Cosimulation Approach for Transient Analysis and Inductor Design of DC-DC Buck Converters

Faraj Alyami[1, 2], Jean C. Gnamien[1] and Pablo Gomez[1*]
[1] Western Michigan University, Kalamazoo, Michigan , USA
[2] Najran University, Najran, Saudi Arabia
[*]pablo.gomez@wmich.edu

2023 IEEE 24th Workshop on Control and Modeling for Power Electronics (COMPEL) | 979-8-3503-1618-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/COMPEL52896.2023.10221080

***Abstract* — This paper introduces a dynamic cosimulation approach to evaluate the effect of the selection of magnetic core material in toroidal inductors for DC-DC converters under varying load conditions. This cosimulation approach is based on the combination of transient analysis and finite element analysis to investigate how different high-frequency magnetic materials perform as potential core components for the converter's inductor. The study considers a DC-DC buck converter modeled in Simulink and a detailed toroidal core inductor modeled through COMSOL Multiphysics. The LiveLink for Simulink tool available in COMSOL Multiphysics is utilized for accurate inclusion of the nonlinear inductor model and its integration into the dynamic buck converter model. The study provides insights into the behavior of different magnetic materials under high current exposure, and their suitability for use in DC-DC converters. The results of this investigation can provide practical guidance for designing and optimizing DC-DC converters in various electrical systems, with a focus on selecting appropriate magnetic materials for toroidal inductors.**

I. Introduction

DC-DC converters are widely utilized in the automotive, aerospace, and power grid industries, among others. High-power-density magnetic designs are in high demand in all these industries. The key to reducing the weight and volume of power converters lies in a compact and efficient magnetic design [1]. The size of the inductor is impacted by several design considerations, such as the number of stages and the choice between continuous and discontinuous conduction modes [2]. The selection of appropriate dimensional ratios for the core can significantly reduce the size of the inductor [3], and additional size reduction can be achieved through the implementation of improved cooling methods [4]. Typical switching frequencies of DC-DC converters lie in the range of 1 kHz to 1 MHz, depending on the semiconductive devices used [15]. Therefore, high frequency magnetic design is required. The designer has access to a range of magnetic materials for high frequency applications, such as powder, ferrite, and tape wound cores [5]. The correct choice of magnetic material is imperative to ensure a cost-effective inductor with minimum size and maximum efficiency for the specific converter to be designed.

Several researchers have proposed solutions that integrate FEM-based simulation tools with time-domain electrical system (TDES) simulation tools (either offline or in real-time) to enhance the electromagnetic design of power components. This allows combining the benefits from both tools: TDES software can model large-scale systems and take advantage of a comprehensive library of components, while FEM-based software can take into account the detailed geometrical and material properties of power components, which is particularly useful for design purposes. The multiphysics features of contemporary FEM tools further enable considering multi-objective design optimization of power components.

Dennetiere et al. developed a link between EMTP (Electromagnetic Transients Program) and FEM software Flux3D to study transformer energization including accurate representation of core nonlinearity and anisotropy [6]. This link enabled the calculation of mechanical stresses and internal fluxes under realistic conditions. Dufour et al. developed a link between real-time simulator RT-LAB and FEM software JMAG for hardware-in-the-loop testing of a motor controller connected to a permanent magnet synchronous motor virtual motor drive, aimed at improving motor and control design methodologies [7]. Melgoza et al. developed a method to interface ATP (Alternative Transient Program) with a custom-made FEM code for accuracy-enhanced inrush current studies of transformers [8].

Asghari et al. reviewed the most common techniques to interface circuit simulation programs with FEM-based software for detailed modeling of electromagnetic behavior of power apparatus [9]. It was concluded that an indirect approach, in which the FEM and circuit simulator portions are handled and solved separately, is very suitable when dealing with multirate simulations (such as those typical in converter-dominated systems) and is more straightforward to implement when using existing simulation programs. Faruque et al. further expanded on the topic of software interfacing for power applications [10]. This paper highlighted the need for interfacing multi-domain/physics simulation tools to tackle the increasingly complex power systems, especially considering the penetration of distributed sources and storage units interconnected by means of high-power electronic converters. This paper discussed current capabilities and challenges for linking TDES and FEM simulation programs, such as COMSOL Multiphysics with MATLAB/Simulink, and ANSYS with CASPOC.

