Cosimulation Approach for Transient Analysis and Transformer Design of Isolated DC-DC Converters

F. Alyami, P. Gomez

Abstract—**The ongoing electric grid modernization efforts have led to a rise in the use of high-frequency (HF) magnetic components within power electronic converters for grid integration of distributed energy resources. However, current methodologies often address the various analysis and design considerations of HF inductors or transformers separately from their operation in power electronic-based systems, extending the timeframe of the studies needed given the iterative and time-consuming nature of the processes involved. Moreover, realistic terminal conditions and operational stresses, such as those related to sudden generation or load variations, as well as the generalized use of HF semiconductive switches, are not typically considered. This work examines the effectiveness of a cosimulation approach for the simultaneous integration of finite element analysis and dynamic analysis tools, aiming to enhance the design of HF transformers in power electronic converters under both transient and steady-state conditions. For this purpose, an isolated full-bridge DC-DC converter is considered as a study case, given its widespread application in grid-connected photovoltaic systems, electric vehicle chargers, and large-scale industrial power supplies. The proposed cosimulation approach allows to identify transient responses of power converters related to the strong interaction between the HF transformer and the power electronic conversion stages, which would otherwise be very difficult to observe, thus providing essential insights for converter design purposes.**

Keywords: **Cosimulation, finite element analysis, high frequency transformer, isolated DC-DC power converter, transient analysis.**

I. Introduction

POWER electronic-based converters are complex and diverse, making their design and analysis challenging. Modeling and simulation tools are essential to support this process. These tools help design engineers gain a better understanding of the circuits' functionalities, enabling them to choose suitable topologies and circuit components that align with the specified requirements. They are also crucial in evaluating the performance of power electronic converters and predicting the impact of changes to circuit component values on operating conditions [1].

From a wide variety of existing power electronic-based converters, the isolated full-bridge DC-DC converter is recognized as a key component for integration of renewable energies, storage systems, electric vehicles, industrial power supplies, among other applications. This converter overcomes the limitations of non-isolated DC-DC converters due to its high power density, wide range of input voltage capabilities, and galvanic isolation [2]. Its basic power topology includes an inverter stage, a rectifier stage, and a high-frequency (HF) transformer. The galvanic isolation provided by the HF transformer substantially enhances human safety and system protection. Additionally, the HF transformer enables high efficiency and compact size of the system [3]. With this in mind, accurate and efficient transformer modeling is paramount for the design of isolated DC-DC converters. This has been tackled by researchers with different approaches and levels of detail, as explained below.

Modeling HF transformers using finite element analysis (FEA) involves the use of software tools that simulate the transformer's electromagnetic behavior based on the numerical solution of Maxwell's equations. This can support the generation of optimized designs with improved performance and efficiency [4], [5], [6]. However, for HF transformers used in power electronic-based systems, the complex terminal conditions provided by switched power conversion stages under different modes of operation need to be simplified in FEA, affecting the accuracy of the responses obtained, particularly during transient analysis.

Lumped parameter models are presented in [7] and [8] as an alternative to FEA to study HF transformer behavior. This approach simplifies the complex electromagnetic interactions within the transformer into equivalent electrical components and allows better dynamic interaction with models of power electronic components in power conversion systems. However, lumped models of HF transformers are commonly tailored for steady-state analysis and may lack the detail required for electromagnetic transient studies, as well as the appropriate inclusion of nonlinear core material behavior.

Cui et al. state in [9] that designing and optimizing HF magnetic components is a challenging task that requires a precise and reliable simulation approach. Magnetic components are critical in high-frequency and high-density applications, but the absence of sufficiently accurate models and understanding of material properties is still a significant issue. This deficiency often leads to oversimplified design assumptions necessitating an iterative physical prototyping (trial-and-error) process that is expensive and time consuming.

Based on the limitations described above, it becomes evident that the appropriate modeling and simulation of power electronic-based systems integrating HF magnetic components requires a synergistic approach that combines electromagnetic simulation and dynamic analysis tools. Cosimulation can serve as an effective methodology for this purpose, ensuring that the mutual influence between different physical domains is considered in a synchronized manner [10], [11]. This approach

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can offer a significant advantage over traditional simulation methods that treat the electromagnetic and circuit domains separately, which may overlook critical interactions and result in suboptimal designs [12].

Mohamed et al. developed a physics-based cosimulation platform for electromagnetic compatibility analysis of bidirectional inductive wireless power transfer systems in electric vehicle applications [13]. This was achieved by integrating a 2D FEA for magnetic components with a circuit model in the Simulink environment. Abed et al. proposed a computational model for high-frequency transformers that utilizes coupled-circuit finite-element (FE) nonlinear analysis to derive the model parameters [14]. The transformer's frequency response is determined by integrating the FE model of the transformer with external electrical circuits. This method facilitates a physical representation of the nonlinear magnetization characteristics.

