

ANALYSIS AND SIMULATION OF A NOVEL COUPLED INDUCTOR BIDIRECTIONAL DC-DC CONVERTER

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Abstract - This paper proposes a novel bidirectional coupled inductor non-isolated DC-DC converter. It is relatively feasible for low-input-voltage applications for interfacing energy storage elements, such as batteries, and ultracapacitors with the high voltage DC bus in hybrid electric vehicles and electric vehicles. The converter can operate as step-up or step-down voltage in both directions, as well, the turns ratio confers a great voltage gain without using transformer, these give versatility and a lot of applications. Both directions of the power flow is analysed and explained, the DC voltage gain versus the duty cycle has been presented, and the mathematical analysis is validity with a simulation model.

Keywords – Bidirectional DC-DC converter, Coupled inductor, Step-up and step-down converter

NOMENCLATURE

- L_1 Inductance L_1 .
- L_2 Inductance L_2 .
- n_1 Turns ratio.
- f_s Operation frequency.
- ΔE_1 Output voltage ripple of E_1 .
- ΔE_2 Output voltage ripple of E_2 .
- Δi_{L1} Current ripple of coupled inductor.

I. INTRODUCTION

Nowadays, is visible an effort by industry of power electronics to search for power converters maximize the efficiency, greater versatility, high power density and low cost to electric vehicles (EV) and mobile gadgets applications, minimizing the weight and maximizing the autonomy [1–4]. Mainly in a context with politics to reduce fossil fuel consumption to decrease the greenhouse effects [5]. In a traditional EV structure, the battery cell needs to step-up voltage by a DC-DC converter for an inverter. A fuel cell (FC) powering system for hybrid electric vehicle (HEV) are consisting of fuel cell stacks, a unidirectional step-up converter, an inverter, battery packs, and a bidirectional DC-DC converter is shown in Figure 1 [6–9]. Sometimes, this DC-DC stages needs a topology which uses a bulky magnetic element, such as a transformer, increasing the costs, weight and decreasing the efficiency of the converter [10]. Other solution which confers high voltage gain is to use the

coupled inductors, and compared with an isolation transform, the coupled inductor provides low conduction losses [10] [11].

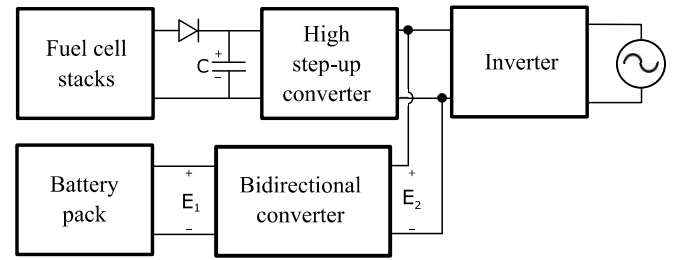


Fig. 1. : Typical fuel cell based hybrid electric vehicle power train application

The use of coupled inductors usually presents practical limitations in its construction which affect the operation of the converter, causing high voltage spike across the switches at their turn-off by the leakage inductances, specially in applications where the input voltage is low and the output voltage is high, this needs high turns ratio increasing the voltage stress in the semiconductors, decreasing efficiency. To minimize this problem a dissipative snubber can be applied to reduce losses and mitigate the voltage-spike across the devices, some authors [10,12–16], use auxiliary capacitors and switches to transfer the energy stored in the leakage inductance and provide soft switching. This paper, aims to provide a basic analysis of the novel bidirectional DC-DC converter with coupled inductor operating in continuous conduction mode (CCM) in first section, in second one a mathematical analysis for both directions of the energy flow and a simulation, and comparison with mathematics analysis in the third section.

II. PROPOSED BIDIRECTIONAL DC-DC CONVERTER

The proposed topology of the bidirectional DC-DC coupled inductor is presented in Figure 2. The circuit is composed of three power switches (S_1 , S_2 and S_3), one coupled inductor (LC), two capacitors (C_1 and C_2) and DC sources (E_1 and E_2). Although the circuit use few components, it allows bidirectional power flow. To facilitate the theoretical description and mathematical analysis, assume:

1. The operation is in steady state;
2. All components are ideal;
3. Input voltages and output currents are constant;
4. The windings of the inductor (LC) is tightly coupled and have a negligible resistance.

