**IOSUD - Universitatea Politehnica Timişoara**
**Şcoala Doctorală de Studii Inginereşti**

# WIDE RATIO BIDIRECTIONAL DC-DC CONVERTERS FOR SUPERCAPACITOR STORAGE APPLICATIONS

**PhD Thesis – Abstract**

for obtaining the doctoral degree at
Universitatea Politehnica Timișoara
in the field of Electrical Engineering

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This thesis presents new wide-ratio bidirectional hybrid DC-DC converters used in supercapacitor storage, frequently employed for enhancing the storage performances in microgrids or electric vehicles. The presented topologies are developed from unidirectional hybrid structures which are characterized by the use of switched cells consisting of identical capacitors or inductors switched between series and parallel connection with the help of diodes. By operating in this manner, the switching cells help achieve a wider (higher in step-up converters or lower in step-down converters) voltage conversion ratio, lower active switch stress, and smaller passive components. The bidirectional structures achieve the same benefits as the unidirectional topologies, with the added benefit of two quadrant operation.

This work if focused on four converter topologies, from which three are proposed by the author. The studied topologies are described analytically, in order to obtain design equations and comparison metrics. Dynamic analysis is performed to achieve a better hardware design of converters, to assess their stability and to design current controllers. Digital simulations are used to aid the design and analysis of the studied converters. Experimental results are acquired for two hybrid topologies in applications with a power scale up to 5kW. In order to measure efficiency and test the influence of different switches, one topology was built using MOSFETs and GaN-FETs. To eliminate some disadvantages, an improved version is proposed for each of the studied topologies.

Power sharing strategies for supercapacitor storage in microgrid applications are proposed and implemented with the help of a hybrid converter. Their operation is tested trough experimental and digital simulations.

**Chapter 1** presents an introduction to the field of microgrids, with highlight on the advantages of DC distribution, and common voltage levels suitable for these applications. A classification of storage elements is made with emphasis on chemical and electrostatic storage, in batteries and supercapacitors (SC) respectively, and their characteristics in terms of power and energy densities are presented

As voltages in a DC microgrid have relatively large values compared to usual SC voltages, and because good SC energy utilization is advantageous, a wide voltage ratio bidirectional DC-DC converter is required as an interface to the DC bus.

An overview of nine, conventional or state-of-the art converter topologies are presented together with their main operation modes and their corresponding steady state equations. These topologies will be used in the following chapters as comparison references for the hybrid structures presented in this work. The topologies are chosen for having a wide voltage conversion ratio without the need of coupled inductors, a reduced number of components, and for requiring simple driving strategies for operation. Parameters such as voltage conversion ratios, total inductor energy, total capacitor energy and total active switch stress are determined for these converters, to be further compared to the proposed topologies in chapter 6. The chosen topologies are:

- a conventional bidirectional buck/boost converter (CBBB),
- a bidirectional Switched-Quasi-Z-Source converter (BSQZ),
- a conventional bidirectional quadratic converter (CBQ),
- three new bidirectional quadratic converters (BQ1, BQ2 and BQ3),
- a bidirectional triangular modular multilevel converter (BTMM),
- two bidirectional switched capacitor converters (BSC1, BSC2).

An introduction to the unidirectional hybrid converters is also presented in this chapter. The hybrid nature of these converters comes from using switched capacitor or switched inductor cells in their structure, presented in Fig. 1 for unidirectional operation, which help achieve the wide voltage conversion ratio.