In [15], a cosimulation method that combines the software packages ANSYS Maxwell, Twin Builder, and Simulink is used to simulate and analyze the performance of a permanent magnet synchronous motor (PMSM) in electric vehicles. This approach allows the integration of magnetic and electrical domains, thus capturing all relevant effects. The developed model is applied to the characterization, optimization, and evaluation of PMSM performance.

Our recent work presented in [16] explored the use of a cosimulation approach to investigate the saturation behavior of inductive components in non-isolated DC-DC converters. The results of this study demonstrated that the unique magnetic characteristics of different magnetic materials used in toroidal inductors can significantly impact the transient and steady state performances of the converter under different loading conditions. This important observation was made possible by the cosimulation model.

Based on our preliminary work in [16], in this paper we evaluate the efficacy of a novel cosimulation-based methodology to support the transient analysis and electromagnetic design of high frequency magnetic components in power-electronic converters, considering a high-frequency transformer in a full-bridge isolated DC-DC converter as a test case. By integrating finite element analysis and dynamic analysis tools, the proposed methodology is able to accurately reflect the physical characteristics of the high-frequency transformer within the power converter under both steady-state and transient conditions. The proposed methodology is implemented through cosimulation between COMSOL Multiphysics [17] and MATLAB/Simulink [18], demonstrating its potential to advance the design and analysis of high-frequency magnetic components in power electronic systems.

II. General Methodology – Cosimulation Process

The proposed cosimulation-based methodology consists of a systematic approach for the design and analysis of magnetic components within power electronic converters, which involves the simultaneous integration of a FEM-based tool with a dynamic analysis technique. This integration is achieved in this work by utilizing the “LiveLink for Simulink” add-on in order to connect COMSOL Multiphysics with Simulink. This approach enables comprehensive assessment of high-frequency magnetic components in power electronics converters. The process is as follows:

1. *Theoretical Parameter Derivation:* The procedure begins with the analytical calculation of the power converter parameters from initial specifications based on the type of converter and its operational characteristics, such as voltage and power ratings, switching frequency, load range, etc.
2. *Initial Magnetic Component Design:* Using the aforementioned parameters, an initial design for the corresponding magnetic component is generated. In this work, an advanced commercial software for magnetic design known as Frenetic AI is applied for this purpose [19]. This software employs artificial intelligence algorithms and incorporates data from real-world measurements to create a design that is both logically robust and fine-tuned to meet the initial set of requirements.
3. *Initial Magnetic Component Design Verification:* The developed design is subjected to a verification process. This involves a comprehensive assessment of the design's effectiveness, focusing on loss characteristics, geometric considerations, magnetic material properties, and overall performance. If the design exceeds physical constraints, such as the winding size surpassing the available window in an E core, or fails to meet other established criteria, it is considered impractical. In this case, the design is iteratively refined through the design tool used (in our case Frenetic AI) until it achieves the acceptable threshold.
4. *Magnetic Component FEM Modeling:* In the development of the magnetic component, once a design that meets the initial criteria is established, a FEM model is constructed using COMSOL Multiphysics. This step is crucial for the magnetic component, as it allows for a comprehensive analysis of its electromagnetic, material, and geometrical properties. The FEM model not only provides deeper insight into the electromagnetic behavior specific to the component, but also validates the theoretical design by simulating its performance.
5. *Determining the Adequacy of the FEM Model:* This is assessed by evaluating the coupling magnetic fields and voltage distributions to ensure conformity with predetermined performance criteria. In cases where the model does not meet these criteria, iterative refinement of the FEM model is employed to align it with the desired simulation outcomes.
6. *Dynamic Modeling and Cosimulation Execution:* After the FEM model is validated, a functional mock-up unit (FMU) file is extracted. This file encapsulates the validated FEM model, facilitating its integration into the dynamic modeling environment. A dynamic model of the power converter is then constructed in Simulink. The FMU file enables the dynamic model to interface directly with the FEM simulation at each time step, creating a cosimulation that reflects the live interaction between the converter’s dynamic behavior and the magnetic component’s electromagnetic response.
7. *Dynamic Performance Assessment:* This stage involves a detailed analysis of the simulation results from both the cosimulated and standalone dynamic models. By

comparing the performance of both models, this assessment can determine the fidelity and additional benefits of the cosimulation approach in capturing the transient and steady state behaviors of the power converter under various operational conditions and magnetic design considerations, thereby providing a more realistic understanding of the system's behavior.

III. Description of Test System – Isolated Full-Bridge DC-DC Converter

The basic representation of the cosimulation model of the isolated full-bridge DC-DC converter is shown in Fig. 1.

