Automotive Battery Charging based on Efficient Capacitive Power Transfer

Filippo Pellitteri*,[1], Nicola Campagna*, Pierpaolo Granello**, Rosario Miceli* and Luigi Schirone**
**Department of Engineering, University of Palermo*, Palermo (Italy)
***Scuola di Ingegneria Aerospaziale*, *Sapienza University of Rome*, Rome (Italy)
[1] filippo.pellitteri@unipa.it

***Abstract*— Isolated power converters find application in different fields of electric mobility, such as battery charging, where galvanic insulation between on-board storage system and electrical grid is required. Conventional isolated systems are based on the use of transformers, which have the drawback to be bulky and expensive. Nevertheless, insulation implemented by capacitances can be attractive due to the recent technological advances, contributing to increasingly compact, cheap and efficient converters. In this paper, an isolated power converter based on capactive power transfer (CPT), along with the switched capacitor concept, is proposed. GaN FETs are employed as switching power devices in order to handle high operation frequencies with limited power losses. In this work a 500 kHz switching frequency has been selected, with notable benefits brought to the overall power converter in terms of compactness. The developed prototype has been experimentally tested according to a target power level of 3 kW, to prove the proper operation of the proposed converter. The experimental tests have demonstrated a power transfer efficiency as high as 95%.**

Index Terms — DC-DC Isolated Power Converters, Switched Capacitor, Capacitive Power Transfer, Electric Vehicles, Battery Charging

I. Introduction

Among the challenges that EV market has to address, improvement of battery charging infrastructures and faster recharge represent the most significant ones, in addition to the use of alternative storage systems, traction power converters and electrical motors [1-7].

Indeed, to deal with the anxiety related to the driving range, due to insufficiency of charging points and to long required recharging times, increasing the battery capacity would be an expensive and therefore not feasible solution. To actually improve charging infrastructure and reduce recharging times, power electronics' designers play a fundamental role aiming at cost reduction and power density increase of battery chargers' power converters.

Different solutions of rectifiers implementing fast chargers have been proposed. Regarding the technical issues related to the implementation of a vehicle battery charger, voltage levels of hundreds of volts shall be taken into account, so that protection of users and vehicle itself is a top level requirement. To address that, galvanic insulation of the battery from the ground and electrical connection of the vehicle chassis to the ground itself are required [8-15].

To implement galvanic insulation, power converters are conventionally equipped with magnetic components, such as transformer and coupled inductors, which generally bring a negative contribution in terms of weight, size, cost and power losses, thus limiting efficiency and power density.

An alternative solution to magnetic components is the use of the switched capacitors (SC) technology, which has been neglected for long time due to the evident technological limitations shown by capacitors under challenging conditions in terms of high levels of voltage, frequency and temperature. Only in recent years, SC-based power converters have been increasingly considered for high power levels and electrical mobility [16-21]. A particular integration between SC approach and Wireless Power Transfer (WPT) is represented by capacitive power transfer (CPT), which has found different applications, including EVs wireless battery charging [22-24].

Nevertheless, the use of CPT to implement an on-board isolated battery charging stage in EVs has not been fully addressed by researchers and industries yet. Non-isolated converters based on CPT for EV battery charging have been proposed instead [25].

In this paper, a fully isolated full-bridge converter based on capacitive power transfer is proposed as EV battery charging output stage. The chosen switching frequency is as high as 500 kHz, to guarantee a compact solution of power conversion stage and allowed by the use of GaN FETs, which have the advantage to guarantee limited switching power losses.

II. Converter Operation

The proposed CPT-based DC-DC converter, whose schematic is shown in Fig. 1, is able to galvanically insulate the source from the load by means of the capacitances C_a and C_b.

The converter consists of two full-bridge stages: an active stage of inverter (DC-AC) in the input side and a passive stage of rectifier (AC-DC) in the output side.

