Highly Compact Partial Power Converter for a Highly Efficient PV-BESS Stacked Generation System

Granello, Pierpaolo; Schirone, Luigi; Bauer, Pavol; Miceli, Rosario ; Pellitteri, Filippo

DOI
10.1109/SMART55236.2022.9990160

Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)

2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART) | 978-1-6654-7146-6/22/$31.00 ©2022 IEEE | DOI: 10.1109/SMART55236.2022.9990160

Highly Compact Partial Power Converter for a Highly Efficient PV-BESS Stacked Generation System

Pierpaolo Granello and Luigi Schirone
Scuola di Ing. Aerospaziale
Sapienza University of Rome
Rome, Italy
Email: pierpaolo.granello@uniroma1.it
luigi.schirone@uniroma1.it

Pavol Bauer
Department of Electrical Sustainable Energy
Delft University of Technology
Delft, The Netherlands
Email: p.bauer@tudelft.nl

Rosario Miceli and Filippo Pellitteri
Dept. of Engineering
University of Palermo
Palermo, Italy
Email: rosario.miceli@unipa.it
filippo.pellitteri@unipa.it

Abstract— **The inherently intermittent nature of photovoltaic (PV) energy has brought increasing interest towards the integration between PV sources and Battery Energy Storage Systems (BESS). In this paper, a Series Partial Power Processing (PPP) converter based on Capacitive Power Transfer (CPT) is proposed to integrate PV and BESS in a grid-connected inverter system. The proposed converter has been simulated according to a PV string capable to provide 1430 W under full irradiance conditions, a BESS nominal voltage equal to 215 V and a solar inverter assumed to operate with a minimum voltage of 150 V and a maximum current of 10 A. Simulation tests carried out at different conditions of solar radiation and required load power aim at demonstrating the correct operation of the proposed system.**

*Keywords — **DC/DC Power Conversion, Partial Power Processing, Switched Capacitor, Capacitive Power Transfer, Battery Energy Storge Systems, Photovoltaic.***

I. INTRODUCTION

In the frame of a more sustainable society, massive electrification of essential goods and increasing use of renewable energies is going to occur in the near future. Design optimization of power electronics and electrical machines will play a major role for an actually efficient and sustainable operation in different applications [1-4].

In the case of grid-connected PV inverter systems, several solutions regarding the PV-BESS integration have been investigated, as widely reported by scientific literature. The main drawback arising from these solutions is represented either by the relatively low efficiency of power converters as they process the full power flowing between PV and the storage system, or by the high cost in case of high-voltage BESS [5].

Recently, the interest towards solid-state power conversion stages processing only a partial part of the total flowing power, commonly referenced as Partial Power Processing (PPP) circuits, Differential Power Processing (DPP) circuits or fractional power processing circuits, is growing due to the increasing number of applications which might benefit from their advantages, for instance PV [6] and BESS [7].

Accordingly, an attractive method to avoid both Full Power Processing (FPP) and high-voltage BESSs is to partialize the energy that the power converter has to process by connecting in series the PV source with the BESS [5]. This solution is implemented by the scheme in Fig. 1, highlighting the well-known Series Partial Power Processing (S-PPP) applied to the series connection between PV and battery. The PPP converter regulates the compensation current I_{node}, as a result of the difference between the PV and BESS current, while providing a regulated DC link to supply the grid-connected inverter with an input voltage which is sum of the PV and the BESS voltage. The Series-PPP architecture is also generally attractive because, as reported in [6], it is more efficient than the Parallel PPP architecture, and provides the lower components' voltage stress as well when compared to the parallel one. Moreover, in the case of Parallel-PPP converter there is a threshold voltage gain above which the resulting system power conversion efficiency becomes less efficient than the relative FPP auxiliary power converter.