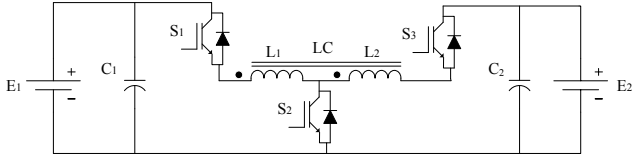


Fig. 2. : Bidirectional DC-DC coupled inductor topology

A. Operating mode from E_1 to E_2

In this sense, the power flow from E_1 to E_2 is obtained by modulating S_2 , keeping S_1 turn on and S_3 turn off. Figure 3 shows the modulation diagram and interval time that will be referred to as operation mode from E_1 to E_2 .

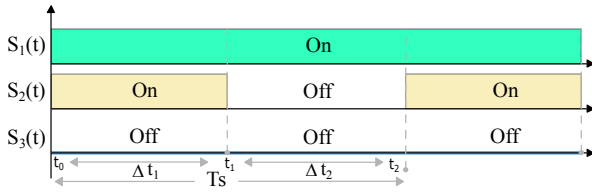


Fig. 3. : Switching diagram of operation mode from E_1 to E_2

In CCM operation, the proposed converter has two topological steps for switching period that can be described as follows.

First step ($0 \rightarrow DT_s$): This stage starts at instant t_0 , when the switches S_2 is turned on. The input current (I_1) is flowing through the switches S_1 , S_2 and inductor L_1 , the current in L_2 is zero and current $i_{L1}(t)$ increases linearly. The voltages on the inductors L_1 and L_2 are E_1 and $E_1 n_1$, respectively. The load (R_2) receives energy from the output capacitor C_2 . The equivalent circuit of this step is illustrated in Figure 4(a). The expressions representing this first step are:

$$\begin{aligned} v_{L1} &= E_1 & v_{L2}(t) &= E_1 n_1 \\ i_1(t) &= i_{L1}(t) & \Delta t_1 &= t_1 - t_0 = D_1 T_s \\ i_{S1}(t) &= i_{S2}(t) = i_1(t) & v_{S1}(t) &= v_{S2}(t) = 0 \\ i_{S3}(t) &= 0 & v_{S3}(t) &= -E_2 - E_1 n_1 \\ i_{C2}(t) &= I_2 & v_{C2}(t) &= E_2 \end{aligned} \quad (1)$$

Second step ($DT_s \rightarrow T_s$): At the instant $t_0 = t_1$, switch S_2 is turned off and the diode of S_3 is forward biased. The currents $i_{L1}(t)$ and $i_{L2}(t)$ decrease linearly. The voltages on the inductors L_1 and L_2 are $(E_1 - E_2)/(1 + n_1)$ and $(E_1 - E_2)n_1/(1 + n_1)$, respectively. The energy stored in the coupled inductor core is transferred to the load (R_2) through inductor L_2 and diode of S_3 . Furthermore, the output current (I_2) is equal $i_{L2}(t) - i_{C2}(t)$. This step is shown in Figure 4(b). The voltages, currents and interval time can be represented as following equations:

$$\begin{aligned} v_{L1} &= \frac{E_1 - E_2}{1 + n_1} & v_{L2}(t) &= \frac{(E_1 - E_2)n_1}{1 + n_1} \\ i_1(t) &= i_{L1}(t) & i_1(t) &= i_{L2}(t) \\ i_{S1}(t) &= i_{S3}(t) = i_1(t) & v_{S1}(t) &= v_{S3}(t) = 0 \\ i_{S2}(t) &= 0 & v_{S2}(t) &= \frac{-(E_1 n_1 + E_2)}{1 + n_1} \\ i_{C2}(t) &= i_{L2}(t) - I_2 & v_{C2}(t) &= E_2 \\ \Delta t_2 &= t_2 - t_1 = (1 - D_1)T_s \end{aligned} \quad (2)$$