The converter is modeled in Simulink in open-loop mode and operates with an inverter stage and a rectifier stage. The inverter stage is fed by a DC source of 800 V and is comprised of an H-Bridge topology based on IGBTs, which is controlled using a switching signal at 30 kHz. The rectifier is comprised of a diode bridge and includes a filtering capacitor of 5 μF.

The high-frequency transformer is modeled in COMSOL Multiphysics, focusing on its geometric design and material properties, and considering the nonlinear behavior of the core materials. This is achieved by introducing the BH curve of the corresponding material into COMSOL according to the saturation curves shown in Fig. 2.

A voltage-dependent and current-dependent transformer model, similar to the approach used in [13] for wireless power transfer, is implemented in Simulink and fed by primary and secondary currents calculated by COMSOL for each time step of the simulation. At the same time, COMSOL's currents calculation depends on the high-frequency primary and secondary voltages of the converter, creating a live interaction between Simulink and COMSOL, as illustrated in Fig. 1.

The FEM-based transformer model includes an E-type core with primary and secondary coils placed around the center leg, as shown in Fig. 3. Meshing for finite element analysis is defined to ensure accurate electromagnetic simulation under various conditions with the lowest possible computational time, which is particularly important for cosimulation purposes.

Coils excitation is driven by the "Coil Geometry Analysis" feature in COMSOL, which defines the coils current flow based on their 3-dimentional physical layout for a proper electromagnetic behavior of the transformer. In addition, this detailed coil representation facilitates the integration of the FEM model with Simulink for the cosimulation process. Through this integration, the transformer model can be evaluated in a dynamic electrical circuit environment, where detailed FEM results influence the behavior of the power electronic conversion stages, and vice versa.

The high-frequency transformer model employs voltages across current-controlled sources in COMSOL as control signals for its voltage sources. At each time step, the coil currents obtained once the COMSOL model is solved are applied to regulate the current-controlled sources in Simulink.

IV. Results and Discussion

The isolated full-bridge DC-DC converter model setup is implemented as illustrated in Fig. 1 to test and validate the cosimulation approach. Following the process described in Section II, the HF transformer with the parameters defined in Tables I and II is implemented in COMSOL.

Several case studies are considered to investigate the performance of powder material and ferrite E-core transformers used in an isolated full-bridge DC-DC converter. Then, different sizes of ferrite core gaps are considered to evaluate the transient response of the system. The gaps in this study include sizes of 0.5, 0.65, 0.78, 0.85, and 1.05, all in millimeters. Each gap size is tested by studying the transient voltage and current performances of the isolated full-bridge DC-DC converter at fixed load (22 Ω) and during sudden load variation. For the latter, the load is modified from an initial value of 22 Ω by connecting a parallel 3 Ω load 0.08 ms after the start of the simulation to produce a sudden overload condition with an equivalent load of 2.64 Ω.

In terms of computational effort, the cosimulation process involves a substantially larger simulation time than a standalone Simulink or COMSOL execution, due to the time needed to exchange information between the two tools via the functional mock-up unit (FMU). The approximate execution time to run a case is 78 minutes using a computer server with the following characteristics: Intel® Xeon Silver 4210R CPU @ 2.40 GHz with 256 GB of installed RAM.

A. Powder Core

Powder material is a high frequency material that has a distributed air gap. It is used for magnetic components in power electronics converters, such as inductors and transformers. Since powder material has an air gap evenly distributed at a microscopic scale, physical gaps are not commonly applied [20]. To investigate the use of powder core in the high frequency transformer core of an isolated DC-DC converter, the study case initially considers a fixed load condition. The material used for this study is KoolMu 60 [21], with the saturation curve shown in Fig. 2 in red.

Fig. 4 shows the initial load voltage of the converter simulated with a non-gapped powder E-core transformer. It can be observed that the time constant under this condition is slow and a substantial voltage drop is produced under the load applied. The load voltage reaches 420 V at approximately 200 μs. This means that the leakage inductance of the high frequency transformer is large, which affects the appropriate operation of the converter system [22]. The slow response of this transformer would also affect the proper operation of the control system of the converter. In addition, it can cause an increase in the size and the cost of the transformer [23]. Lastly, increased leakage inductance can significantly impact the converter's power transfer, especially for heavy loads [24].

B. Ferrite Core – Non-gapped

Fig. 5 shows the transient load voltage response when a ferrite material is used for the transformer core of the converter. The saturation curve of this material is shown in Fig. 2 in blue. The load voltage rises sharply at 50 μs to the steady state, which is a much faster response time compared to the powder core case in Fig. 4. However, the voltage does not reach its nominal value of 500 V with a load of 22 Ω, staying at approximately 450 V. Due to the lack of an air gap to control saturation in this case, the nonlinear behavior of the core is reflected in the results. This behavior impacts the transformer's magnetizing inductance [25], [26], affecting the overall performance of the converter.