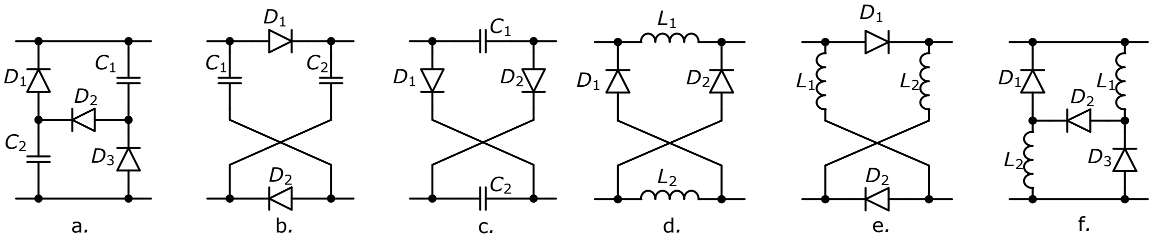

Fig. 1. Unidirectional switched capacitive (a-c) and switched inductive cells (d-f) [1], [2]

**Chapter 2** presents a Bidirectional Hybrid Switched Capacitor converter (BHSC1), which was previously proposed in the scientific literature [3]. This topology uses a switched capacitive cell in its structure, similar to the unidirectional topology from [1]–[4], in order to achieve a wider voltage conversion ratio, lower switch stress and smaller passive components.

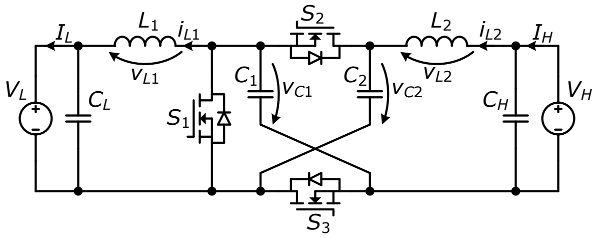
Fig. 2. The Bidirectional Hybrid Switched Capacitor converter (BHSC1) [3], [5]–[7]

The analysis of this converter includes a steady state analysis, performed in a similar manner to the CBBB converter from chapter 1, and a dynamic analysis which is used for the design of an analog and a digital controller. The analytical description of the BHSC1 is desired in order to obtain the metrics used for comparing this topology to other converters. The dynamic modeling was performed in order to obtain the linear model of the BHSC1, which was used for designing the controllers.

In addition to the two controllers, a Valley Current Mode Controller is employed for a fast implementation. Frequency response of the linearized converter model, simulation and experimental results for transient operation are used to test the stability of the design. As a single inductor current controller was used, and because of the increased number of state variables, damped oscillations were observed in the second inductor current. The oscillations were attenuated by slowing down the controller with the help of a low pass filter placed at the reference. The simulation results have a good similitude to the dynamic results obtained by mathematical analysis, and with the experimental results, for the transient operation.

Topology improvements are proposed for this converter in order to eliminate a shortcoming: high frequency common voltage between the inputs.

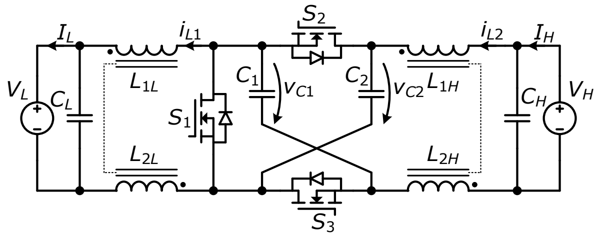


Fig. 3. The Improved Bidirectional Hybrid Switched Capacitor converter (I-BHSC1)

**Chapter 3** presents another Bidirectional Hybrid Switched Capacitor converter (BHSC2), presented in Fig. 4, which uses a different switched capacitive cell in its structure, which was previously tested in unidirectional operation [2], [8], achieving the same benefit of wide voltage conversion ratio as the BHSC1 but with the added benefit of common ground between the two inputs [9]. This advantage helps to achieve simple multiphase operation, or it allows the upgrade of the topology in a multi-level structure.