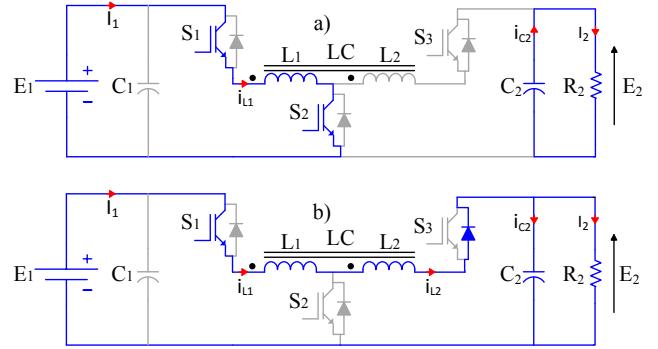


Fig. 4. : Topological steps in CCM for operation mode from E_1 to E_2

B. Operating mode from E_2 to E_1

In this sense, the power flow from E_2 to E_1 is obtained by modulating S_3 , keeping S_2 and S_1 off. Figure 5 shows the modulation diagram and interval time that will be referred to as operation mode from E_2 to E_1 .

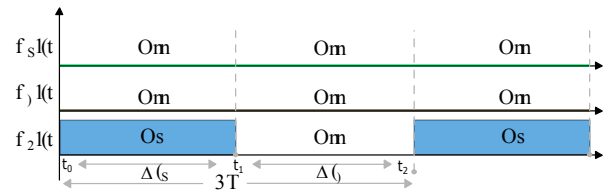


Fig. 5. : Switching diagram of operation mode from E_2 to E_1

In each switching period the proposed converter presents two topological steps for CCM. These steps are described as follows:

First step ($0 \rightarrow DT_s$): During this stage, the primary and secondary winding of coupled inductor store energy when the switch S_3 is turned on. The input current (I_2) is flowing through the switches S_1 , S_3 and inductor L_2 and L_1 , the current I_2 , i_{L1} and i_{L2} are equals and they increase linearly. The voltages across L_1 and L_2 are equal $(E_1 - E_2)/(1 + n_1)$ and $(E_1 - E_2)n_1/(1 + n_1)$, respectively. The load (R_1) and output capacitor (C_1) receive energy from inductor L_1 through the diode of S_1 . The equivalent circuit of this step is shown in Figure 6(a) and its expressions can be presented as follows:

$$\begin{aligned}
v_{L1} &= \frac{E_1 - E_2}{1 + n_1} & v_{L2}(t) &= \frac{(E_1 - E_2)n_1}{1 + n_1} \\
i_2(t) &= i_{L2}(t) = i_{L1}(t) & \Delta t_1 &= t_1 - t_0 = (D_2)T_S \\
i_{S1}(t) &= i_{S3}(t) = i_2(t) & v_{S1}(t) &= v_{S3}(t) = 0 \\
i_{S2}(t) &= 0 & v_{S2}(t) &= -E_2 - \frac{(E_1 - E_2)n_1}{1 + n_1} \\
i_{C1}(t) &= i_{L1}(t) - I_1 & v_{C1}(t) &= E_1
\end{aligned} \quad (3)$$

Second step ($DT_s \rightarrow T_s$): During this stage, the switch S_3 is turned off and the diode of S_2 is forward biased. The current $i_{L2}(t)$ is zero and $i_{L1}(t)$ decrease linearly, the voltage inductor of L_1 and L_2 are E_1 and $E_1 n_1$, respectively. The energy stored in the coupled inductor core is transferred to the load (R_1) through inductor L_1 and diode of S_1 and S_2 . Additionally, output and input current is equal $I_{L1} - i_{C1}$ and 0, respectively. The equivalent circuit of second step of proposed topology is shown in Figure 6(b). The voltages, currents and interval time can be determined by the following expressions:

$$\begin{aligned}
v_{L1} &= E_1 & v_{L2}(t) &= E_1 n_1 \\
i_2(t) &= i_{L2}(t) = 0 & i_{S3}(t) &= 0 \\
i_{S1}(t) &= i_{S2}(t) & v_{S1}(t) &= v_{S2}(t) = 0 \\
i_{S2}(t) &= i_{L1}(t) & v_{S3}(t) &= -E_2 - E_1 n_1 \\
i_{C1}(t) &= i_{L1}(t) - I_1 & v_{C1}(t) &= E_1 \\
\Delta t_2 &= t_2 - t_1 = (1 - D_2)T_S
\end{aligned} \quad (4)$$

