

Improved Non-Isolated Bidirectional DC-DC Converter Assisted with an Active Resonant Network

V.V.Subrahmanya Kumar Bhajana^{1,2}, Pavel Drabek²

¹ School of Electronics Engineering, KIIT University, Bhubaneswar, Odisha, India

² Regional Innovation Centre for Electrical Engineering, University of West Bohemia, Pilsen, Czech Republic

Email : bvvs.kumarfet@kiit.ac.in, kumarbv@fel.zcu.cz, drabek@fel.zcu.cz, drabek@ieee.org

Abstract— This paper proposes a new non-isolated bidirectional dc-dc converter (NI-BDC) with an auxiliary resonant network (ARN) that is typically operated in both boost and buck modes. Regardless the direction of power flow, soft-switching capabilities such as zero voltage switching (ZVS) and zero current switching (ZCS) conditions has been obtained under light and heavy loads. This converter avoids the need of coupled inductors as against conventional converters thus reducing the size of the converter and minimizes the device count. The auxiliary resonant network mainly consisting of resonant inductor, capacitor, auxiliary switch and a diode. Furthermore, the zero voltage switching and zero current switching conditions have been achieved in both boost and buck modes that reduces reverse recovery conduction period of the body diodes of all the power switches. The proposed converter operates with soft-switching at constant switching frequency giving continuous inductor current. The detailed operating principles for boost and buck modes are described. The theoretical analysis and simulation results are presented.

Keywords— Active resonant network, Bidirectional converter, soft-switching, zero voltage switching (ZVS), zero current switching (ZCS)

I. INTRODUCTION

Non-Isolated Bidirectional dc-dc converters (NI-BDC) are commonly used in many energy storage applications like battery storages systems (BSS) [1], electric vehicle charging stations (EV-CS) [2] and other renewable energy systems such as fuel cell and solar cell [3]. The amplitude of reverse currents [4] through the main switching devices are minimized through control strategies mainly operated under discontinuous conduction mode. The zero voltage switching transitions are obtained at different loads. Regardless of power transfer, minimized switching stresses, reduced current ripples and improved battery life, are the significant aspects to develop an efficient bidirectional converter. To achieve these advantages, a coupled inductor, auxiliary switches and auxiliary inductor are used in a bidirectional converter (BDC) [5]. In addition to the aforementioned merits other literatures focused on reducing the usage of auxiliary switches and eliminating the control complexity. BDCs implemented with an auxiliary winding [6-7] in addition to main inductor and an auxiliary inductor to provide the ZVS turn-on feature. However, this converter reduces switching stresses at light load conditions. In contrast to the previous soft-switching methods, combination of both coupled inductors and auxiliary switches [8] are sufficient to obtain zero voltage switching condition without using an additional inductor. Besides, the turn-on losses are greatly reduced at light load conditions. However, this converter suffers from high turn-off losses at low output power.

Different approaches were proposed in developing soft-switching based non-isolated bidirectional converter are classified as below:

1. In the first approach, in order to eliminate the large circulating current and minimal reverse recovery phenomenon, an active snubber circuit is used to reduce turn-on losses that includes lossless diodes, auxiliary switches, inductor, and capacitor in addition to the main switching devices. The ZVS condition is obtained in both the converters [9-10]. Besides, simple auxiliary cell [10] based converter can have more circulating current and conduction losses at light loads. However, active snubber based BDC drastically increases the total number of auxiliary device count. The operating switching periods of main MOSFETs and auxiliary MOSFETs are almost same. Further, the ZVS condition causes reduced voltage and current stresses. The conduction losses are more in auxiliary MOSFETs due to their wide operating turn-on periods.
2. Another approach is to use lossless passive snubber cell adopted in a BDC [12] without using auxiliary switches to achieve ZVS turn-on in both the boost and buck modes. It aims to minimize the circulating currents at light loads. However, the total numbers of passive devices are increased and coupled inductor may lead to increase the additional stresses.

This paper proposes a new soft-switching bidirectional converter with soft turn-on and soft turn off through a simple auxiliary circuit without increasing the additional losses. The next section presents description and operation principles of the converter and section III presents the simulation results.