To analyze the proposed converter's operation, the following simplifications may be considered: all switches and diodes are ideal thus representing short-circuits when in conduction; across the output filter capacitance C_o the small-ripple approximation occurs; dead times regarding the gate control signals of the FETs are neglected.

In order to attenuate potential electromagnetic noises generated by the power converter, reactive filtering networks shall be added at the terminal sections, so that the current ripple at the source side and at the load side can be smoothed. In this case, series inductances and parallel capacitances have been inserted, thus resulting into L_a-C_i

filter in the input side and L_b-C_o filter at the output side. Filtering capacitances C_i

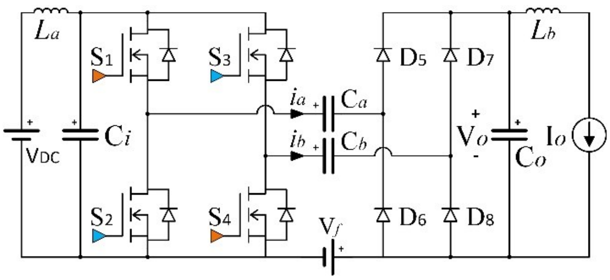


Fig. 1. CPT-based Full Bridge converter schematic.

and C_o are essential to absorb the current peaks of the converter and stabilize input and output voltage.

In Fig. 2 the circuits during Mode 1 and Mode 2 are highlighted, thus describing the operation of the whole converter. Mode 1 corresponds to S1-S4 on state, resulting in the conduction path including S_1, C_a, D_5, D_8. C_b and S_4; Mode 2 corresponds to S2-S3 on state, resulting in the conduction path including S_3, C_b, D_7, D_6, C_a and S_2.

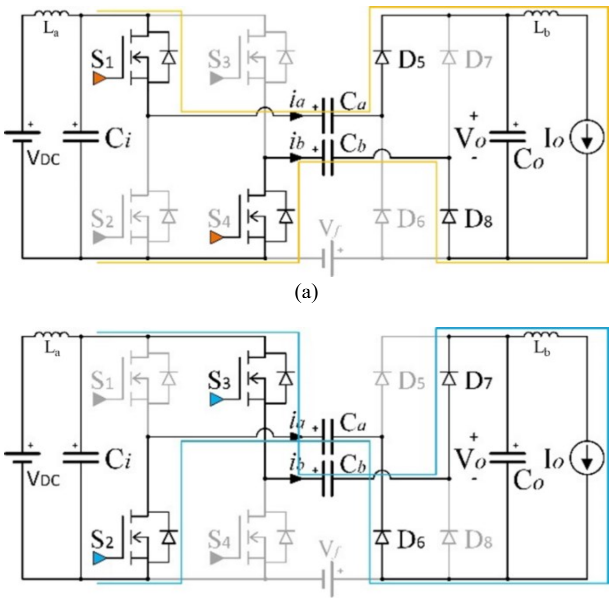


Fig. 2. Current paths during Modes 1 (a) and 2 (b).

Therefore, the resulting current flowing in C_a and C_b is pulsed, with a sign corresponding to the operation Mode, so that the capacitances' voltage is trangular, according to the simulation plots reported in Fig. 3, referring to the gate driving signals on switches 1,4 (v_{gS1} plot) and switches 2,3 (v_{gS2} plot) which are in phase opposition with a 50% of nominal duty cycle shifted by the required amount of dead time. Similarly as in the transformer-based counterpart, a 50% nominal duty cycle provides an ideal 1:1 ratio between input and output voltage.

Insulation capacitors shall be chosen accurately, with great attention towards the maximum appliable voltage, which should be equal to the insulation voltage level. Indeed, the latter one is equivalent to a voltage offset source V_f between the negative terminals of input and output sections, as highlighted in Fig. 1.

Therefore, each insulation capacitance shall be rated according to a maximum voltage equal to V_f.

In order to guarantee a proper working of the converter, current shoot-throughs on the active switches belonging to the same leg of the full-bridge shall be avoided. This means that a minimum dead time should occur between the switch-off of a transistor and the switch-on of the transistor on the same leg [26-27].