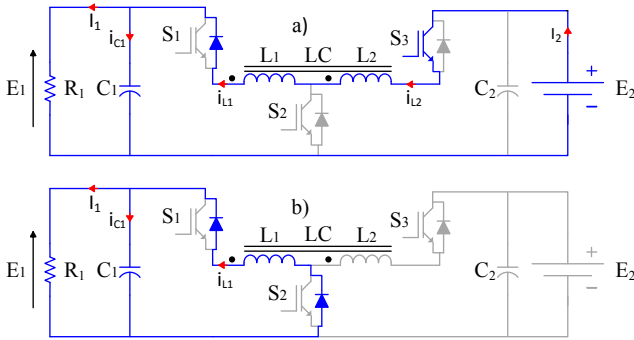


Fig. 6. : Topological steps in CCM for operation mode from E_2 to E_1

III. MATHEMATICAL ANALYSIS OF PROPOSED CONVERTER IN CCM

In this section, the main expressions to calculate the DC voltage gain, input inductance and output capacitor of the proposed topology in CCM are done.

A. DC voltage gain in operation mode from E_1 to E_2

The energy of bidirectional DC-DC coupled inductor can flow in both directions; in operation mode from E_1 to E_2 , voltage through inductor L_1 in first and second step is E_1 and $(E_1 - E_2)/(1 + n_1)$, respectively. According to equations (1)-(2) and based on the voltage-second balance principle in L_1 , the DC voltage gain in CCM can be derived as:

$$\frac{E_2}{E_1} = \frac{1 + n_1 D_1}{1 - D_1} \quad (5)$$

The voltages across inductance L_1 can be represented as follow: [?]

$$V_{L1}(t) = L_1 \frac{\Delta i_{L1}}{\Delta t_1} \quad (6)$$

Where $V_{L1}(t)$ and Δt_1 are equal to E_1 and DT_s , respectively. Working at the previous equation, (7) is obtained the input inductance for operation mode from E_1 to E_2 .

$$L_1 = \frac{E_1}{\Delta i_{L1} \cdot f_s} D_1 \quad (7)$$

Output capacitor value (C_2) is determined by equation (8).

$$C_2 = \frac{I_2}{\Delta E_2 \cdot f_s} D_1 \quad (8)$$

Figure 7 shows the graphic of ideal DC voltage gain characteristic as a function of duty cycle. A comparison is done clearly, because in this operation mode offers higher DC voltage gain compared to the conventional boost DC-DC converter. As shown in Figure 7, in the case of $D_1 = 0.5$ and $n_1 = 0.5$, the proposed converter has a higher voltage step up gain than the conventional boost converter. In addition, it may be noted that, when $n_1 = 0.5$, the proposed converter is step-up converter and it is continued has higher DC voltage gain.

B. DC voltage gain in operation mode from E_2 to E_1

The DC voltage gain expression in operation mode from E_2 to E_1 , for a CCM, can be obtained from the analysis of the average voltage through the inductor winding L_1 . According to equations (3)-(4), the voltage-second balance principle in L_1 is given by equation (9).

$$\frac{1}{T_s} \left[\int_0^{D_2 T_s} \frac{E_1 - E_2}{1 + n_1} dt + \int_0^{(1-D_2)T_s} E_1 dt \right] = 0 \quad (9)$$