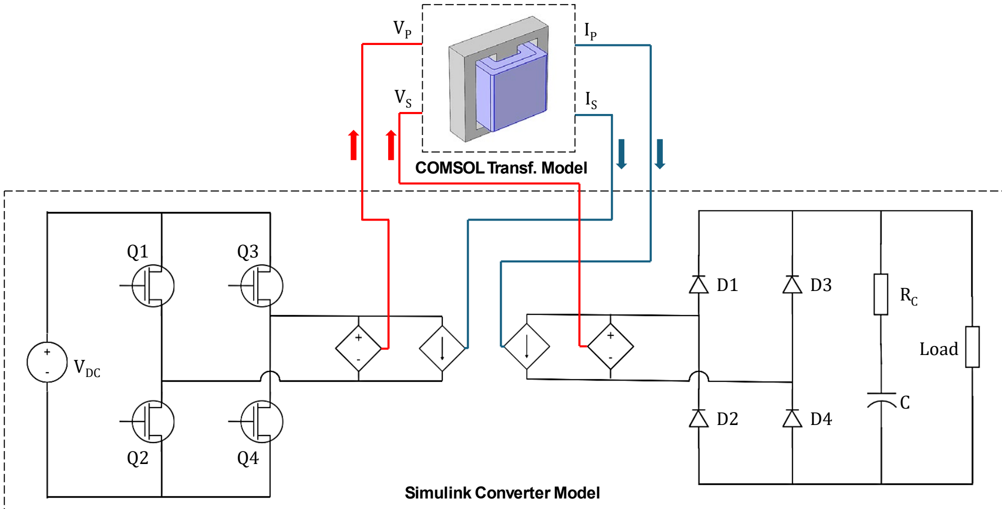

Fig. 1. Cosimulation model of isolated full-bridge DC-DC converter

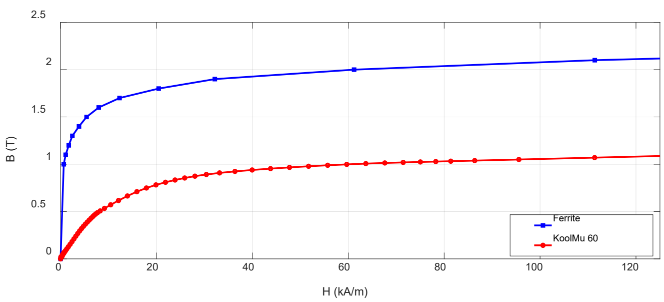

Fig. 2. BH curves of the core materials under study

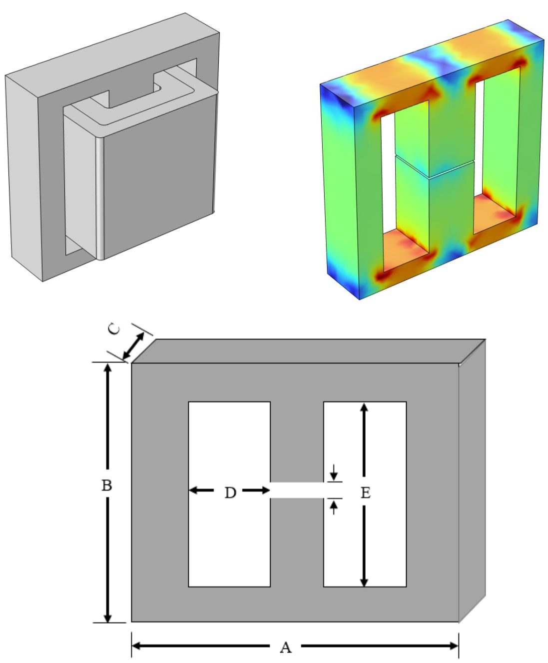

Fig. 3. High-frequency E-Core transformer model: (a) geometrical configuration, (b) sample magnetic flux density distribution for gapped ferrite core, (c) main core dimensions.

TABLE I. CORE DIMENSIONS

Dimension	Value (mm)
A	80
B	76.2
C	19.8
D	19.65
E	56.4
Gap	variable

TABLE II. MAIN PARAMETERS OF THE TRANSFORMER

Parameter	Value
Primary Voltage	800 V
Secondary Voltage	500 V
Primary Turns	54
Secondary Turns	34
Core Material	Powder or Ferrite

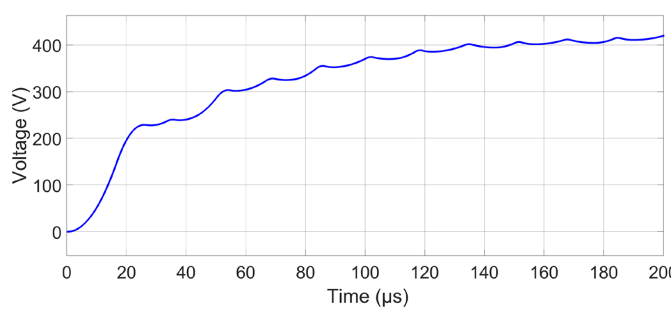

Fig. 4. Transient output voltage of the converter with powder core in the HF transformer