This study aims to examine the transient analysis of a 75 W, 15 V DC-DC buck converter, with a particular focus on the selection of magnetic materials to be used in the toroidal core

This work was supported by the US National Science Foundation (NSF) under award #2138408.

inductor. Different powder cores are selected as recommended in [5]. The online high-frequency magnetics design software Frenetic AI is utilized to determine the number of turns and dimensions for each material considered. The behavior of the selected materials is evaluated under different load conditions (nominal load, saturation, and deep saturation) using a cosimulation approach via the live interface between Simulink and COMSOL Multiphysics (LiveLink for Simulink [11]). The main findings of this research paper highlight that the dynamic performance of the converter under varying conditions is significantly affected by the properties of each magnetic material, as observed through transient analysis.

II. DC-DC Buck Converter

The buck converter is a widely used direct current (DC) voltage regulator in power applications such as grid integration of photovoltaic (PV) systems. It is characterized by its average output voltage, v_o, being lower than the input voltage, v_i. The schematic representation of a typical buck converter is shown in Figure 1.

The initial design of the converter is carried out in this work through a two-stage process. The first stage involves the calculation of main parameters of the converter, and the second stage involves the design of the nonlinear toroidal inductor, as described below.

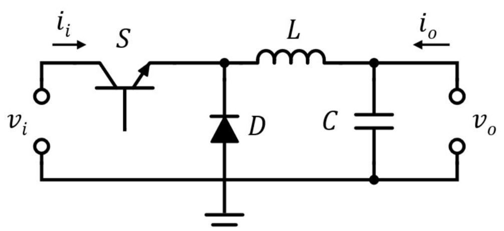


Fig. 1. Typical DC-DC buck converter representation.

A. Buck Converter Design

The buck converter operates in two modes: continuous conduction mode (CCM), and discontinuous conduction mode (DCM). In CCM, the inductor current remains non-zero throughout a single switching cycle. This results in a continuous input current due to the inductor being connected in series with the power source [12].

The initial parameters of the buck converter are obtained from the equations presented in [13]. In order to achieve appropriate power conversion for $v_i = 30$ V and $v_o = 15$ V. The switching frequency is selected as 50 kHz with a duty cycle $D = 0.5$, so that:

$$v_o = Dv_i \qquad (1)$$

To ensure that the buck converter is operated in CCM mode, the lower margins of inductor ($L_{\min}$) and smoothing capacitor ($C_{\min}$) are calculated as follows:

$$L_{\min} = \frac{(1-D)\,R}{2 f_{sw}} \qquad (2a)$$

$$C_{\min} = \frac{(1-D)}{16\,L\,(f_{sw})^2} \qquad (2b)$$

where R is a resistive load, f_{sw} is the switching frequency of the semi conductive device, and L is the inductor value selected for the design. In practice, L is typically chosen to be about 10 times the margin inductor value. The resulting values for the cases studied in Section IV of this paper are listed in Table 1.

B. Toroidal Inductor Design

The performance of a buck converter is significantly impacted by the design of its magnetic components [5]. Inductor design plays a crucial role in the overall design stage. To determine the number of turns required to achieve a minimum of 1 mH, this work studies the use of three high-frequency magnetic materials, as listed in Table 2. The use of Frenetic AI resulted in the selection of a T35/22/9.8 core type, as well as the calculation of the required number of turns for each type of material. T35/22/9.8 represents the core dimensions: outside diameter of 35.2 mm, inside diameter of 22.5 mm, and height of 9.8 mm (with two stacks), as presented in Table 2.

For COMSOL simulations, the toroidal inductor dimensions and materials from Frenetic AI's design (T35/22/9.8) are introduced as listed in Table III, also including an external region of air to provide an outside boundary to the problem.