Developing equation (9), the DC voltage gain is done:

$$\frac{E_1}{E_2} = \frac{D_2}{1 + n_1(1 - D_2)} \quad (10)$$

When the switch S_3 is turned off, the current through the inductor L_1 decreases and the current through the switch S_3 is zero. According to second step analysis, the voltage equation of inductor L_1 is obtained as:

$$E_1 = L_1 \frac{\Delta i_{L1}}{1 - D_2} \quad (11)$$

Hence, the input inductance (L_1) obtained from equation (12) is

$$L_1 = \frac{E_1}{\Delta i_{L1} \cdot f_s} (1 - D_2) \quad (12)$$

The following equation can be used to adjust the output capacitor value (C_1) for a desired output voltage ripple:

$$C_1 = \frac{I_1 D_2 - I_2}{\Delta E_1 \cdot f_s} \quad (13)$$

Figure 8 shows the relationship of DC voltage gain versus the duty cycle for proposed DC-DC converter and conventional Buck DC-DC converter. Obviously, the voltage gain of proposed converter is smaller than that of the conventional Buck converter under the same duty cycle and with various turns ratio values.

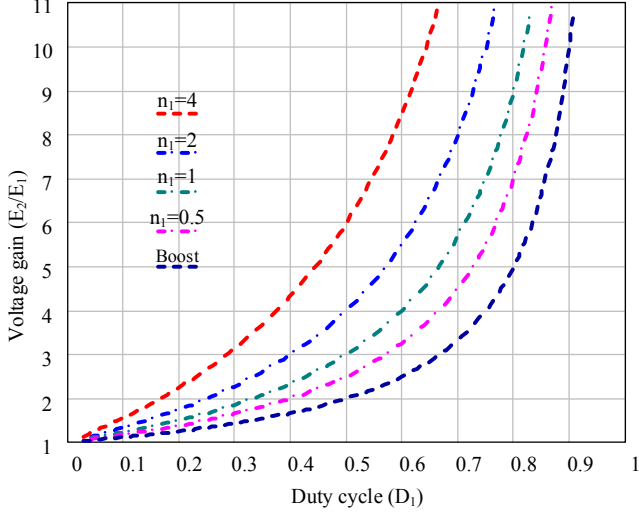


Fig. 7. : DC voltage gain as function of duty cycle during operation from E_1 to E_2

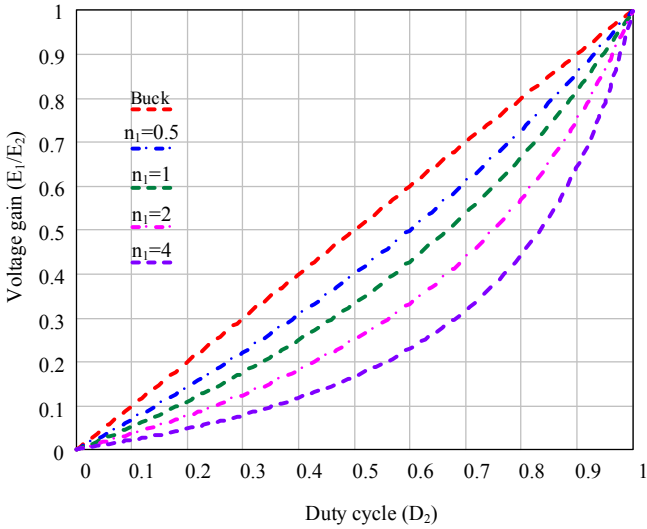


Fig. 8. : DC voltage gain as function of duty cycle during operation from E_2 to E_1

IV. SIMULATION RESULTS

Simulation studies of the proposed topology are presented to verify the performance, it has been carried out in OrCAD Capture using ideal components. Table I shows the parameters used for calculate the values of simulation components.

Using the design equations (8), (12) and (13), the values of inductors and capacitors are found and show on Table II. The

TABLE I: Simulation parameters

Description	Power flow	
	From E_1 to E_2	From E_2 to E_1
Input voltage	200 V	400 V
Output voltage	400 V	200 V
ΔE_1	2 %	
ΔE_2	2 %	
Δi_{L1}	5 %	
Output power	1 kW	
n_1	2.5	
f_s	50 kHz	

converter is designed such that it can remain in CCM in both operation modes.