II. DESCRIPTION OF PROPOSED BIDIRECTIONAL CONVERTER AND ITS PRINCIPLES OF OPERATION

Fig.1 shows the ZVS bidirectional converter topology [5] with an additional coupled inductor, auxiliary diodes D_{a1} , D_{a2} , auxiliary MOSFETs, S_{a1} , S_{a2} , and auxiliary capacitors, C_{a1} , C_{a2} . The proposed soft-switching bidirectional converter shown in Fig.2 is the modified version of the topology shown in Fig.1 with reduced auxiliary devices. It consists of an input inductor, L , two MOSFETs, S_1 , S_2 , a capacitor, C_o , and an active resonant network (ARN) which consists of an auxiliary MOSFET, S_a , a resonant inductor, L_a , a resonant capacitor, C_a and a diode, D_a . When the proposed converter is operating in

boost mode, ARN provides the soft-switching condition to the main MOSFETs S_1, S_2 . In buck mode operation, the same ARN provides soft-switching condition to the main switching devices. The operating principles of boost mode are divided into ten intervals from t_0 - t_{10} , as shown in Fig.3 and Fig.4 shows the equivalent circuits of each interval. In similar way, operating intervals for buck mode are divided in to nine intervals t_0 - t_9 , as shown in Fig.5.

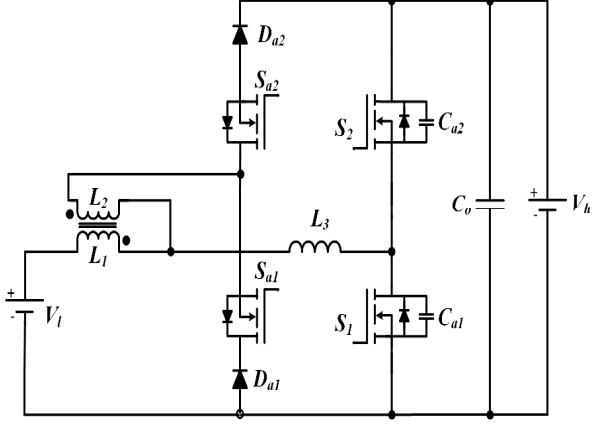


Fig. 1. ZVS Bidirectional DC-DC Converter [5]

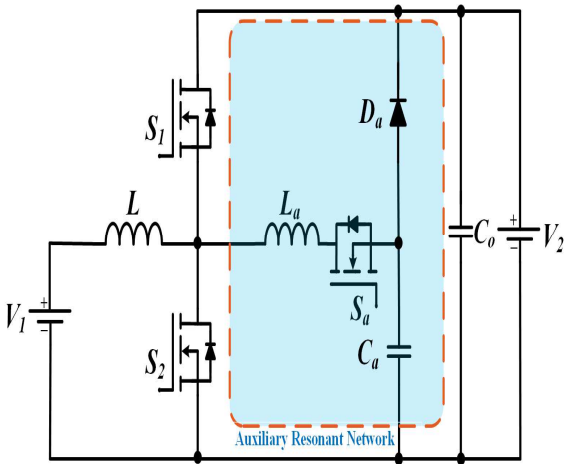


Fig. 2. Proposed Bidirectional DC-DC Converter with ARN

A. Boost mode Principles of Operation

At t_0 , S_1 is turned-off and voltage across input inductor L changes its direction from $+V_1$ to $-V_1$. The current through L starts decreasing and continues throughout the interval. At t_1 , S_2 is turned-on and output power transfers via L -body diode of S_1 - R_o . At t_2 , the auxiliary MOSFET, S_a is turned on, S_2 current falls to zero and body diode of S_2 starts conducting. Hence, the zero current switching (ZCS) turn off is achieved. During the interval, t_2 - t_3 , the resonant capacitor, C_a charges from $-V_1$ to $+V_1$. In the interval, t_3 - t_4 , S_1 is turned off and S_a is already conducting. The voltage across S_1 becomes zero and its body diode starts conducting. Thus, zero voltage switching (ZVS) condition is achieved. The current through S_q is zero and ZCS turn-off condition is achieved. At t_4 , S_1 is turned-on. During the interval, t_4 - t_5 , the body diode of S_a is in conduction. The resonant capacitor C_a discharges to zero from $+V_1$. At t_5 , S_a is

turned off and C_a starts charging from 0 to $-V_1$. At t_6 , the current flows linearly.