During these dead times, no current flows across the isolation capacitances, so that their voltage is constant during these time intervals. Dead times lead to notably high current peaks, as highlighted in Fig. 4, reporting the simulation plots according to 50% dead times.

The voltage across the insulation capacitances is determined by their repetitive charging and discharging process, resulting in a triangular waveform whose peak-to-peak value V_{pp}, at steady state and supposing a 50% duty-cycle, is equal to:

$$V_{pp} = \frac{I_o}{2 \cdot f_s \cdot C} \tag{1}$$

where C is the value of C_a and C_b, assuming:

$$C = C_a = C_b \tag{2}$$

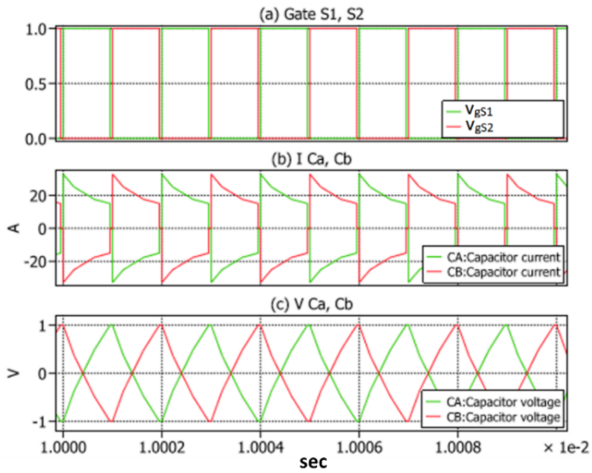


Fig. 3. Simulation results according to 50% Duty Cycle, 2.5% Dead Time, 500 kHz.

The offset voltage of the V_{pp} ripple would correspond to the voltage V_f. In the simulation case, since no voltage V_f is applied between the input ground and the output ground, the average voltage of the insulation capacitances is zero. Since the maximum difference between the insulation capacitance voltages corresponds to V_{pp}, the minimum output voltage, according to all the voltage drops of the converter, is expressed as:

$$V_o = V_{DC} - 2V_{DS} - V_{pp} - 2V_D \tag{3}$$

where V_{DS} is the drain-source voltage of a single primary side switch and V_D is the voltage drop of a single secondary side rectifying diode. Accordingly, it is possible to express these voltage drops as

$$V_{DS} = R_{DS_{ON}} \cdot I_{DS} \tag{4}$$

$$V_D = V_{fr} + R_D \cdot I_D \tag{5}$$

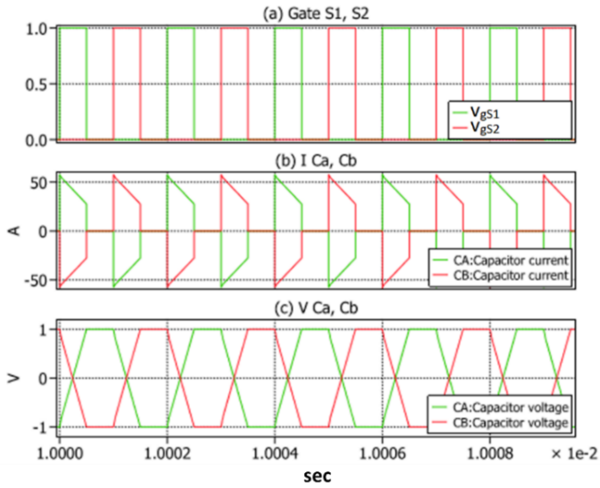


Fig. 4. Simulation results according to 50% Duty Cycle, 50% Dead Time, 500 kHz.

where $R_{DS_{ON}}$ is the switch ON resistance, I_{DS} is the switch current, V_{fr} is the forward diode voltage drop, R_D is the diode forward resistance and I_D is the diode forward current.

III. Experimental Results

A 600V-20A prototype of the proposed converter has been assembled, as shown in Fig. 5, in order to experimentally validate the simulation results.