TABLE 1: Buck Converter Selected Parameters

Parameter	Value
Input Voltage, V_{in}	30 V
Output Voltage, V_o	15 V
Duty Cycle, D	0.5
Inductor, L	1 mH
Smoothing Capacitor, C	22 uF
Load, R	3.75
Switching frequency, f_{sw}	50 kHz

TABLE 2: Toroidal Inductor Design for Different High-Frequency Magnetic Materials and Core Type T35/22/9.8

Magnetic Material	Number of Turns
High Flux 60	123
XFlux 60	122
MPP 60	180

TABLE 3: Inductor Parameters in COMSOL

Inductor Core	Circle dimensions (radius)	Applied Material
Outside Air region	50 mm	Air
Outer Coil	21.35 mm	Copper
Inner Coil	7.5 mm	
Outer Core	11.25 mm	HiFlux 60
Inner Core	17.6 mm	

III. Modeling Approach

A. Cosimulation Model

The main representation of the cosimulation approach for buck converter modeling is shown in Fig 2. The buck converter is modeled in Simulink in open-loop mode feeding a variable resistive load to evaluate different loading conditions. The converter's inductor is modeled in COMSOL Multiphysics based on its geometrical configuration and material properties, considering the non-linear (B-H curve) behavior of the core material. A current-dependent inductance model is implemented in Simulink and fed by the inductance value calculated by COMSOL for each timestep of the simulation. At the same time, COMSOL's inductance calculation depends on the current of the converter, creating a live interaction between Simulink and COMSOL, as illustrated in Fig. 2.

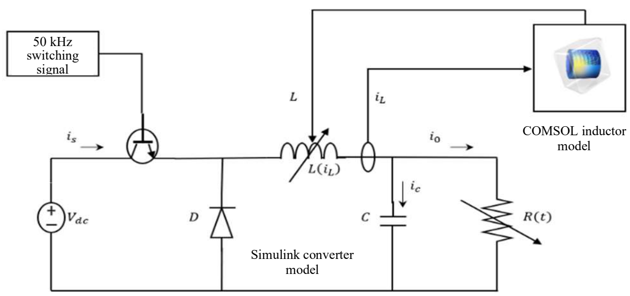


Fig. 2. Basic representation of cosimulation model of buck converter.

B. FEM-based inductor model

FEM-based inductor calculation is performed using COMSOL Multiphysics. A 2D geometrical approximation is considered in the AC/DC - magnetic fields module of COMSOL. The magnetic energy method is used for the calculation of inductance. This method requires the calculation of magnetic energy density distributed in the inductor core, its integration over the core area, and the calculation of inductance using the following equation:

$$L = 2HW_m/I^2 \quad (3)$$

where H is the core height in meters, W_m is the magnetic energy per meter, and I is the current applied to the inductor coil. A sample COMSOL simulation is shown in Fig. 3, which evidences the concentration of magnetic flux in the inductor core due to its high permeability.

C. Simulink converter model

An open-loop buck converter topology is modeled with the parameters presented in Table 1. This model is shown in the purple block of the diagram shown in Fig. 4. The Simulink model includes a variable inductor based on eq. (4), with the purpose of modeling an inductor able to provide an immediate inductor value in response to load changes.

$$i_L(t) = \frac{1}{L(t)} \int_0^t v_L(\tau)d\tau \quad (4)$$

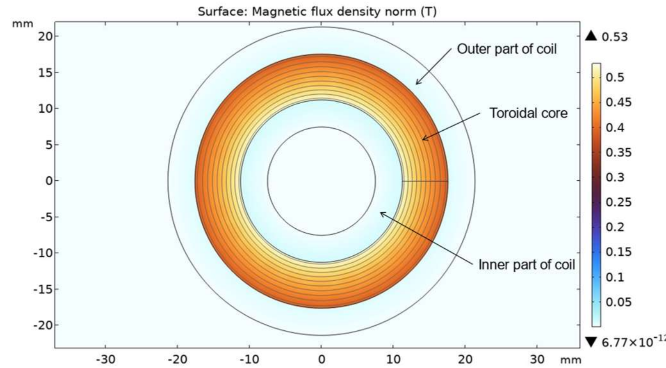


Fig. 3. COMSOL-based model of toroidal inductor.