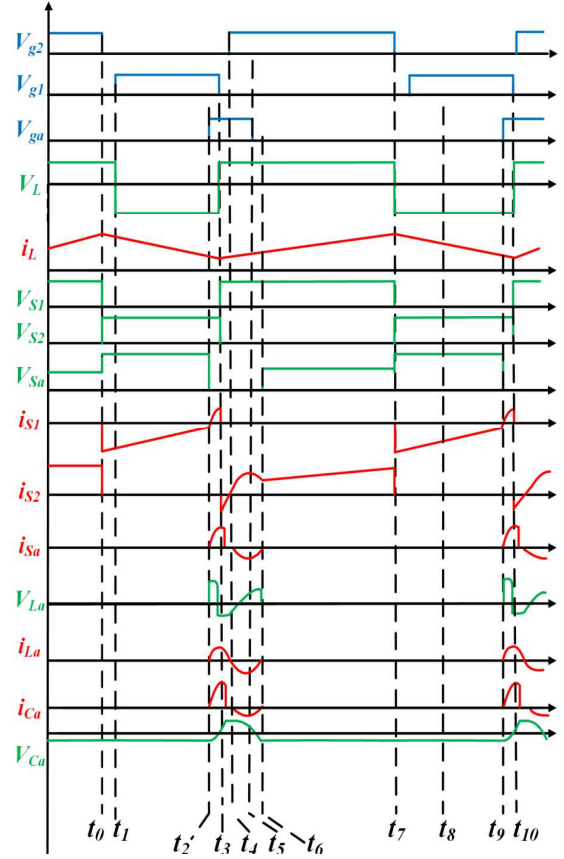


Fig.3 Key waveform : Boost mode

B. Buck mode Principles of Operation

The operating principle of buck mode has been divided into nine intervals, t_0 - t_9 , as shown in Fig.3. At t_0 , S_1 is turned off and S_a is turned on. The current through L_a and voltage across C_a are at constant input current and voltage levels, respectively. Prior to t_1 , voltage across S_2 is zero. At t_1 , both i_{La} and V_{Ca} starts decreasing and body diode of S_2 starts conducting. Hence the zero voltage switching (ZVS) condition is achieved for S_2 . At t_2 , S_2 is turned on and S_a is turned off. Throughout the interval t_2 - t_3 , i_{La} and V_{Ca} are constant. At t_3 , S_2 is turned off, i_{La} starts increasing and C_a starts discharging. At t_4 , S_1 is turned on. At t_5 , the body diode of S_1 starts conducting and at t_6 , it stops conducting. The time intervals t_6 - t_9 are same as the intervals t_0 - t_4 .

C. Soft-switching Condition and Design Example

The soft-switching condition can be obtained for the main switches only when the parameter, y is less than one.

$$y = \frac{I_{\max}}{V_1} \sqrt{\frac{L_a}{C_a}} \quad (1)$$

$$y_1 = \frac{L_a}{L} < 1 \quad (2)$$

Where; $I_{\max} = \frac{P_{\max}}{V_o}$; maximum input current, V_o = output voltage.