The chosen components are reported in Table I.

The target switching frequency is 500 kHz, so that notable care has been addressed to the minimization of parasitic inductances resulting from the printed circuit board (PCB) layout. Moreover, particular attention has been paid to a proper selection of the electronic components. More in detail, the selected active switches are GaN FETs, showing low input capacitance and total gate charge, so that reduced switching losses occur under switching frequency as high as 500 kHz. Regarding the passive rectifier, SiC Schottky diodes have been selected, so that no reverse recovery charge is present [28]. Regarding the capacitors C_a and C_b, they must provide a low Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL). Accordingly, the chosen capacitors are ceramic ones, which well comply with these requirements. C_a and C_b are chosen basing on the voltage drop they provide at the given switching frequency. For instance, as stated in Equation (1), the magnitude of capacitance value depends on the desired maximum voltage drop allowed on these isolation capacitors. For this design, being the switching frequency 500 kHz, a 10 uF value was enough to prove the concept. Obviously, it can be increased or decreased. Even though the chosen X7R technology is prone to wide capacitance variations, its effects can be neglected as far as the considered application is concerned. Indeed at 500 kHz and 20 A current, the magnitude of the capacitance voltage is 2 V, according to Equation (1) for a 10 µF capacitance. Therefore, even considering a 50% capacitance variation, the respective voltage is doubled, so that a total 8 V voltage drop occurs across both the insulation capacitances, which is neglectable if compared to the ideal output voltage. Line filters are completed by inductors with 0.95 mΩ ESR, thus minimizing conduction losses.

The experimental tests were performed according to a fixed dead time of 100 ns and to different levels of input voltage and load current. Fig. 6 shows the correct operation of the converter, since the voltage waveforms at the output of the insulation capacitors are highlighted.

In Fig. 7 voltage drop from input to output and power losses are plotted as function of the input voltage, for a fixed load current of 10 A. It can be noticed that the voltage drop is almost constant, mainly depending on the output rectifier diode voltage drops. Similarly, the power losses are not greatly dependent on the applied voltage, mainly depending on the processed current. In Fig. 8 converter losses are presented in terms of input-output voltage drop and power waste as functions of the load current; a linear increase of voltage drop can be noticed. The efficiency plots are shown in Fig. 9, highlighting that notable values are obtained, especially at the highest valued of load current.

Table I – Prototype Components

Component	Value
$S_{1,2,3,4}$	IGT60R070D1
$D_{5,6,7,8}$	IDDD20G65C6
$C_{a,b}$	2220Y6300105KXTWS2
$L_{a,b}$	B82559B2102A019
Gate Driver	1EDF5673K
Aux Supplies	PES1-S5-S9-M
Heatsink	511-3M
Fan	AUC0512DB-AF00

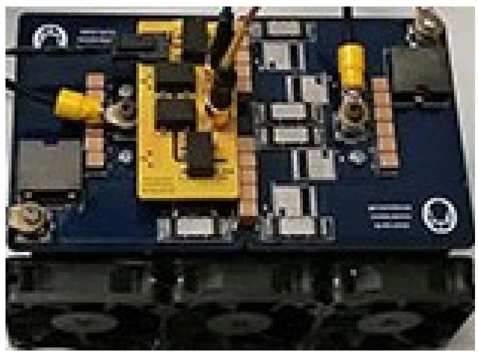
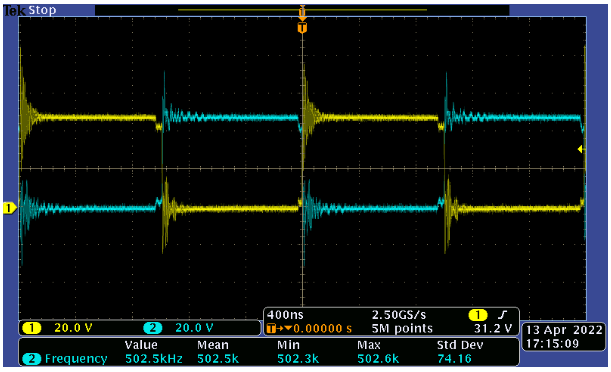


Fig. 5. The realized CPT-based DC-DC converter's prototype.