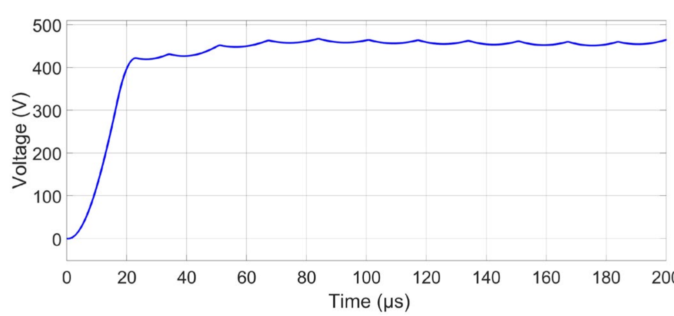

Fig. 5. Transient output voltage of the converter with non-gapped ferrite core in the HF transformer

C. Ferrite - Gapped

After exploring E-core transformer behavior for powder (distributed gap) core and non-gapped ferrite material, different air gap sizes are considered for the ferrite core. These gaps are physical distances in the middle leg of the E-core, where the magnetic circuit behavior is deliberately interrupted to control the transformer's inductance. The air gap size plays an important role in transformer design as it affects its magnetizing and leakage inductances. A properly sized air gap in the core can help improve the overall performance of a high-frequency transformer [27]. Thus, examining the impact of air gap sizing on the dynamic behavior of the isolated DC-DC converter is very important.

In Table III, which is generated as a quantitative summary of the results shown in Figs. 6 and 7, the peak voltage and peak current represent the maximum overvoltage and overcurrent reached during the initial transient stage of the converter's operation.

The peak time in all cases is approximately 20.5 µs, while the peak voltages range from 613.1 V (22.62% above nominal value of 500 V) to 641.9 V (28.38% above nominal value), and the peak currents vary from 27.25 A (19.9% above nominal value of 22.73 A) to 28.53 A (25.53% above nominal value), indicating that the transient behavior of the converter is moderately affected by the choice of gap size. In addition, the settling-time voltage and current, which represent the stabilization of the waveforms after the initial transient stage, are also depicted in Table III. This time is approximated as 67 µs for all cases under study.

The settling-time voltage ranges from 473.6 V (94.72% of nominal value) to 485.4 V (97.08% of nominal value), while the settling-time current ranges from 21.05 A (92.62% of nominal value) to 21.57 A (94.91% of nominal value). Furthermore, the steady-state voltage and current, corresponding to the arithmetic mean of the waveforms from the settling time until the end of the simulation (from 67 µs to 200 µs), are also depicted in Table III.

The steady-state voltage ranges from 458.3 V (91.66% of nominal value) to 464.9 V (93.46% of nominal value), while the current steady-state current ranges from 20.37 A (89.63% of nominal value) to 21.13 A (92.97% of nominal value).

Overall, the results in Table III indicate that the best performance of the isolated full-bridge DC-DC converter is achieved with air gaps sizes between 0.78 and 0.85 mm. However, the transient voltage and current responses and steady state ripples are still considerable, which could be improved by optimizing the size of the output capacitor filter.

TABLE III. PEAK AND SETTLING-TIME OUTPUT VOLTAGE AND CURRENT OF THE CONVERTER WITH DIFFERENT GAPPED E-CORE TRANSFORMERS

Gap Size	Peak voltage/current	Settling-time voltage/current	Steady-state voltage/current
[mm]	Percentage of nominal value [%]		
0.5	122.62/119.90	94.72/92.62	91.66/89.63
0.65	128.38/125.53	96.94/94.73	92.84/90.77
0.78	127.12/124.30	97.08/94.91	92.98/92.97
0.85	127.12/124.30	97.08/94.91	93.46/91.39
1.05	122.74/120.03	95.76/93.63	92.86/90.82