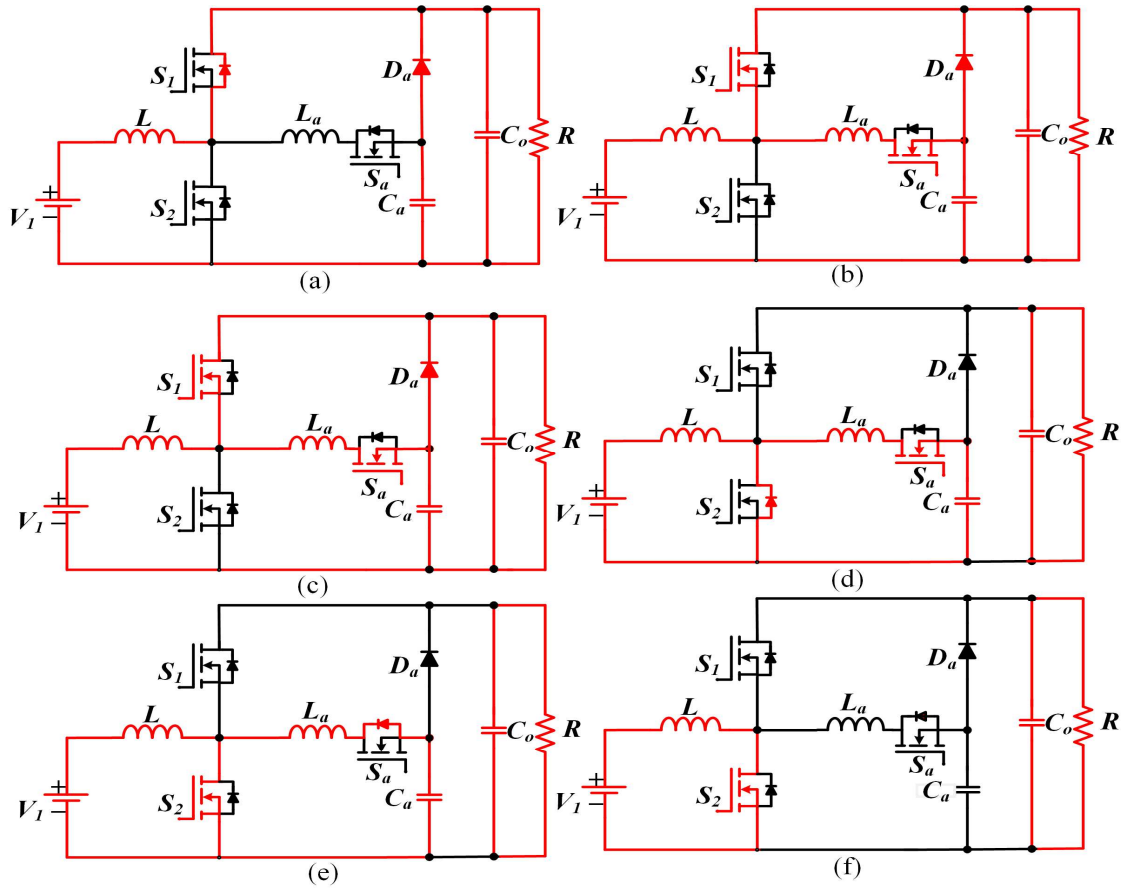


Fig. 4. Equivalent circuits of Boost mode : (a)Interval (t_0-t_1) (b) Interval (t_1-t_2) (c) Interval (t_2-t_3) (d) Interval (t_3-t_4) (e) Interval (t_4-t_5) & (t_5-t_6) (f) Interval (t_6-t_7)

The soft-switching condition is obtained only if the following conditions are satisfied.

$$y_1 < 1 \quad (3)$$

$$y > y_1 \quad (4)$$

Design Example: Input voltage $V_1 = 100 V$; Output voltage $V_o = 330 V$; Output power = $1 kW$; Switching frequency $f_s = 50 kHz$.

$$f_r = \frac{1}{2\pi\sqrt{L_a C_a}} \quad (5)$$

1. The maximum input current calculated for auxiliary resonant network is, $I_m = 3A$
2. Resonant parameters L_a and C_a are obtained from equations (1) and (2), $L_a = 20 \mu H$; $C_a = 40 nF$

3. The characteristic impedance of the auxiliary resonant network is given as $Z = \sqrt{\frac{L_a}{C_a}}$

Higher values of characteristic impedance results in lower current stress in the auxiliary resonant network.