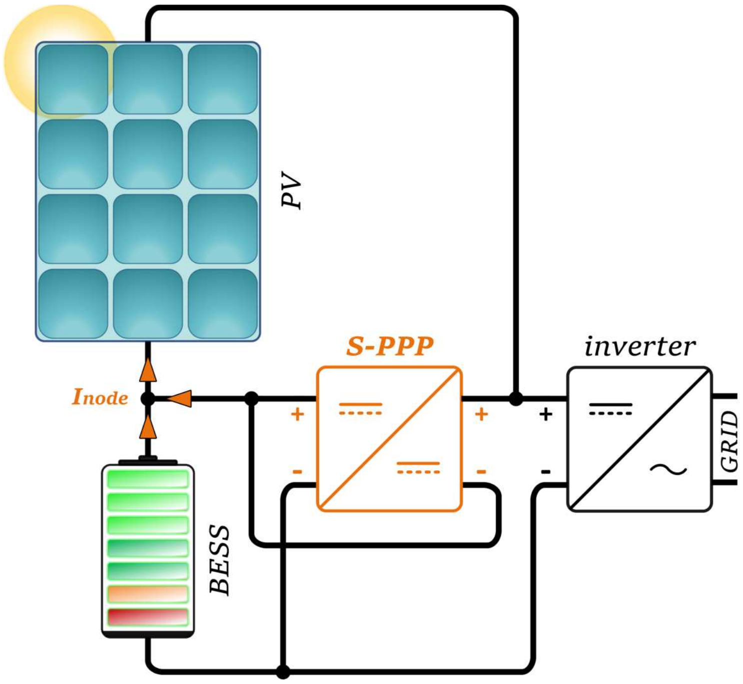

Fig. 1a): S-PPP converted applied to the PV-BESS series connection

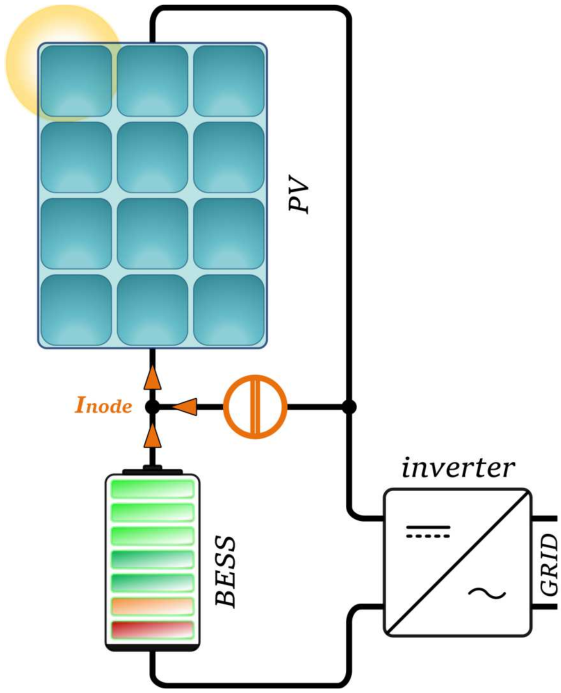

Fig. 1b):Current source I_{node}, equivalent to the S-PPP scheme

In the case of Series-PPP architecture this limitation is overcome, as even if the processed power by the converter increases, together with its voltage gain, the resulting system efficiency is always higher with respect to the relative FPP solution.

The Series-PPP architecture results in a non-isolated conversion system even if isolated topologies are involved for the power converter, so that the galvanic isolation is lost in PPP circuits where isolated power conversion topologies are involved, thus making the requirement for galvanic isolation unfeasible. Nevertheless, some non-isolated topologies shall not be employed for the PPP implementation due to potential short circuits, as a non-direct ground connection is a mandatory requirement for PPP solutions.

Some non-isolated topologies could be employed for PPP, but at the cost of obtaining an equivalent FPP components' applied voltage or current stress. Consequently, the main advantage of processing only a partial part of the power in the conversion stage with a reduced components' stress would be lost, which is the main reason why aiming towards the power density of PPP converters is convenient. Accordingly, the use of isolated topologies is strongly recommended for PPP implementation [8], [9], as isolated topologies in Series-PPP configuration might also exhibit advantages in terms of components applied stress, thus driving towards a higher overall system efficiency.