The elements required to implement eq. (4) in Simulink are shown in the yellow block of Fig. 4. Furthermore, the COMSOL component of the model for cosimulation is shown as a green block in the same figure. It can be noticed that the variable inductor model requires an initialization step that provides the first value of inductance, so that the simulation process can start for $t = 0$. The initial value selected for this purpose is 1 mH, which aligns with the designed inductor value.

IV. Results and discussion

The test cases under study consider the buck converter parameters listed in Table I, as well as the nonlinear inductors with core materials listed in Table II. Three cases are studied: a) nominal load of 3.75 Ω, b) overload condition of 2 Ω to evaluate converter performance under inductor saturation condition, and c) overload condition of 0.5 Ω to evaluate converter performance under deep saturation condition. The results obtained with each material under evaluation are compared for the three cases. For each case, the cosimulation model was executed with a uniform time step of 2 μs. All simulations were performed using a computer server running at 2.40 GHz with 256 GB or RAM.

A. Nominal load condion (3.75 Ω)

Fig 5(a) shows the transient behavior of the inductance value under nominal load. Although the value of inductance is similar for all three materials when steady state is reached, its transient behavior is different due to differences in their BH curves, which is reflected in the transient current and voltage responses observed, as seen in Figs. 5(b) and 5(c). Although some differences are evident during transient state, a similar output voltage is achieved with all materials under evaluation.

B. Overload condition (2.0 Ω)

In this case the differences in the transient behavior of different materials becomes substantially more evident. Specifically, the MPP core inductor exhibits very poor performance, reaching deep saturation that results in wildly varying inductance and corresponding spikes in inductor current and output voltage, as seen in Fig 6. This large and fast-rising overcurrent and overvoltage values would trigger protection elements of the converter. This complex behavior is only possible to predict by means of a detailed nonlinear inductor model included in the transient converter simulation.

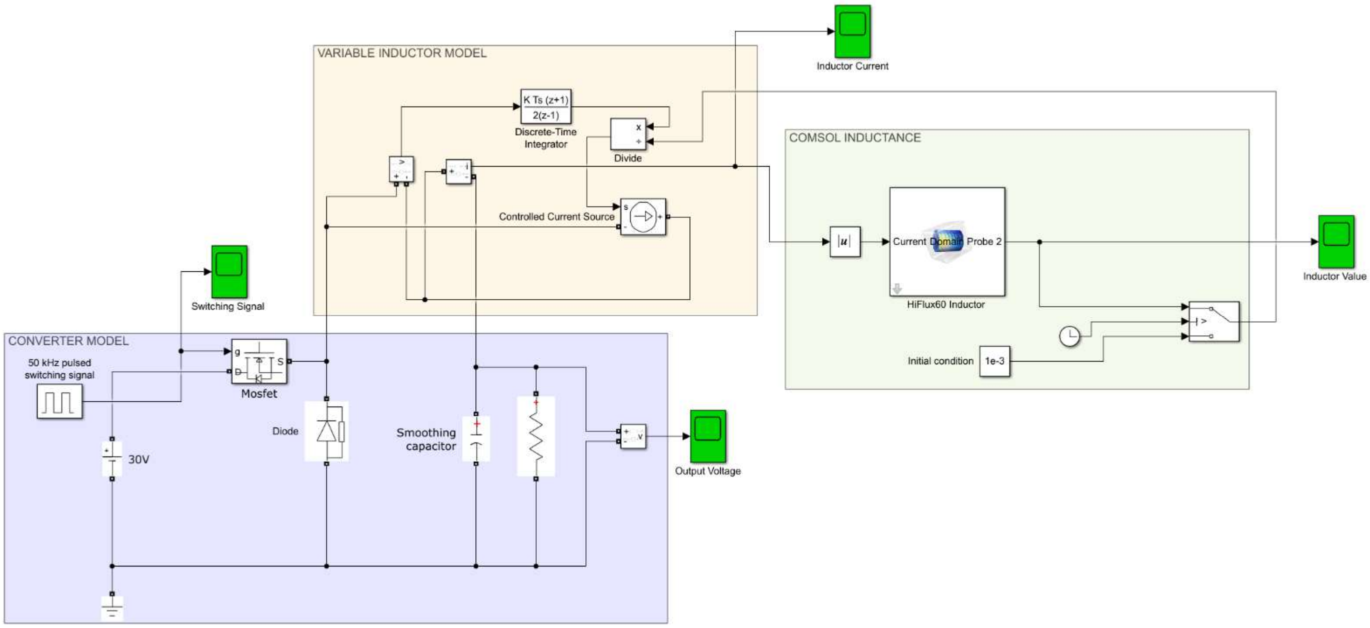
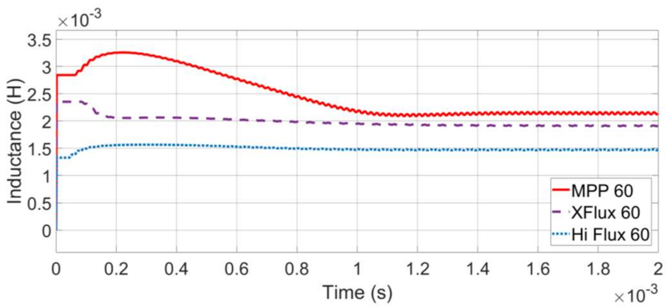
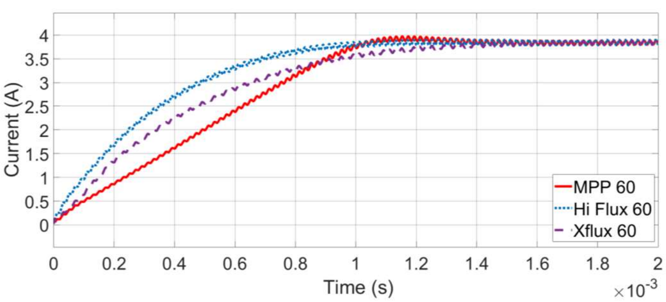