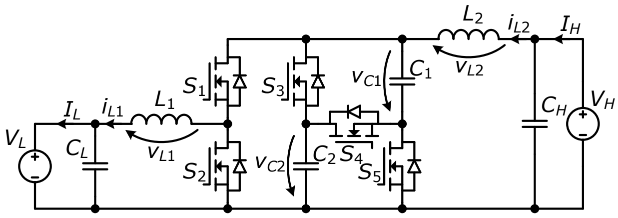


Fig. 4. The Bidirectional Hybrid Switched Capacitor converter (BHSC2) [9]

Similar to the BHSC1, this chapter includes the steady state and the dynamic analysis of the BHSC2. The steady state operation analysis of the BHSC2 was performed in order to achieve the metrics required for comparisons with other topologies, achieving identical passive components requirements to the BHSC1.

The dynamic modeling was performed in order to obtain a linear model of the BHSC2 which was initially used to achieve a more stable design, and afterwards it was used to design a current controller which controls the power flow. The stability of the converter is investigated from the frequency response, and from the poles and zeros of the system. The influence of the passive components is analyzed in order to achieve the best design in terms of stability. A controller is designed for the BHSC2, and simulation results are used to demonstrate the transient operation of the converter between step-up and step-down operation modes.

In comparison to the BHSC1, this converter does not require slowing the reference current with a low pass filter, and a faster response is achieved. A disadvantage of the topology is an increase in the total active switch stress, as the BHSC2 has two more additional switches in comparison to the BHSC1.

An improved BHSC2 topology, presented in Fig. 5, is proposed, which translates the initial schematic into a multilevel topology, having the additional benefits of the multi-level structures.

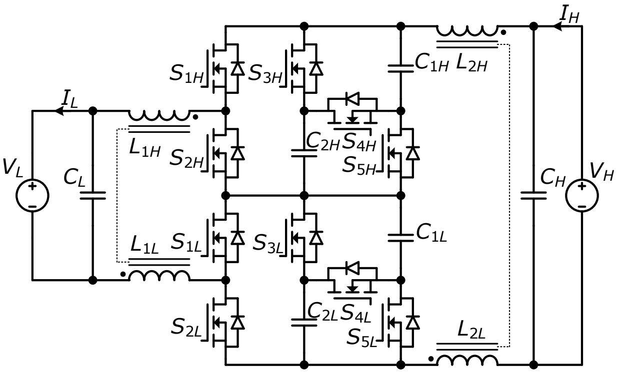


Fig. 5. Three level improved topology for the BHSC2 converter (3L-BHSC2)

**Chapter 4** presents a Bidirectional Hybrid Switched Inductor converter (BHSI), which, as the name suggests, uses a switched inductor cell in order to achieve the wider voltage conversion ratio. Initially proposed as a step-down unidirectional converter in [2], and later as a step-up unidirectional converter in [10], the BHSI is a combination between the two, as shown in Fig. 6. Apart from the wide voltage conversion ratio, this topology has the advantage of a lower system order of the linearized model, because the currents from the two switched inductors are considered identical.

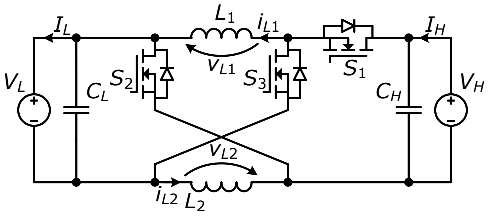


Fig. 6. The Bidirectional Hybrid Switched Inductor converter (BHSI) [11]

A theoretical analysis was performed for the BHSI converter in steady state and dynamic operation. The steady state analysis performed for the BHSI, in a similar fashion to the CBBB converter, is used for passive components sizing and for obtaining the metrics required for an objective comparison to other topologies. Based on the dynamic model of the BHSI, a digital controller was designed and the influence of an incorrect modelling of the microcontroller was analyzed in the frequency response of the system and from experimental results.

Two prototypes are built for the BHSI converter using conventional Silicon MOSFETs and new Gallium-Nitride FETs, and their influence on the topology is presented. The efficiency of the prototypes is measured and compared to the theoretical results. The two prototypes built for the BHSI show an insignificant difference in the operation of the converter, but significant results for its efficiency. Simulation results confirm the dynamic modeling and are in good concordance to the experimental results.