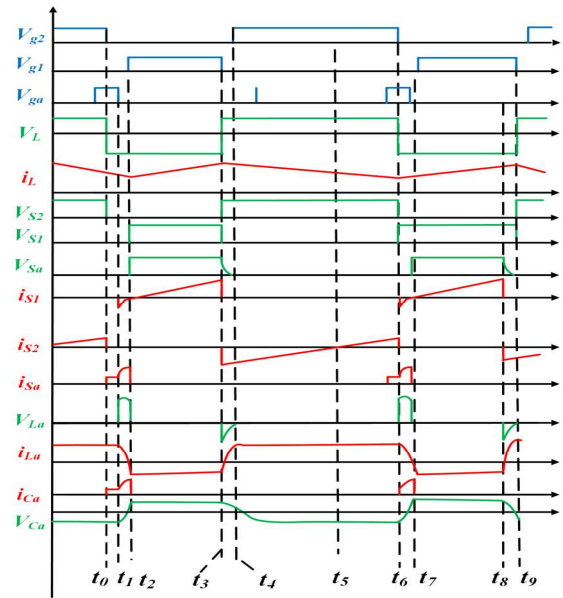


Fig.5. Key waveform : Buck mode

III. SIMULATION RESULTS

The designed converter performance is validated through MATLAB simulations. The proposed converter simulations are performed for both boost and buck operating modes separately. The simulation parameters are considered as follows: Input voltage: 100V ; Output voltage: 330V; Switching frequency: 50kHz; Output power: 1kW; Input inductor: 100 μ H; Resonant inductor, L_a : 20 μ H; Resonant capacitor, C_a : 40nF ; Output capacitor, C_o : 470 μ F.

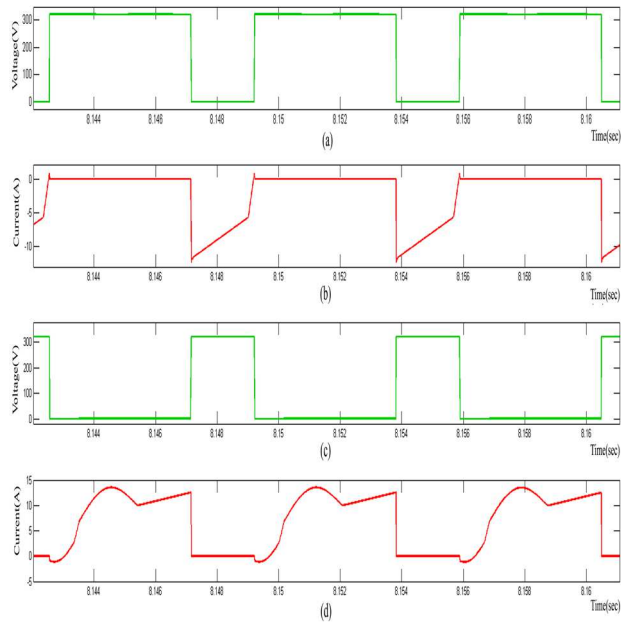


Fig. 6. Simulated waveforms : Boost mode (a) V_{S1} (b) i_{S1} (c) V_{S2} (d) i_{S2}

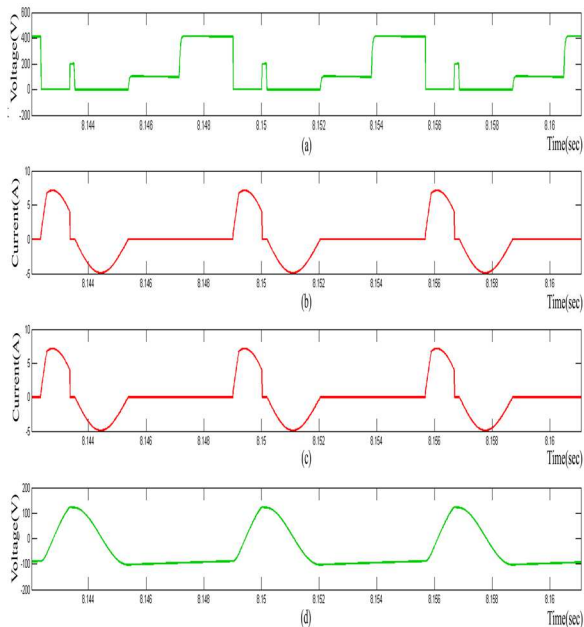


Fig.7 Simulated waveforms: Boost mode (a) V_{Sa} (b) i_{Sa} (c) i_{La} (d) V_{Ca}