IV. Conclusions

In this work an isolated power converer based on capacitive power transfer and switched capacitor technology is proposed, for automotive battery charging applications. A protoype of full-bridge CPT-based converter has been assembled using GaN FETs as switching power devices. GaN technology allows to operate at high switching frequencies due to the small input capacitance and total gate charge, so that a 500 kHz frequency has been tested for the given converter.



(a)

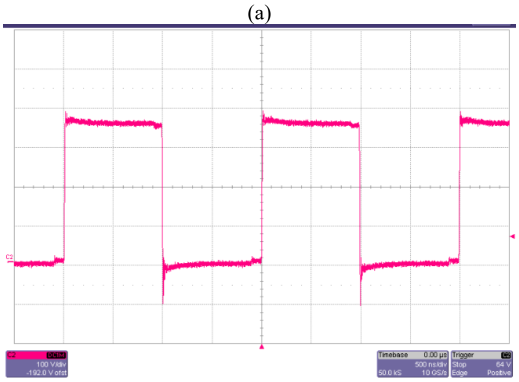

(b)

Fig. 6. Switches V_{DS} Waveforms. (a) 50 V; (b) 400 V.

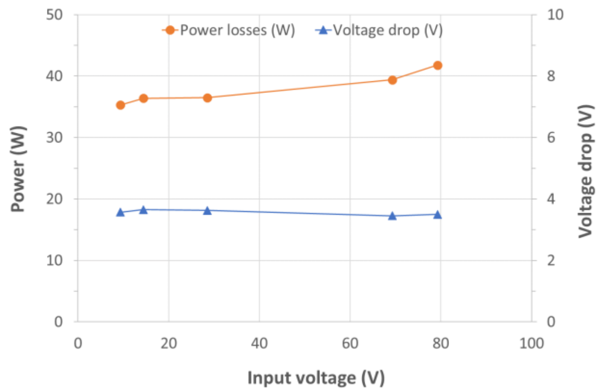


Fig. 7. Power losses Vs input voltage for input current I_{in} = 10 A.

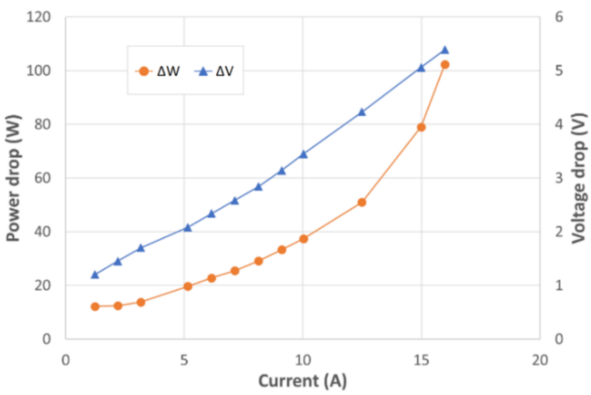


Fig. 8. Power losses Vs load current.

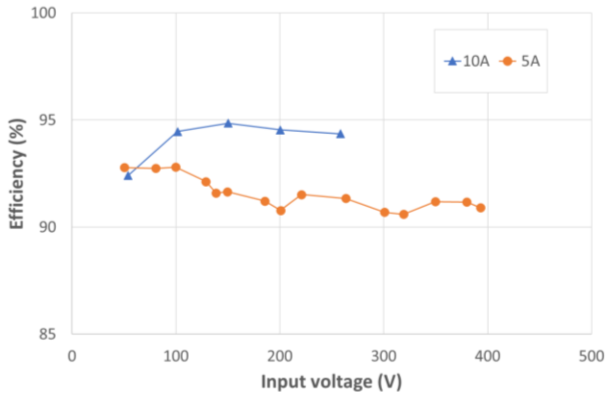


Fig. 9. Conversion effciency Vs input voltage for 5 A and 10 A.