Inductor voltage oscillations, which were also found in the unidirectional topologies, are also present in the BHSI, but can be damped by using an simple RC snubber, or they can be eliminated with the improved version of this topology, shown in Fig. 7, which is also presented and analyzed in this chapter.

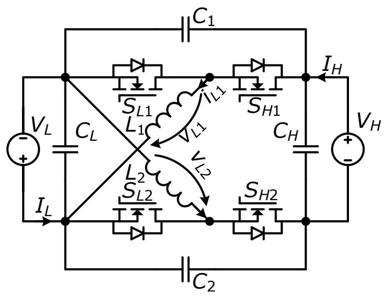

Fig. 7. The Improved Bidirectional Hybrid Switched Inductor converter (I-BHSI) [12]

**Chapter 5** presents a Bidirectional Hybrid Switched Inductor Switched Capacitor converter (BHSISC), shown in Fig. 8, which uses a combination between a switched inductor and a switched capacitor cell, similar to the BHSI converter in chapter 4 and the BHSC1 in chapter 2, while achieving a much wider conversion ratio, and better overall performances [13].

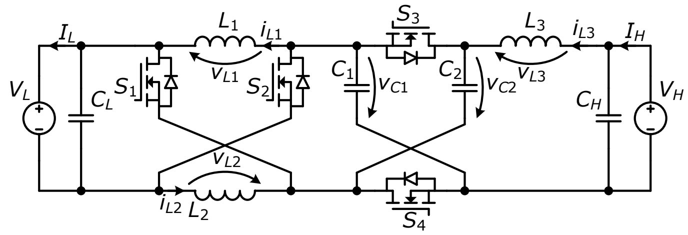

Fig. 8. The Bidirectional Hybrid Switched Inductor Switched Capacitor converter (BHSISC) [13]

Steady state and dynamical analysis are performed in order to describe the main characteristics of the converter, similar to the rest of the converters in this work, and to improve the hardware design and control architecture of the topology, respectively. Comparing this topology to other converters, from the perspective of the metrics obtained by steady state analysis, a good performance is observed.

The dynamic analysis is used to achieve a more stable design of the passive components, and for designing the current controller required to control the power flow in the converter. Even if only one inductor current is controlled, no significant oscillations appear in the other inductors. Simulation results are used to confirm the dynamic model and to present the operation of the BHSISC converter in steady state and transient operations.

An improved topology is proposed in the end, which eliminates high frequency switching voltage between inputs and reduces inductor voltage oscillations, further improving the characteristics of this topology.

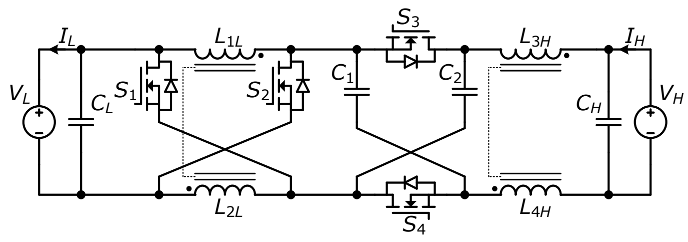

Fig. 9. The Improved Bidirectional Hybrid Switched Inductor Switched Capacitor converter (I-BHSISC)

**Chapter 6** presents a comparison between the different hybrid topologies presented in chapters 2 to 5, and other topologies proposed in literature, described in chapter 1. As the literature presents many converter topologies under the same category of bidirectional non-isolated converters, different means to compare the topologies are needed. The converters are compared in terms of step-up and step-down voltage conversion ratios, total inductor energy, total capacitor energy and total active switch stress, all presented in graphical plots with values normalized to the conventional bidirectional buck-boost converter.

The conversion ratios provide an overall information about the performance of the converter, as it shows the operation range for the two inputs. The total inductor energy and total capacitor energy gives information about the size and costs of these passive components. The total active switch stress provides information about the cost or the losses in the active switches.