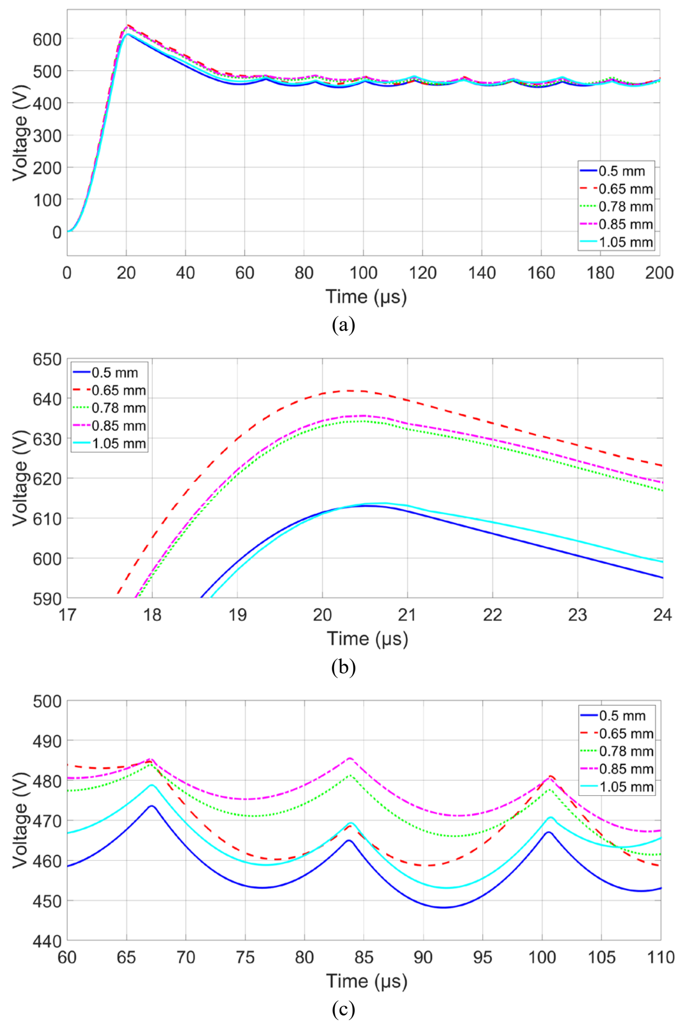

Fig. 6. Output voltage of the converter for different air gap sizes under comparison: (a) transient response, (b) zoom-in at max. overshoot time, (c) zoom-in at settling time

Fig, 6 shows the transient output voltage of the converter after energization under fixed load. Fig. 6a corresponds to the complete time window for the first 0.2 ms. Fig. 6b shows a zoom-in of the maximum transient overvoltage, while Fig. 6c illustrates the converter's response as the output voltage settles to its steady state. Similar waveforms for the transient output current are shown in Fig. 7.

D. Overload Condition

Fig. 8 illustrates the transient output voltage of the isolated full-bridge DC-DC converter using different transformer core models (gapped and non-gapped) under a sudden overload condition (3 Ω load suddenly connected in parallel to an initial 22 Ω load). Figs. 9 and 10 depict the output current of the converter under the same conditions. Currents for gapped and non-gapped topologies are separated into two figures because the non-gapped response produces substantially higher values.

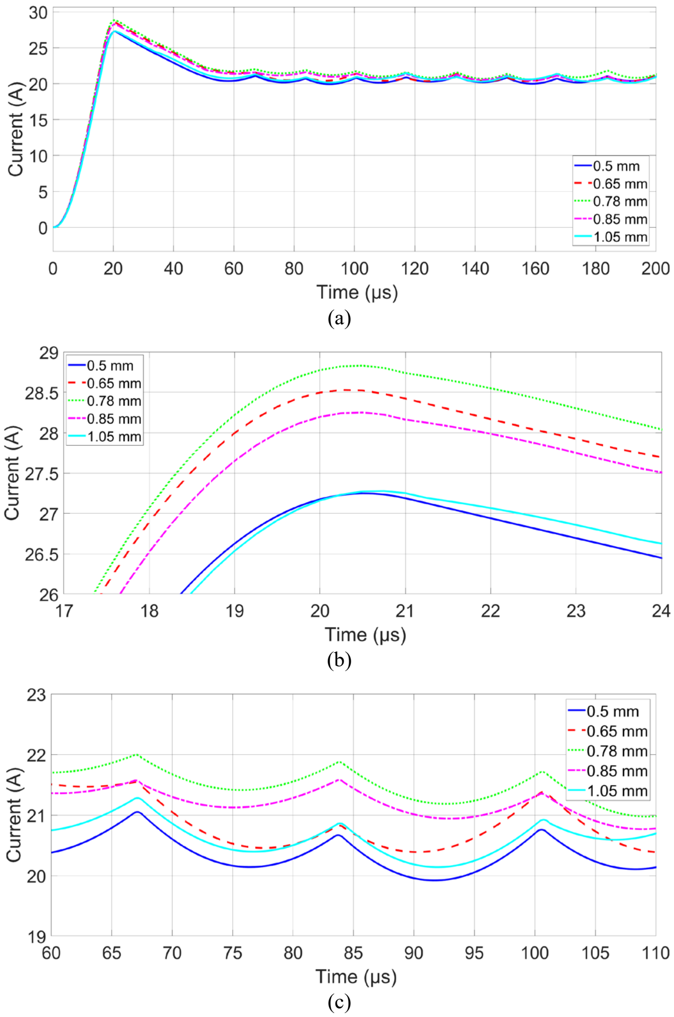

Fig. 7. Output current of the converter for different air gap sizes under comparison: (a) transient response, (b) zoom-in at max. overshoot time, (c) zoom-in at settling time