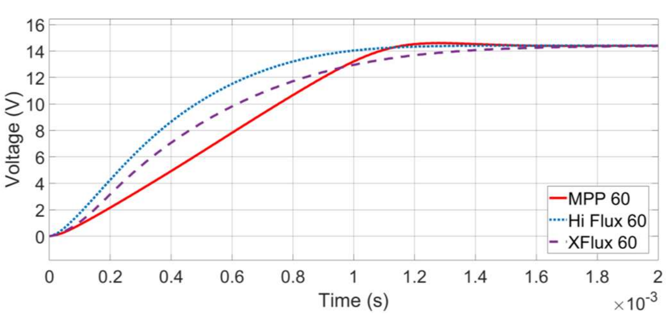
Fig. 4. DC-DC Buck converter Simulink model interfaced with COMSOL.



(a)

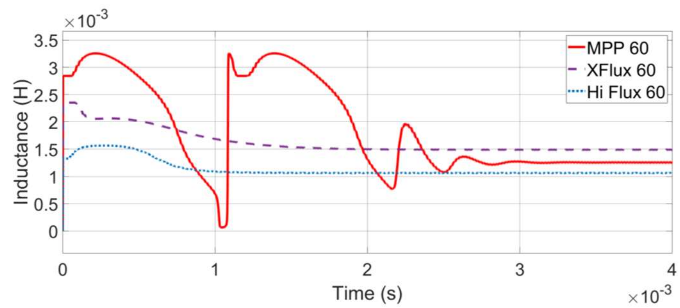


(b)

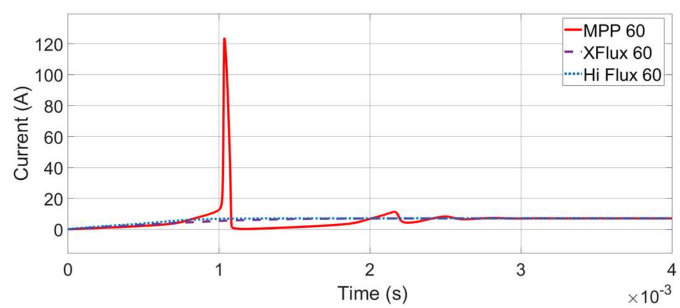


(c)

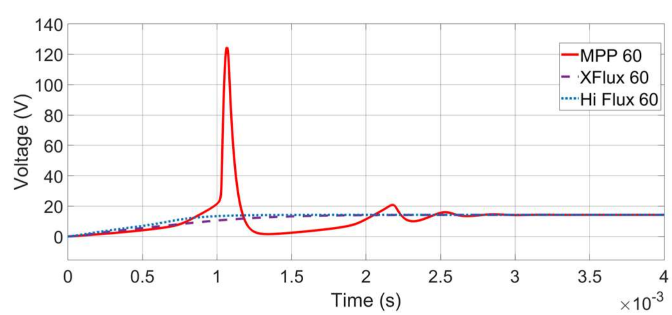
Fig. 5. Results for nominal load condition.