Overall, each topology may be more suitable for a specific application, depending on the range of the voltage ratio, number of switches, or the total active switch stress, passive components size, or the costs of the components.

In terms of conversion ratio, the quadratic converters offer the widest conversion ratios, but they are closely followed by the BHSISC converter. The rest of the hybrid converters are situated between the quadratic and the conventional converter, and this aspect can be beneficial if these are the conversion ratios that are desired.

In terms of total inductor and total capacitor energy, the switched capacitor converters BSC1 and BSC2 offer very good performance but with the cost of current spikes while charging and discharging capacitors with different voltages by connecting them in parallel. Next, the hybrid converters offer good characteristics in this aspect, similar to the conventional converter but with much wider conversion ratios. The rest of the topologies have much larger requirements for capacitors or inductors.

Regarding the total active switch stress, the BHSISC converter and the rest of the hybrid topologies achieve the best results, much lower than the conventional converter, and followed by the rest of the topologies.

An interesting conclusion that can be drawn for the quadratic converters, is that the characteristics of the converters considered for this analysis, are identical for under almost all aspects, regardless of their schematic.

Overall, the hybrid topologies, especially the BHSISC converter, offer good characteristics which make them good candidates for applications where a wide voltage conversion ratio is desired.

**Chapter 7** presents an application of bidirectional wide ratio converters: as an interface between a DC voltage bus in a microgrid and a supercapacitor used for storage. This chapter starts with an overview of the microgrid control strategies, with applications for DC-DC bidirectional wide ratio converters. A classification of the microgrid control strategies is initially presented, as shown in Fig. 10, based on the type of communication between the microgrid devices (centralized, distributed and decentralized) and the hierarchy in which the control structures are classified (tertiary, secondary or primary) [14]–[18].

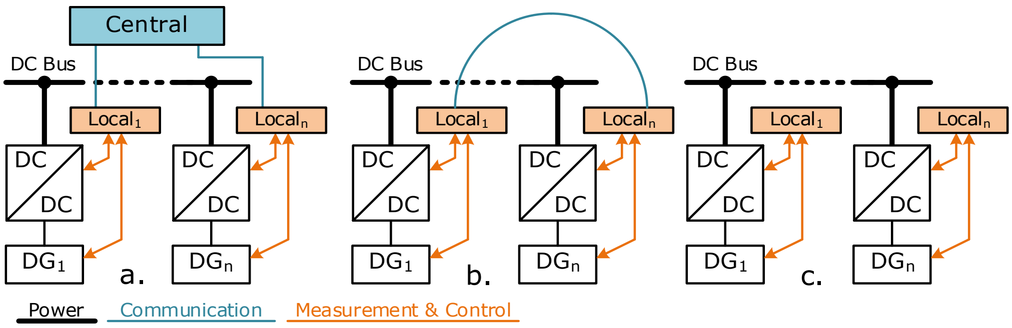

Fig. 10. DC Microgrid control strategies, categorized from the communication perspective:
a. Centralized control, b. Distributed control, c. Decentralized control [14]–[18] (DG - distributed generators)

This work focuses on three decentralized strategies, with applications in droop controlled microgrids, useful for nanogrid control, or as local controllers for the centralized or distributed strategies. Droop control methods for power sharing in supercapacitor storage methods are based on different virtual impedances, two on the nonlinear droop strategy [19], and one on a nonlinear virtual impedance [20], with the equivalent schematics, which are implemented in the control structure of the interface converter, presented in Fig. 11, and their respective characteristics presented in Fig. 12.