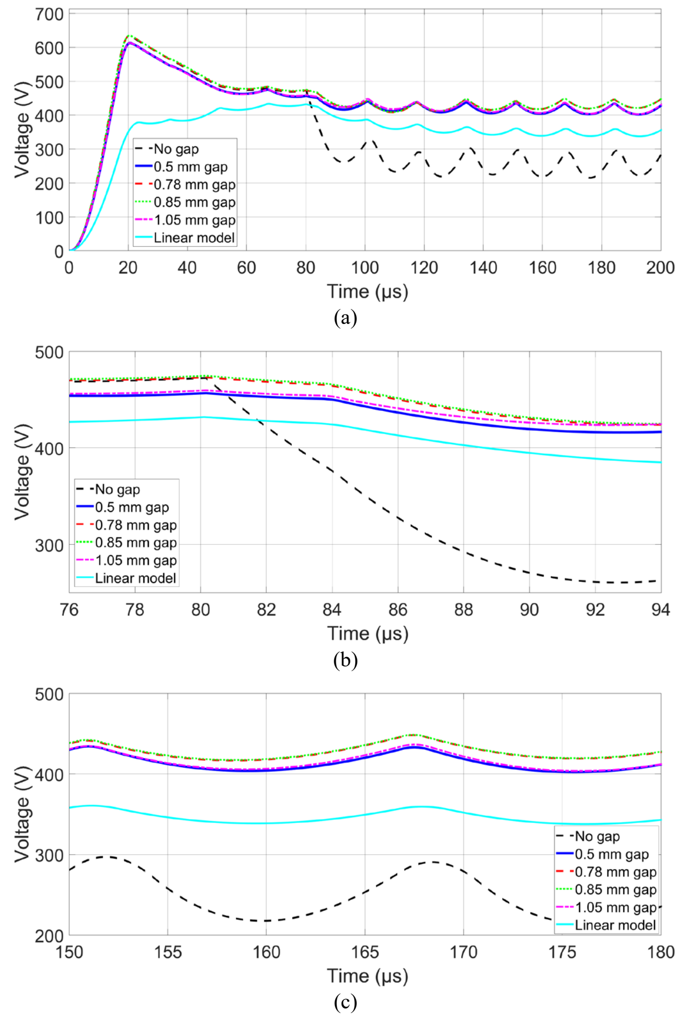

Fig. 8. Output voltage of the converter with non-gapped and different air gapped transformer models under sudden overload condition: (a) transient response, (b) zoom-in at time of overload, (c) zoom-in after settling time

According to Fig. 8, the voltages show a higher initial peak and significant ripple for the non-gapped core. However, when an air gap is introduced, the voltage ripple diminishes. The gapped transformer helps reduce core saturation, which leads to a smoother voltage and less fluctuation under dynamic load conditions [28]. In addition, an appropriate choice of gap size can balance magnetic flux density (between a high value that can take the transformer into saturation and a low value that would increase leakage flux) to further reduce the voltage ripple and limit voltage drop during overload [28], as noticed in the relatively stable output of the converter using the 0.78 mm and 0.85 gapped cores.

As shown in Fig. 9, gapped transformers in the range of 0.78 to 0.85 mm exhibit smooth current transitions and lower ripple. The gap helps limit core saturation under overload conditions, which limits inrush currents and reduces losses associated with switching transients [29]. In contrast, the plot in Fig. 10 shows that the non-gapped transformer results in very high initial current spikes in the converter's output and maintains substantially higher current values during steady state when compared with gapped topologies. This is due to core saturation and can result in high inrush currents and power losses [30].

On the other hand, responses considering a linear transformer model (no cosimulation) are included for both voltage and transient responses. It can be observed in Figs. 8 and 9 that the use of a linear transformer model, very common in dynamic analysis of power conversion systems, is unable to provide an appropriate prediction of the system's behavior for both transient and steady state conditions, completely underestimating the transient overvoltage at the beginning of the event and resulting in very different steady state voltage and current magnitudes during overload. This further exbibits the benefits of the use of the proposed cosimulation approach to study the effects of different transformer design considerations in the dynamic analysis of DC-DC converters.

By comparing the results for different gapped E-core transformer models (all using ferrite material), the models with 0.78 mm and 0.85 are considered the most appropriate ones because they provide better power transfer capability while limiting voltage and current ripples under fixed load and sudden overload conditions. From these two options, the isolated full-bridge DC-DC converter with 0.78 mm gapped transformer would be preferred since a smaller air gap can help avoid the fringe magnetic flux in the gap and corresponding eddy currents and losses at high frequency [31].