Among the isolated DC-DC converters, topologies based on transformer or coupled-inductors add complexity, weight and cost to the system design, thus limiting its power density and forcing to deal with core and copper losses. Power converters using Switched Capacitors (SC) technology offer an alternative which might reduce the need for magnetic components [10], [11]. Application of this type of converters has been limited for long time to low power levels, due to the lack of a capacitor technology able to deliver sufficient high voltage, temperature and frequency ratings. Recently, increasing attention to SC converters has been paid regarding high power and automotive applications [12], as various hybridized topologies inspired from the switched capacitor domain have been proposed to enable the use of lower voltage devices [13], [14], [15], [16].

Accordingly, inspired on Wireless Power Transfer (WPT) and SC technology, the Capacitive Power Transfer (CPT) is being proposed as it allows the power transfer through metal barriers leading to high design flexibility, low cost of the coupling interface and low eddy current losses [17]. The CPT has been widely researched in some fields such as EVs wireless battery charging [18], [19] and power supplies for LED applications [20], [21].

The use of CPT represents a valid alternative to magnetic isolated technologies, potentially leading to highly compact conversion stages with respect to the use of the latter technological solution. Moreover, recent technological advancements allowed ceramic capacitors to achieve higher voltage ratings and capacitance values in a compact footprint, still retaining remarkable frequency and temperature stability. Among the different works known in literature, SC technology for CPT has been researched mostly for low power applications [20-23], while recent works are focusing on extending its application for higher power conversion. Accordingly, the CPT functionality has been assessed for a 2.5 kW power converter in [24].

Switched Capacitors (SC) converters then provide a feasible solution to implement performant isolated DC-DC converters. In this paper an isolated bidirectional Dual Active Bridge DC-DC converter based on CPT is proposed for the PV-BESS series integration in Series-PPP configuration, capable of controlling step-up and step-down conversion in the relevant power conversion direction. A work on low power PPP CPT converter for LED driving is available in literature [21], assessing a relatively high conversion efficiency within a compact converter design.

This technology however requires particular attention for peak current control during turn-on transients in order to maximize its conversion efficiency. This work focuses on the optimal design of a Series PPP CPT for the proposed application. The proposed converter has been simulated considering a maximum power level of around 1.5 kW and different conditions of solar irradiance in order to evaluate its correct behaviour.

II. THE PROPOSED CONVERTER

The proposed converter, whose schematic is shown in Fig. 2, provides capacitive insulation between input and output with conversion ratio ideally equal to 1. The circuit consists of a full-bridge inverter on the source side and a full-wave diode rectifier on the load side, whose phase nodes are connected by the insulation capacitances Ca and Cb.

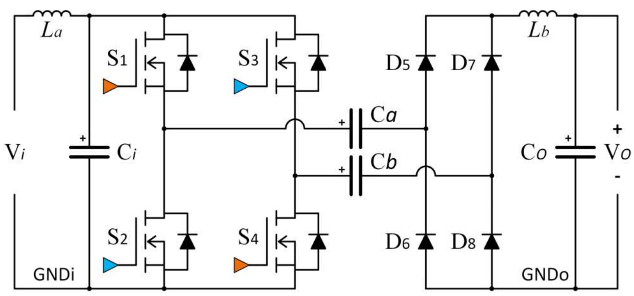

Fig. 2: CPT isolated Full Bridge converter circuit

L_a-C_i and L_b-C_o represent the input and output passive filters used to smooth the current ripple generated by the converter towards the external sections and responsible for potential electromagnetic interferences. A detailed description of the circuit operation has been reported in [24]: by driving the switches S1-S4 in phase opposition with S2-S3 and with a 50% duty cycle, the full-bridge inverter provides a pulsed square wave with amplitude equal to the input voltage Vi and frequency equal to the switching frequency fs.