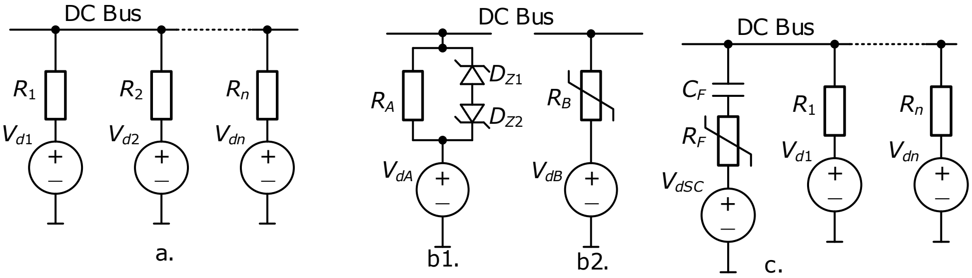


Fig. 11. Equivalent schematic of the conventional droop (a.) and the nonlinear droop methods (b1, b2, c)

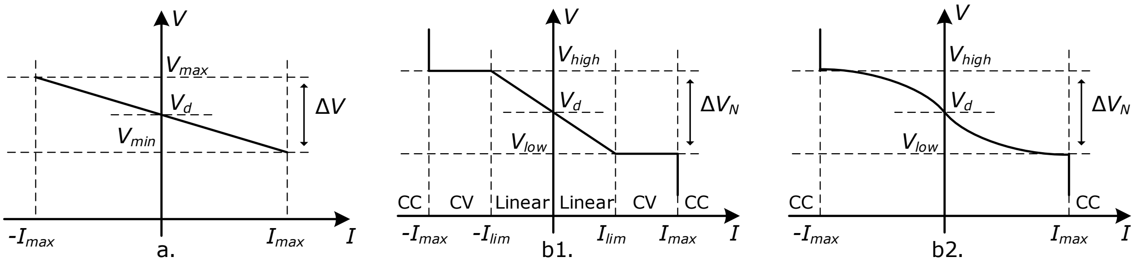


Fig. 12. Static characteristics for the conventional droop (a.) and nonlinear droop methods (b1, b2)

The nonlinear droop methods are considered as a simple alternative to the conventional centralized methods for supercapacitor storage. The state-of-the-art virtual impedance methods are considered as they offer good performance for decentralized methods. The virtual impedance method was improved by using a nonlinear characteristic for the filter, achieving the advantage of a variable influence of the storage system, based on the amplitude of grid voltage variation. In other words, a variable cutoff filter frequency was achieved with the benefit of having more parameters to be controlled by a higher, centralized energy management system, or different influences depending on the voltage variation on the grid.

All strategies were validated by simulation and experimental results.

**Chapter 8** presents the conclusions of this thesis, original contribution of the author and future work for the presented subjects.

This thesis is focused on bidirectional DC-DC converters which achieve wide voltage conversion ratios by using hybrid capacitive or inductive switching cells, initially proposed for unidirectional topologies. Four topologies are thoroughly studied, from which three are proposed by the author. The studied schematics are two switched-capacitor topologies, one switched-inductor topology, and one combined switched-inductor and switched-capacitor topology.

The analysis of the hybrid converters is performed for steady-state operation in order to obtain their performance metrics: the energy required to be stored by the passive components, and the total active switch stress of the transistors.

An in-depth comparison is realized between the studied topologies and other 9 state-of-the-art structures that can be classified in the same category. From this comparison it results that the hybrid converters achieve good overall performances.

The dynamic analysis is performed for each of the four topologies, in order to assess its stability, to improve the converter design, and to design a stable controller. All topologies are tested with simulations, while two topologies are tested experimentally, obtaining similar results compared to the simulations. All proposed converters present a stable operation in both step-up and step-down operation mode. Methods for improving the schematics for each of the four topologies are presented.

Finally, the switched-capacitor topology is used as a platform for employing 3 new power sharing control strategies for supercapacitor storage in microgrid applications, proposed by the author.