When the power flows from E_1 to E_2 , the converter operates in a step-up mode. The DC voltage gain and duty cycle in this operation mode can be calculated as

$$q_{E_1 \rightarrow E_2} = \frac{E_2}{E_1} = \frac{400 \text{ V}}{200 \text{ V}} = 2$$

$$D_1 = \frac{q_{E_1 \rightarrow E_2} - 1}{n_1 + q_{E_1 \rightarrow E_2}} = \frac{2 - 1}{2.5 + 2} = 0.222 \quad (14)$$

The value of load resistance is

$$R_2 = \frac{E_2^2}{P} = \frac{(400 \text{ V})^2}{1 \text{ kW}} = 160 \Omega \quad (15)$$

When the power flows from E_2 to E_1 , the converter operates in a step-down mode, the DC voltage gain and duty cycle value are:

$$q_{E_1 \rightarrow E_2} = \frac{E_1}{E_2} = \frac{200 \text{ V}}{400 \text{ V}} = 0.5$$

$$D_2 = \frac{q_{E_2 \rightarrow E_1} \cdot (1 + n_1)}{1 + q_{E_2 \rightarrow E_1}} = \frac{0.5(1 + 2.5)}{1 + 0.5 \cdot 2.5} = 0.778 \quad (16)$$

The load resistance in operation mode from E_2 to E_1 is obtained as:

$$R_1 = \frac{E_1^2}{P} = \frac{(200 \text{ V})^2}{1 \text{ kW}} = 40 \Omega \quad (17)$$

TABLE II: Components designed according to the proposed equations

Description	Power flow	
	From E_1 to E_2	From E_2 to E_1
D	$D_1 = 0.23$	$D_2 = 0.784$
L_1	3.6 mH	
Output capacitor	2.8 μF	6.9 μF
Load	$R_2 = 160 \Omega$	$R_1 = 40 \Omega$

A. Simulation results in operation mode from E_1 to E_2

From the results obtained in figure 9(a), it is clearly observed that the proposed converter steps up the voltage from 200 V to 400 V. In addition, the simulated voltage gain is equal to the calculated one, as shown in (14).

$$q_{\text{Calculated}} = \frac{1 + n_1 D_1}{1 - D_1} = \frac{1 + (2.5 \cdot 0.222)}{1 - 0.222} = 1.99$$

$$q_{\text{Simulated}} = \frac{400}{200} = 2.00 \quad (18)$$

In Figure 9(b), the current across winding coupled inductors L_1 and L_2 for the operation mode from E_1 to E_2 . It is observed that the winding inductor current flows continuously during the entire switching cycle in steady-state operation, these simulation results have similar trends to the theoretical operational analysis. In Figure 9(c), the winding inductor voltage of the L_1 . Waveform shows that the converter presents two operation steps during a switching period. It has been observed the voltage values of the winding inductor (L_1) during the first and second steps are the same presented in the mathematical analysis, according to equations (1) and (2). The simulation waveform, shown in Figure 9(d), illustrates the input and output current of proposed converter. It is noted that input current ($I_1(t)$) is the same winding inductor current ($I_{L1}(t)$).