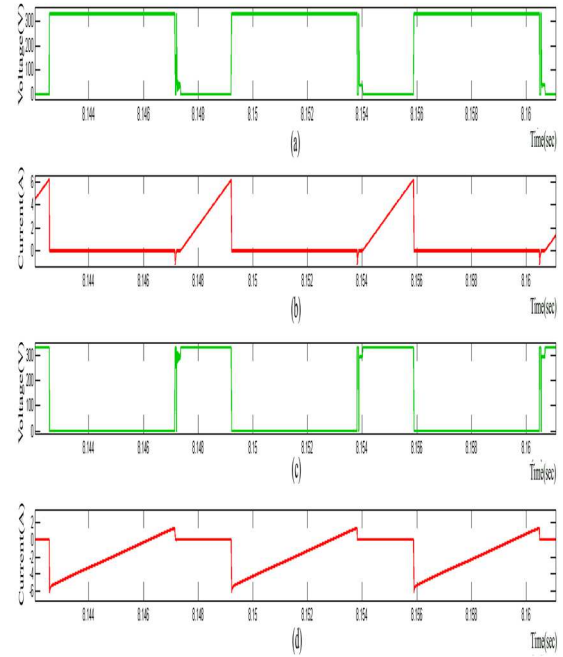


Fig.8 Simulated waveforms: Buck mode (a) V_{S1} (b) i_{S1} (c) V_{S2} (d) i_{S2}

Fig.6 shows the main switches, S_1 , S_2 , voltage and current waveforms. It is observed from the obtained results that ZCS turn off and ZVS turn on conditions are achieved. Fig.7 shows the auxiliary switch, S_a , L_a , C_a voltage and current waveforms. Similarly, the simulations are performed in buck mode and the obtained results are shown in Fig.8 & Fig.9. In the buck mode of operation, the soft-switching conditions are achieved without additional losses. Fig.10 shows the turn-on and turn-off transients of MOSFETs S_1 , S_2 operated at 1.5 kW output power, clearly.

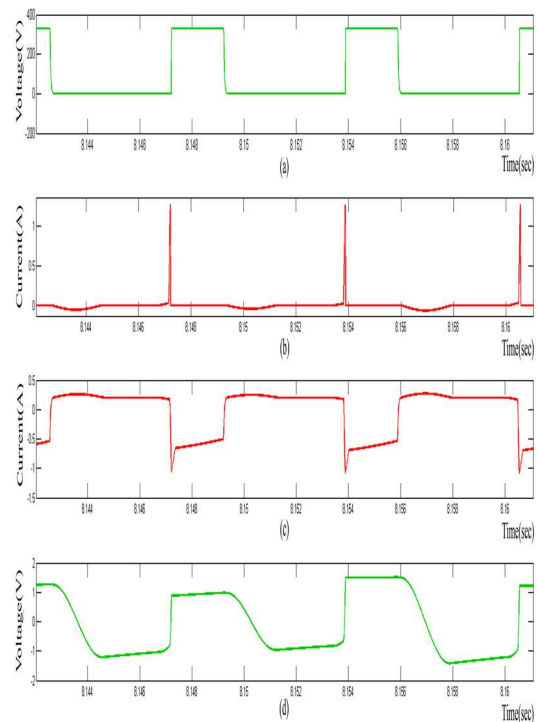


Fig.9. Simulated waveforms: Buck mode (a) V_{S1} (b) i_{S1} (c) i_{La} (d) V_{Ca}

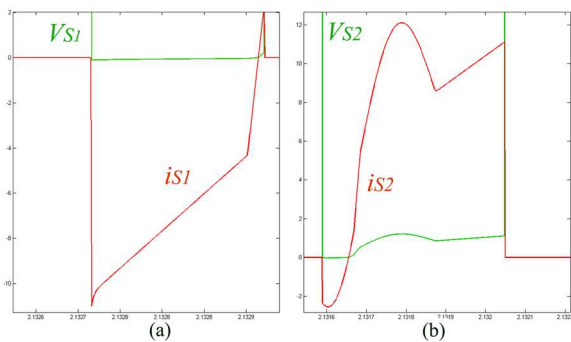


Fig. 10. Turn on and Turn off Transition of MOSFETs (a) S_1 (b) S_2

IV. CONCLUSION

This paper presents a novel non-isolated bidirectional converter with a simple auxiliary resonant network. The operating principles and simulation results are presented for a 100V/330V/1kW converter. The zero current switching (ZCS) turn off and zero voltage switching (ZVS) turn on conditions are achieved without considerably increasing losses for both boost and buck modes of operation. The proposed converter will be a better solution for future needs in energy storage applications with better efficiency.