The built prototype is compact and proves the opportunity of a power transfer until 3 kW, even though a potential 12 kW power transfer is feasibile due to the specific features of GaN FETs, i.e. maximum voltage of 600 V and maximum current of 20 A. The converter, that has been tested up to 3 kW with maximum voltage of 400 V and maximum current of 15 A, shows a power transfer efficiency as high as 95%.

ACKNOWLEDGMENT

This work was realized with the contribution of: PON R&I 2014-2020 (PON R&I FSE-REACT EU), Azione IV.6 “Contratti di ricerca su tematiche Green” to fund and support the research; research project “Sustainable Innovative transport SYstems for MEtropolitan Cities (SISYMEC)”, in the frame of the call EUROSTART from University of Palermo, funded by DM 737/2021 of the Italian Ministry of University and Research; PNRR Project “SAMOTHRACE - Sicilian Micro and Nano Technologies Research and Innovation Center” - SPOKE 3 S2-COMMs (Micro and Nanotechnologies for Smart & Sustainable Communities); PNRR Project “Sustainable Mobility Center (Centro Nazionale per la Mobilità Sostenibile – CNMS)”.

REFERENCES

[1] Schettino, G., et al. Experimental study on B-spline-based modulation schemes applied in multilevel inverters for electric drive applications. *Energies*, 2019, 12.23: 4521.

[2] V. Castiglia, P. Livreri, R. Miceli, F. Pellitteri, G. Schettino and F. Viola, "Power Management of a Battery/Supercapacitor System for E-Mobility Applications," 2019 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Turin, Italy, 2019, pp. 1-5.

[3] V. Castiglia et al., "Modelling, Simulation and Characterization of a Supercapacitor in Automotive Applications," 2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte-Carlo, Monaco, 2020, pp. 1-6.

[4] Caruso, M., et al. Characterization of the parameters of interior permanent magnet synchronous motors for a loss model algorithm. *Measurement*, 2017, 106: 196-202.

[5] F. Pellitteri, V. Boscaino, A. O. Di Tommaso, F. Genduso and R. Miceli, "E-bike battery charging: Methods and circuits," 2013 International Conference on Clean Electrical Power (ICCEP), Alghero, Italy, 2013, pp. 107-114.

[6] M. Caruso, A. O. Di Tommaso, F. Genduso and R. Miceli, "Experimental investigation on high efficiency real-time control algorithms for IPMSMs," 2014 International Conference on Renewable Energy Research and

Application (ICRERA), Milwaukee, WI, USA, 2014, pp. 974-979.

[7] G. Ala, G. Di Filippo, F. Viola, G. Giglia, A. Imburgia, P. Romano, V. Castiglia, F. Pellitteri, G. Schettino, R Miceli. (2020). Different scenarios of electric mobility: Current situation and possible future developments of fuel cell vehicles in Italy. *Sustainability*, *12*(2), 564.

[8] P. Kadav and Z. D. Asher, "Improving the Range of Electric Vehicles," 2019 Electric Vehicles International Conference (EV), 2019, pp. 1-5.

[9] M. Burunkaya and O. F. Demirkol, "Increase in the Use of Electric Vehicles and Its Potential Effects on Electricity Distribution Network and Situation Analysis for Turkey," 2019 6th International Conference on Electrical and Electronics Engineering (ICEEE), 2019, pp. 33-37.

[10] A. Meintz et al., "Enabling fast charging - Vehicle considerations," Journal of Power Sources. 367. 216-227.

[11] R. Qiang, Y. Wu, T. B. Soeiro, P. Granello, Z. Qin and P. Bauer, "A New Input-Parallel-Output-Series Three-Phase Hybrid Rectifier for Heavy-Duty Electric Vehicle Chargers," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 2022, pp. 1-6.