The following list summarizes the contributions of the author:

- General overview of supercapacitor storage in microgrid applications and benefits of wide-ratio converters for these applications.
- Literature review for bidirectional wide-ratio converters.
- Steady state and dynamic analysis of a hybrid switched capacitor converter. Experimental and simulation tests of the converter. Improved the initial topology.
- Proposed a common ground bidirectional hybrid switched capacitor and analyzed in steady state and dynamic operation. Designed the current controller. Validated the converter operation by simulation. Improved the initial topology in multilevel structure.
- Proposed a bidirectional hybrid switched inductor converter and analyzed in steady state and dynamic operation. Designed a digital current controller. Built two prototypes based on GaN-FETs and MOSFETs and analyzed their influence and efficiency. Proposed an improved topology, tested by means of digital simulation.
- Proposed a bidirectional hybrid switched-inductor and switched-capacitor and described analytically, for the steady state and dynamic operation. Improved the converter design in terms of stability by using the dynamic analysis and designed the current controller. Confirmed the performances of the topology by simulations. Proposed an improved topology.
- Realized a comprehensive comparison between the 4 studied converters and 9 state-of-the-art topologies.
- Proposed three nonlinear droop power sharing methods for supercapacitor storage in a microgrid applications and implemented in a bidirectional hybrid converter.

A few paths are open for further research, such as:

- Testing in practical implementation the improved topologies.
- Developing advanced comparison methods in order to optimize the selection of a topology depending on the application.
- Evaluating better control methods for the higher order systems of the converters.
- Analyzing the stability of the power sharing.
- Assessing new ways to improve the bidirectional hybrid topologies, such as into multiphase, multilevel, or multi-input structures.

The thesis is centered on a number of 7 ISI-indexed conference papers, and two ISI-indexed journal papers to which the thesis author is first author or co-author. One of the mentioned papers received the “EPE Young Author Best Paper Award” at the EPE conference in 2019.

The thesis is structured in 8 chapters over 178 pages, from which 11 are for the bibliographic references. This work contains 155 figures, 26 tables and 135 bibliographic titles.

## References

[1] B. Axelrod, Y. Berkovich, and A. Ioinovici, “Switched-capacitor (SC)/switched inductor (SL) structures for getting hybrid step-down Cuk/Sepic/Zeta converters,” in *2006 IEEE International Symposium on Circuits and Systems*, May 2006, p. 4 pp.-, doi: 10.1109/ISCAS.2006.1693770.

[2] B. Axelrod, Y. Berkovich, and A. Ioinovici, “Switched-Capacitor/Switched-Inductor Structures for Getting Transformerless Hybrid DC–DC PWM Converters,” *IEEE Trans. Circuits Syst. Regul. Pap.*, vol. 55, no. 2, pp. 687–696, Mar. 2008, doi: 10.1109/TCSI.2008.916403.

[3] H. Nomura, K. Fujiwara, and M. Y. Kochi, “A new DC-DC converter circuit with larger step-up/down ratio,” in *2006 37th IEEE Power Electronics Specialists Conference*, Jun. 2006, pp. 1–7, doi: 10.1109/pesc.2006.1712228.

[4] B. Axelrod, Y. Berkovich, and A. Ioinovici, “Transformerless DC-DC converters with a very high DC line-to-load voltage ratio,” in *Proceedings of the 2003 International Symposium on Circuits and Systems, 2003. ISCAS ’03.*, May 2003, vol. 3, p. III–III, doi: 10.1109/ISCAS.2003.1205049.

[5] O. Cornea, E. Guran, N. Muntean, and D. Hulea, “Bi-directional hybrid DC-DC converter with large conversion ratio for microgrid DC busses interface,” in *Automation and Motion 2014 International Symposium on Power Electronics, Electrical Drives*, Jun. 2014, pp. 695–700, doi: 10.1109/SPEEDAM.2014.6872065.

[6] D. Hulea, N. Muntean, and O. Cornea, “Valley current mode control of a bi-directional hybrid DC-DC converter,” in *2015 Intl Aegean Conference on Electrical Machines Power Electronics (ACEMP), 2015 Intl Conference on Optimization of Electrical Electronic Equipment (OPTIM) 2015 Intl Symposium on Advanced Electromechanical Motion Systems (ELECTROMOTION)*, Sep. 2015, pp. 274–279, doi: 10.1109/OPTIM.2015.7427024.