(a)



(b)



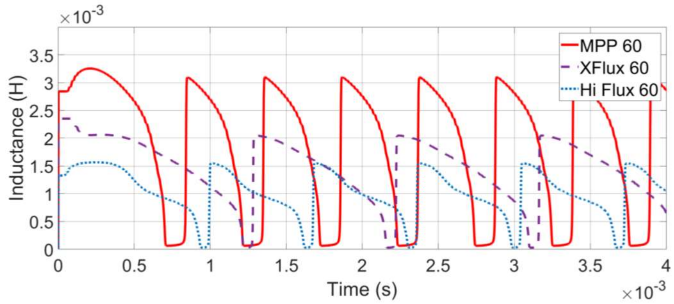
(c)

Fig. 6. Results for overload condition - 2 Ω.

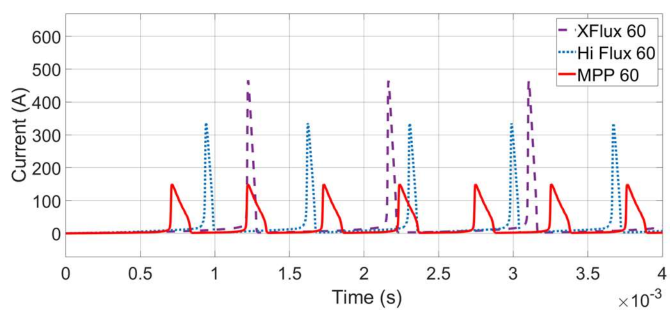
C. Deep saturation condition (0.5 Ω)

For this final case the load is substantially larger than the nominal load, so the inductor is expected to reach deep saturation. This is evident from Fig. 7(a), which shows how the inductance value oscillates between a maximum and a minimum value, corresponding to the limiting slopes of the B-H curve for each core material. Very large and sustained overcurrent and overvoltage oscillations are observed in all cases (Figs. 7(a) and 7(b)). Although in practice the protection element(s) of the converter are expected to act at the first spike of the transient response (around 0.7 ms), the plot for a longer period of time is presented to showcase the appropriate performance of the cosimulation model.

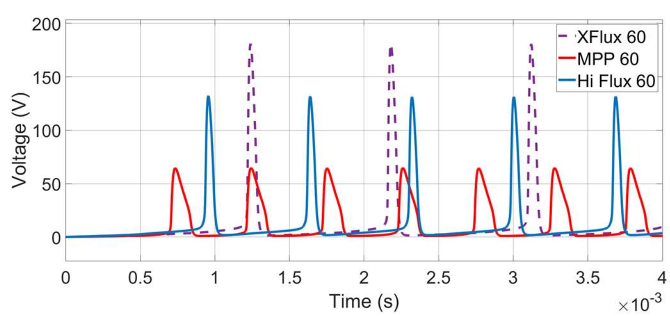
Overall, it is observed that the converter load has a very important effect on the shape and behavior of the transient response for each material considered. Different inductance values are achieved during transient state, which strongly affect the output voltage obtained by each converter.



(a)



(b)



(c)

Fig. 6. Results for overload condition – 0.5 Ω.

V. Conclusions

This paper proposed the use of a novel cosimulation approach to investigate the impact of magnetic material selection on the dynamic behavior of DC-DC buck converters. The results and observations of this study demonstrate that the unique magnetic characteristics of each magnetic material can significantly impact the transient and steady state performance of the converter under different loading conditions. Thus, the use of cosimulation tools can offer valuable insights into the appropriate selection of magnetic materials to achieve a cost-effective inductor with minimum size, which can benefit a wide range of industries that utilize DC-DC converters.

