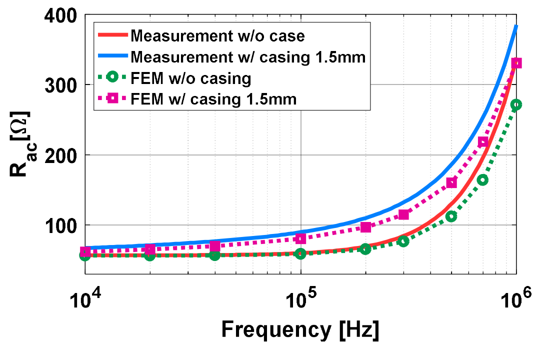
Measured and computed leakage inductances are plotted in Fig. 17a for the transformer without and with the 1.5mm casing. The relative error between measured and computed values are plotted in Fig. 17b. The error does not exceed 6% for the leakage inductance without casing and 2% in the presence of casing. As a consequence, the double 2D FEA modeling seems very effective to model such leakage inductance problem and it allows high accuracy results.

Regarding the equivalent resistance, measurements and FEA results are plotted in Fig. 18a without and with the 1.5mm casing. The relative error between measurements and simulations are reported in Fig. 18b. The model resistance is also quite accurate with a relative error which is less than 12% up to 500kHz. For higher frequencies, the relative error is under 20%. For the loss computation, the accuracy of the numerical model is affected by the simplification of Litz wires in 2D FEA.

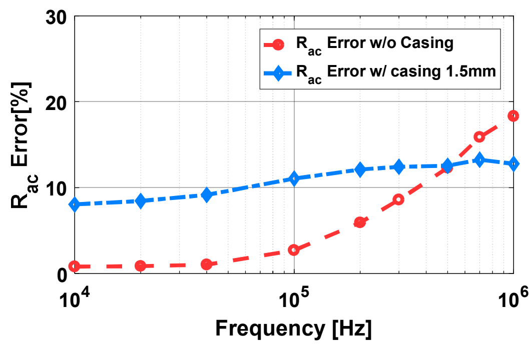


(a) (b)

Fig. 17: Comparison of leakage inductance without and with 1.5mm casing: (a) Measurements / FEA results, (b) relative error



(a)



(b)

Fig. 18: Comparison of AC resistance without and with 1.5mm casing: (a) Measurements / FEA results, (b) relative error

Conclusion

In this paper the effect of an aluminum casing on the leakage inductance and losses of a HF transformer is investigated. A case study is defined based on a ferrite core and Litz wire. Double 2D FEA and measurements on prototype are performed to highlight and quantify the impact of casing on leakage inductance and losses. According to the results, the casing surrounding the transformer significantly affect the leakage inductance and the losses. Indeed, leakage inductance decreases by 20% and losses increase by more than 40%, particularly in the frequency range commonly used in HF converters. Three casing thickness have also been studied and the thickness influence seems to be negligible because the casing thickness is greater than aluminum skin depth. Casing effects must be considered while designing the converter, especially for high power density where the transformer is in contact with metallic part used for thermal management.

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