[12] D. Lan, Y. Wu, T. B. Soeiro, P. Granello, Z. Qin and P. Bauer, "12-pulse Rectifier with DC-Side Buck Converter for Electric Vehicle Fast Charging," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 2022, pp. 1-6.

[13] V. M. Iyer, S. Gulur, G. Gohil and S. Bhattacharya, "Extreme fast charging station architecture for electric vehicles with partial power processing," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), 2018, pp. 659-665.

[14] T. Kanstad, M. B. Lillholm and Z. Zhang, "Highly Efficient EV Battery Charger Using Fractional Charging Concept with SiC Devices," 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), 2019, pp. 1601-1608.

[15] L. Dickerman and J. Harrison, "A New Car, a New Grid," in IEEE Power and Energy Magazine, vol. 8, no. 2, pp. 55-61, March-April 2010.

[16] S. R. Sanders, E. Alon, H. -P. Le, M. D. Seeman, M. John and V. W. Ng, "The Road to Fully Integrated DC–DC Conversion via the Switched-Capacitor Approach," in IEEE Transactions on Power Electronics, vol. 28, no. 9, pp. 4146-4155, Sept. 2013.

[17] M. D. Seeman and S. R. Sanders, "Analysis and Optimization of Switched-Capacitor DC–DC Converters," in IEEE Transactions on Power Electronics, vol. 23, no. 2, pp. 841-851, March 2008.

[18] Y. Lei, W. Liu and R. C. N. Pilawa-Podgurski, "An Analytical Method to Evaluate and Design Hybrid Switched-Capacitor and Multilevel Converters," in IEEE Transactions on Power Electronics, vol. 33, no. 3, pp. 2227-2240, March 2018.

[19] M. Chen, K. K. Afridi, S. Chakraborty and D. J. Perreault, "A high-power-density wide-input-voltage-range isolated dc-dc converter having a MultiTrack architecture," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), 2015, pp. 2017-2026.

[20] Y. Li, J. Chen, M. John, R. Liou and S. R. Sanders, "Resonant switched capacitor stacked topology enabling high DC-DC voltage conversion ratios and efficient wide range regulation," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), 2016, pp. 1-7.

[21] F. Pellitteri, V. Di Dio, C. Puccio, and R. Miceli: "A Model of DC-DC Converter with Switched-Capacitor Structure for Electric Vehicle Applications". 2022, *Energies*, *15*(3), 1224.

[22] X. -D. Qing, Z. -H. Wang, Y. -G. Su, Y. -M. Zhao and X. -Y. Wu, "Parameter Design Method With Constant Output Voltage Characteristic for Bilateral LC-Compensated CPT System," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 3, pp. 2707-2715, Sept. 2020.

[23] J. Dai and D. C. Ludois, "Capacitive Power Transfer Through a Conformal Bumper for Electric Vehicle Charging," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 1015-1025, Sept. 2016.

[24] M. Kline, I. Izyumin, B. Boser and S. Sanders, "A transformerless galvanically isolated switched capacitor LED driver," 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2012, pp. 2357-2360.

[25] P. Granello, T. B. Soeiro, N. H. Van der Blij and P. Bauer, "Revisiting the Partial Power Processing Concept: Case Study of a 5 kW 99.11 % Efficient Flyback Converter-Based Battery Charger," in IEEE Transactions on Transportation Electrification.

[26] L. Schirone and M. Macellari, "Loss Analysis of Low-Voltage TLNPC Step-Up Converters," in IEEE Transactions on Industrial Electronics, vol. 61, no. 11, pp. 6081-6090, Nov. 2014.

[27] Schirone, L., Macellari, M. and Pellitteri, F., "Predictive dead time controller for GaN-based boost converters", in IET Power Electronics, Vol. 10, no. 4, March 2017, pp. 421-428.

[28] Schirone, L., Granello, P., 2023. "The power diode", in Encyclopedia of Electrical and Electronic Power Engineering, vol. 1. Elsevier, pp. 92–105.