[7] O. Cornea, G. Andreescu, N. Muntean, and D. Hulea, “Bidirectional Power Flow Control in a DC Microgrid Through a Switched-Capacitor Cell Hybrid DC–DC Converter,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3012–3022, Apr. 2017, doi: 10.1109/TIE.2016.2631527.

[8] N. Muntean, O. Cornea, O. Pelan, and C. Lascu, “Comparative evaluation of buck and hybrid buck DC-DC converters for automotive applications,” in *2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC)*, Sep. 2012, p. DS2b.3-1-DS2b.3-6, doi: 10.1109/EPEPEMC.2012.6397272.

[9] D. Hulea, N. Muntean, M. Gireada, and O. Cornea, “A Bidirectional Hybrid Switched-Capacitor DC-DC Converter with a High Voltage Gain,” in *2019 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) 2019 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, Aug. 2019, pp. 289–296, doi: 10.1109/ACEMP-OPTIM44294.2019.9007160.

[10] L. Yang, T. Liang, and J. Chen, “Transformerless DC–DC Converters With High Step-Up Voltage Gain,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3144–3152, Aug. 2009, doi: 10.1109/TIE.2009.2022512.

[11] D. Hulea, B. Fahimi, N. Muntean, and O. Cornea, “High Ratio Bidirectional Hybrid Switched Inductor Converter Using Wide Bandgap Transistors,” in *2018 20th European Conference on Power Electronics and Applications (EPE’18 ECCE Europe)*, Sep. 2018, p. P.1-P.10.

[12] D. Hulea, M. Gireada, D. Vitan, O. Cornea, and N. Muntean, “An Improved Bidirectional Hybrid Switched Inductor Converter,” presented at the 2020 22nd European Conference on Power Electronics and Applications (EPE ’20 ECCE Europe), to be

published.
[13] D. Hulea, N. Muntean, M. Gireada, O. Cornea, and E. Serban, “Bidirectional Hybrid Switched-Inductor Switched-Capacitor Converter Topology with High Voltage Gain,” in *2019 21st European Conference on Power Electronics and Applications (EPE ’19 ECCE Europe)*, Sep. 2019, p. P.1-P.10, doi: 10.23919/EPE.2019.8915535.
[14] D. E. Olivares *et al.*, “Trends in Microgrid Control,” *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014, doi: 10.1109/TSG.2013.2295514.
[15] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, “State of the Art in Research on Microgrids: A Review,” *IEEE Access*, vol. 3, pp. 890–925, 2015, doi: 10.1109/ACCESS.2015.2443119.
[16] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, “DC Microgrids—Part I: A Review of Control Strategies and Stabilization Techniques,” *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4876–4891, Jul. 2016, doi: 10.1109/TPEL.2015.2478859.
[17] L. Meng *et al.*, “Review on Control of DC Microgrids and Multiple Microgrid Clusters,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 5, no. 3, pp. 928–948, Sep. 2017, doi: 10.1109/JESTPE.2017.2690219.
[18] Z. Cheng, J. Duan, and M. Chow, “To Centralize or to Distribute: That Is the Question: A Comparison of Advanced Microgrid Management Systems,” *IEEE Ind. Electron. Mag.*, vol. 12, no. 1, pp. 6–24, Mar. 2018, doi: 10.1109/MIE.2018.2789926.
[19] D. Hulea, O. Cornea, and N. Muntean, “Nonlinear droop charging control of a supercapacitor with a bi-directional hybrid DC-DC converter,” in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, Jun. 2016, pp. 1–6, doi: 10.1109/EEEIC.2016.7555540.
[20] D. Hulea, O. Cornea, and N. Muntean, “Energy Management Strategy for Supercapacitor Storage Using a Nonlinear Virtual Impedance,” in *2018 IEEE 18th International Power Electronics and Motion Control Conference (PEMC)*, Aug. 2018, pp. 375–380, doi: 10.1109/EPEPEMC.2018.8521858.