ACKNOWLEDGMENT

This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic under the project OP VVV Electrical Engineering Technologies with High-Level of Embedded Intelligence CZ.02.1.01/0.0/0.0/18_069/0009855 and project No. SGS-2021-021.

REFERENCES

- [1] H. Chen, H. Kim, R. Erickson and D. Maksimović, "Electrified Automotive Powertrain Architecture Using Composite DC-DC Converters," in IEEE Transactions on Power Electronics, vol. 32, no. 1, pp. 98-116, Jan. 2017, doi: 10.1109/TPEL.2016.2533347.
- [2] S. Dusmez and A. Khaligh, "A Compact and Integrated Multifunctional Power Electronic Interface for Plug-in Electric Vehicles," in IEEE Transactions on Power Electronics, vol. 28, no. 12, pp. 5690-5701, Dec. 2013, doi: 10.1109/TPEL.2012.2233763.
- [3] H. Chiu and L. Lin, "A bidirectional DC-DC converter for fuel cell electric vehicle driving system," in IEEE Transactions on Power Electronics, vol. 21, no. 4, pp. 950-958, July 2006, doi: 10.1109/TPEL.2006.876863.
- [4] T. Konjedic, L. Korošec, M. Truntič, C. Restrepo, M. Rodič and M. Milanović, "DCM-Based Zero-Voltage Switching Control of a Bidirectional DC-DC Converter With Variable Switching Frequency," in IEEE Transactions on Power Electronics, vol. 31, no. 4, pp. 3273-3288, April 2016, doi: 10.1109/TPEL.2015.2449322. IEEE PE 2016
- [5] 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," in IEEE Transactions on Industry Applications, vol. 49, no. 6, pp. 2730-2740, Nov.-Dec. 2013, doi: 10.1109/TIA.2013.2265874. IEEE ind applications
- [6] H. Do, "Nonisolated Bidirectional Zero-Voltage-Switching DC-DC Converter," in IEEE Transactions on Power Electronics, vol. 26, no. 9,

pp. 2563-2569, Sept. 2011, doi: 10.1109/TPEL.2011.2111387. IEEE PE 2011

- [7] Y. Zhang, X. Cheng, C. Yin and S. Cheng, "Analysis and Research of a Soft-Switching Bidirectional DC-DC Converter Without Auxiliary Switches," in IEEE Transactions on Industrial Electronics, vol. 65, no. 2, pp. 1196-1204, Feb. 2018, doi: 10.1109/TIE.2017.2733485.
- [8] M. R. Mohammadi and H. Farzanehfard, "A New Family of Zero-Voltage-Transition Nonisolated Bidirectional Converters With Simple Auxiliary Circuit," in IEEE Transactions on Industrial Electronics, vol. 63, no. 3, pp. 1519-1527, March 2016, doi: 10.1109/TIE.2015.2498907.
- [9] J. Yang and H. Do, "Soft-Switching Bidirectional DC-DC Converter Using a Lossless Active Snubber," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 61, no. 5, pp. 1588-1596, May 2014, doi: 10.1109/TCSI.2013.2285700.
- [10] P. Das, B. Laan, S. A. Mousavi and G. Moschopoulos, "A Nonisolated Bidirectional ZVS-PWM Active Clamped DC-DC Converter," in IEEE Transactions on Power Electronics, vol. 24, no. 2, pp. 553-558, Feb. 2009, doi: 10.1109/TPEL.2008.2006897.
- [11] M. R. Mohammadi and H. Farzanehfard, "A New Family of Zero-Voltage-Transition Nonisolated Bidirectional Converters With Simple Auxiliary Circuit," in IEEE Transactions on Industrial Electronics, vol. 63, no. 3, pp. 1519-1527, March 2016, doi: 10.1109/TIE.2015.2498907.
- [12] M. R. Mohammadi, H. Farzanehfard and E. Adib, "Soft-Switching Bidirectional Buck/Boost Converter With a Lossless Passive Snubber," in IEEE Transactions on Industrial Electronics, vol. 67, no. 10, pp. 8363-8370, Oct. 2020, doi: 10.1109/TIE.2019.294