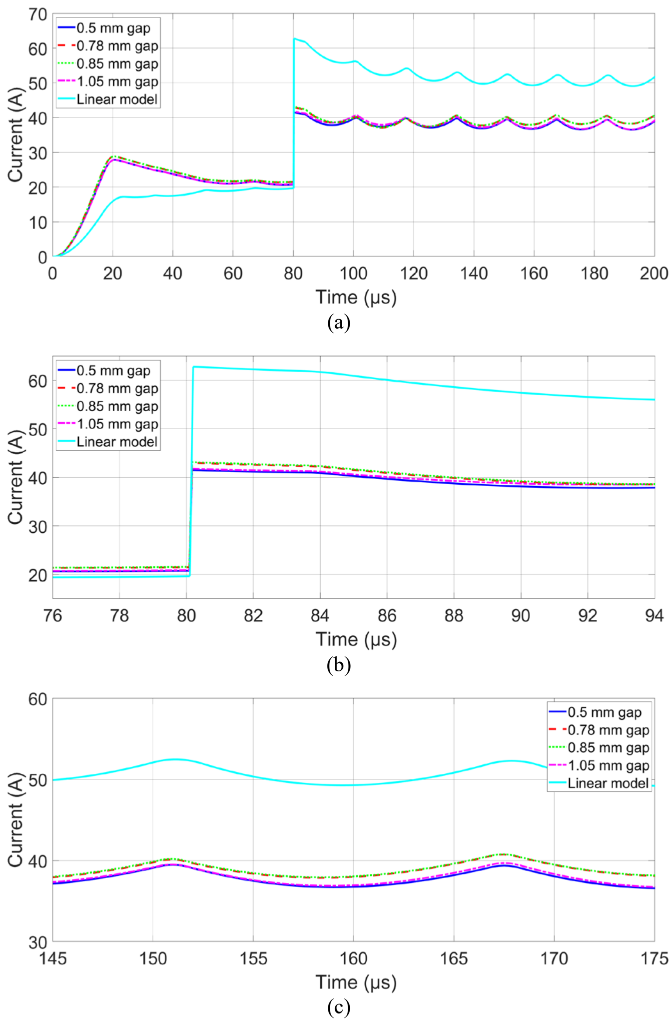

Fig. 9. Output current of the converter with different air gapped transformer models under sudden overload condition: (a) transient response, (b) zoom-in at time of overload, (c) zoom-in after settling time

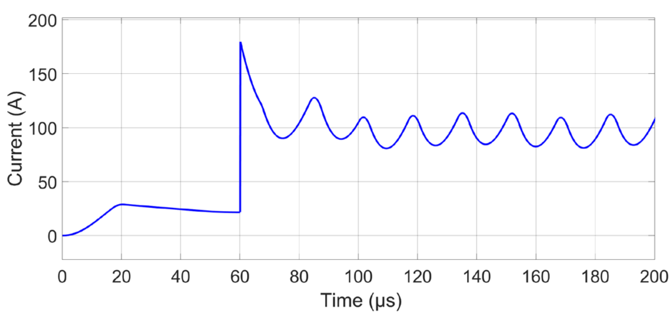

Fig. 10. Output current of the converter with non-gapped transformer model under sudden overload condition

V. Conclusions

This paper evaluated the transient and steady state performance of powder and ferrite material E-core transformers in an isolated full-bridge DC-DC converter, by means of a cosimulation approach between a FEM-based model of the high-frequency transformer in COMSOL and a dynamic simulation-based model of the power electronic conversion stages in Simulink. The study focused on transformers with different core materials and gap sizes. Each transformer configuration was tested under fixed load and sudden overload conditions to assess voltage and current transient and steady state behaviors.

For the selected powder material core, the distributed air gap increases the leakage inductance in the transformer, which results in a slower response of the converter when compared to the use of ferrite core. This would negatively impact the converter's performance. Ferrite material core is then tested with both non-gapped and gapped configurations.

For the non-gapped ferrite material core, a rapid increase in voltage is observed, although it does not achieve the nominal value. Conversely, the introduction of various gap sizes enables control over the magnetizing and leakage inductances, thereby enhancing the converter's performance. In particular, E-cores with gaps of 0.78 mm and 0.85 mm produced the best performance, effectively balancing peak and steady-state voltage and current values.

This work also evaluated different load conditions, which showed that gapped transformers can be more effective in reducing core saturation and limiting voltage ripple. The 0.78 mm gap transformer in the isolated full bridge DC-DC converter is selected for its balanced performance, which could be further enhanced by increasing the size of the capacitive output filter.

Finally, although the evaluation of the dynamic behavior of the converter as a function of the transformer's geometrical and material properties using cosimulation offers a great insight into potential performance enhancements, a more comprehensive design process should also consider core losses and overall efficiency, as well as other design aspects such as insulation and thermal stresses. Cosimulation can be further applied for this purpose combined with multiphysics optimization procedures.

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