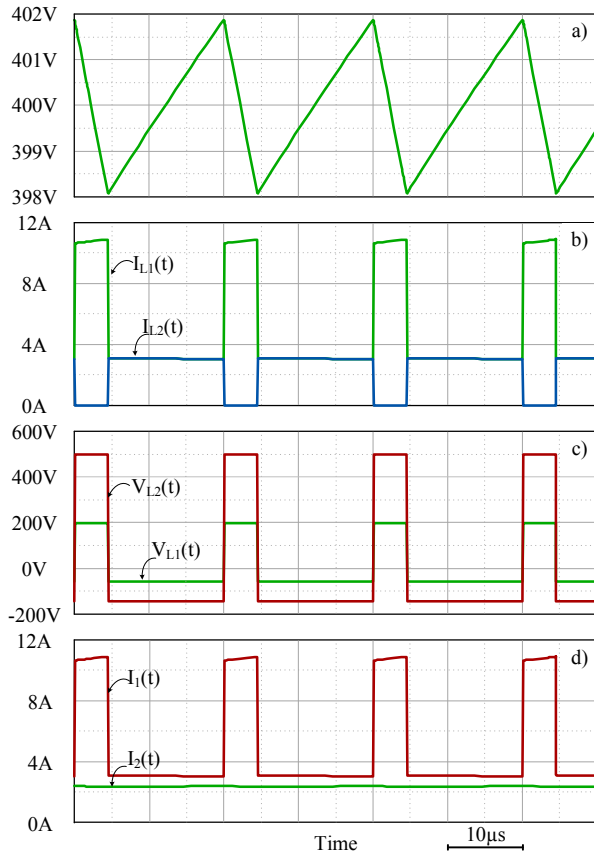


Fig. 9. : Simulated waveforms in the operation mode from E_1 to E_2 . a) Output voltage; b) Current I_{L1} and I_{L2} ; c) Voltage V_{L1} and V_{L2} ; d) Current I_1 and I_2

B. Simulation results in operation mode from E_2 to E_1

Figure 10 shows the simulation waveforms when the converter works in operation mode from E_2 to E_1 . The output voltage (E_1) is illustrated Figure 10(a), it is verified that the output voltage value is confirmed to the theoretical value (According to equation (10)). Furthermore, It can also be observed the converter operates as a step-down converter. In Figure 10(b), is shown the winding inductor voltage of the L_1 . It has been observed that the voltage values in first and second steps is equal to theoretical values presented in (3)

and (4). In Figure 10(c), the current across winding coupled inductors L_1 and L_2 . It can be observed from the waveform that the converter operates in continuous conduction mode. In addition, it is verified that the simulation results are similar of the theoretical operational analysis. The simulation waveform, exposed in figure 10(d), illustrates the input and output current of proposed converter. It is noted that input current ($I_2(t)$) is the same winding inductor current ($I_{L2}(t)$).

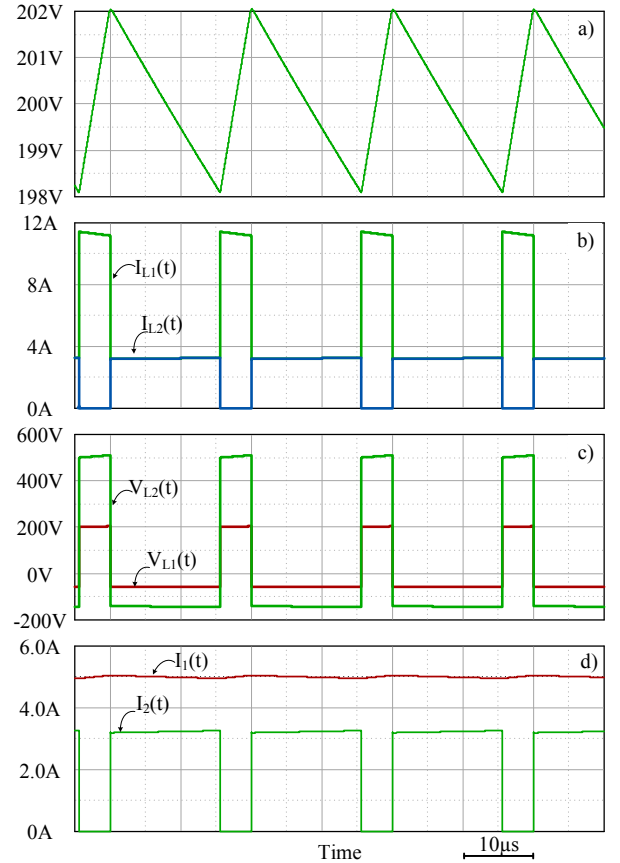


Fig. 10. : Simulated waveforms in the operation mode from E_2 to E_1 . a) Output voltage; b) Current I_{L1} and I_{L2} ; c) Voltage V_{L1} and V_{L2} ; d) Current I_1 and I_2

V. CONCLUSION

The proposed DC-DC converter with coupled inductor was introduced in this paper. Compared to the conventional DC-DC converters, it has advantages in terms of DC voltage gain without any isolation, capability of operation in different converter topologies (buck, boost), as well as bidirectional operation. Mathematical analyses were presented considering all ideal components, which show a basis for understanding the operation of the converter. Detailed analyses as well as simulation results were presented for the bidirectional DC-DC coupled inductor operating in both operation mode and compared with the ideal analytical results.