Further research should focus on the experimental verification of the simulation results achieved in this work, as well as its extension to other DC-DC converter topologies. Furthermore, a similar approach can be applied to study the behavior of other magnetic components in grid applications, such as transformers and motors.

References

[1] B. J. Masserant, E. W. Beans and T. A. Stuart, "A study of volume versus frequency for soft switching IGBT converters," *IEEE Trans. Aerospace and Electronic Systems*, vol. 31, no. 1, pp. 280-287, Jan. 1995.

[2] R. M. Schupbach and J. C. Balda, "35 KW ultracapacitor unit for power management of hybrid electric vehicles: bidirectional DC-DC converter design," *2004 IEEE 35th Annual Power Electronics Specialists Conference,* Aachen, Germany, 2004, pp. 2157-2163.

[3] R. A. Jensen and C. R. Sullivan, "Optimal core dimensional ratios for minimizing winding loss in high-frequency gapped-inductor windings," 2003 *IEEE Applied Power Electronics Conference and Exposition (APEC '03)*, Miami Beach, FL, USA, 2003, pp. 1164-1169.

[4] M. Gerber, J. A. Ferreira, I. W. Hofsajer and N. Seliger, "A very high density, heatsink mounted inductor for automotive applications," *IEEE Industry Applications Conf.*, Pittsburgh, PA, USA, 2002, pp. 948-954.

[5] C. L. Shen and H. Liou, "Magnetic Material Assessment of a Novel Ultra-High Step-Up Converter with Single Semiconductor Switch and Galvanic Isolation for Fuel-Cell Power System," *Materials*, vol. 10, no. 11, pp. 1311, Nov. 2017.

[6] B. J. Masserant, E. W. Beans, T. A. Stuart, "A study of volume versus frequency for soft switching IGBT converters," *IEEE Trans. Aerospace and Electronic Systems*, vol. 31, no. 1, pp. 280-287, Jan. 1995.

[7] S. Dennetière, Y. Guillot, J. Mahseredjian, M. Rioual, "A link between EMTP-RV and FLUX3D for transformer energization studies", *Electric Power Systems Research*, vol. 79, no. 3, pp. 498-503, March 2009

[8] C. Dufour, V. Lapointe, J. Belanger, S. Abourida, "Hardware-in-the-loop closed-loop experiments with an FPGA-based permanent magnet synchronous motor drive system and a rapidly prototyped controller," *IEEE Int. Symp. on Industrial Electronics*, Cambridge, UK, June 2008

[9] E. Melgoza, C. A. Cruz, V. Venegas, R. Escarela-Perez, J. L. Guardado, "Strong Coupling of Electromagnetic Transients and Finite Element Magnetic Field Solvers," *IEEE Trans. Magnetics*, vol. 47, no. 11, pp. 4574-4581, Nov. 2011

[10] B. Asghari, V. Dinavahi, M. Rioual, J. A. Martinez, R. Iravani, "Interfacing Techniques for Electromagnetic Field and Circuit Simulation Programs," *IEEE Trans. Power Delivery*, vol. 24, no. 2, pp. 939-950, April 2009

[11] M. O. Faruque et al., "Interfacing Issues in Multi-Domain Simulation Tools," *IEEE Trans. Power Delivery*, vol. 27, no. 1, pp. 439-448, Jan. 2012

[12] S. C. Chung, S. R. Huang, C. I. Lin, "Applications of describing functions to estimate the continuous and discontinuous conduction mode for a DC-to-DC buck converter," *IEE Proc. Electric Power Applications*, vol. 147, no. 6, pp. 513-519, Nov. 2000.

[13] N. Mohan, T. M. Undeland and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*. Hoboken, NY: John Wiley & Sons, 2003.

[14] Integrate COMSOL Multiphysics® into Simulink® with LiveLink™ for Simulink®. Available online: https://www.comsol.com/livelink-simulink, COMSOL Inc., 2021

[15] R. W. Erickson, "DC-DC Converters," in *Wiley Encyclopedia of Electrical and Electronics Engineering*, J. G Webster, Ed. Hoboken, NY: John Wiley & Sons, 2007, pp. 1-18