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REFERENCES

- [1] A. Bindra, "Projecting the evolution of power electronics: Highlights from feppcon viii," *IEEE Power Electronics Magazine*, vol. 3, no. 1, pp. 32–44, 2016.
- [2] C. L. Remes, M. B. Rosa, and S. V. G. Oliveira, "A two-switch forward converter application for battery charging," in *Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), 2015 IEEE 13th Brazilian*. IEEE, 2015, pp. 1–6.
- [3] A. Emadi, *Advanced electric drive vehicles*. CRC Press, 2014.
- [4] R. Mayer, A. Péres, and S. V. G. Oliveira, "Conversor cc-cc multifásico bidirecional em corrente não isolado aplicado a sistemas elétricos de tração de veículos elétricos e híbridos," *Revista de Eletrônica Sobraep*, vol. 20, no. 3, Agosto 2015.
- [5] B. K. Bose, "Energy, global warming and impact of power electronics in the present century," *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications*, pp. 1–26, 2014.
- [6] L. Zhang, D. Xu, G. Shen, M. Chen, A. Ioinovici, and X. Wu, "A high step-up dc to dc converter under alternating phase shift control for fuel cell power system," *IEEE Transactions on Power Electronics*, vol. 30, no. 3, pp. 1694–1703, 2015.
- [7] K. Yedavalli, L. Guo, and D. S. Zinger, "Simple control system for a switcher locomotive hybrid fuel cell power system," *IEEE Transactions on Industry Applications*, vol. 47, no. 6, pp. 2384–2390, 2011.
- [8] K. Jin, X. Ruan, M. Yang, and M. Xu, "Power management for fuel-cell power system cold start," *IEEE Transactions on power electronics*, vol. 24, no. 10, pp. 2391–2395, 2009.
- [9] S. N. Motapon, L.-A. Dessaint, and K. Al-Haddad, "A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft," *IEEE transactions on industrial electronics*, vol. 61, no. 3, pp. 1320–1334, 2014.
- [10] T.-F. Wu, Y.-S. Lai, J.-C. Hung, and Y.-M. Chen, "Boost converter with coupled inductors and buck–boost type of active clamp," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 1, pp. 154–162, 2008.
- [11] M. B. El Kattel, R. Mayer, and S. V. G. Oliveira, "Analysis and simulation of a three-phase push-pull/flyback interleaved bidirectional dc-dc converter," in *Industrial Electronics Society, IECON 2016-42nd Annual Conference of the IEEE*. IEEE, 2016, pp. 1274–1279.
- [12] G. Chen, Y. Deng, L. Chen, Y. Hu, L. Jiang, X. He, and Y. Wang, "A family of zero-voltage-switching magnetic coupling non-isolated bidirectional dc-dc converters," *IEEE Transactions on Industrial Electronics*, 2017.
- [13] R. H. Ashique and Z. Salam, "A family of true zero voltage zero current switching (zvzcs) non-isolated bidirectional dc-dc converter with wide soft switching range," *IEEE Transactions on Industrial Electronics*, 2017.
- [14] I. Barbi and F. P. Souza, *Conversores CC-CC isolados de alta frequência com comutação suave*. Edição dos Autores, 1999.
- [15] L. Jiang, C. C. Mi, S. Li, M. Zhang, X. Zhang, and C. Yin, "A novel soft-switching bidirectional dc–dc converter with coupled inductors," *IEEE Transactions on Industry Applications*, vol. 49, no. 6, pp. 2730–2740, 2013.
- [16] B. Narasimharaju, S. Dubey, and S. Singh, "Design and analysis of coupled inductor bidirectional dc–dc convertor for high-voltage diversity applications," *IET Power Electronics*, vol. 5, no. 7, pp. 998–1007, 2012.