Care shall be addressed towards the maximum voltage rating of the insulation capacitors, in order to be compliant with the full voltage isolation requirements. Indeed, the insulation voltage can be modelled as a voltage source between the ground reference levels of input and output sides, which, according to the circuital analysis, corresponds to a DC offset voltage superimposed on the capacitors' voltage ripple.

In this paper, as shown in Fig. 3 the dual-active bridge version of the described converter is proposed, consisting of the full-wave active bridge S5-S6-S7-S8 in place of the passive diode rectifier D5-D6-D7-D8. This allows also to control the required bi-directional power transfer to offset current I_{node} between the BESS, PV and the inverter.

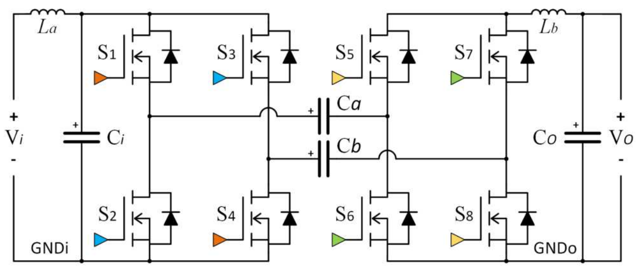

Fig. 3: CPT isolated Dual Active Bridge converter circuit

Therefore, the proposed converter can be properly used to implement the previously mentioned BESS current compensation in the series partial power processing architecture based on the series connection with a PV module, according to the schematic shown in Fig. 4.

Accordingly, the battery is supposed to be capable of either supplying the inverter or to be recharged by the PV module when needed.

Particular care should be addressed to the maximum DC voltage of the insulation capacitors, since it has to be equal to the PV string voltage.

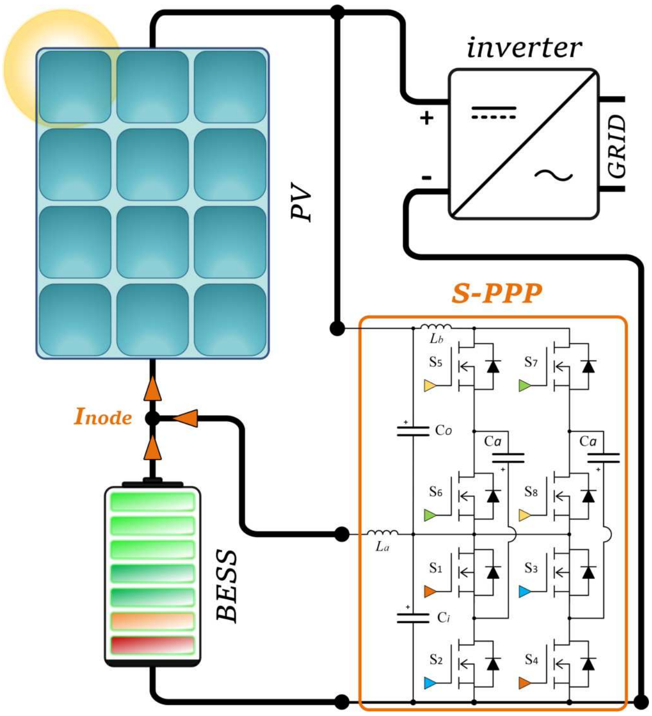

Fig. 4: CPT isolated Full Bridge converter circuit

In order to evaluate the system operation different simulation tests have been performed by means of the software *PLECS*. For the system modelling common PV and Inverter specifications have been taken into account, and the BESS voltage has been sized to achieve the optimum working point. The main system features are given in Table 1.

For the simulation a series connection of 22 modules *BP-365 65W* has been considered for the PV string modelling, which is thus capable to provide 1430 W under full irradiance conditions. The solar inverter is assumed to operate with a minimum voltage of 150 V and a maximum current of 10 A. The battery stack is composed to achieve a nominal voltage of 215 V.

Due to the 500 kHz switching frequency of the S-PPP converter, the isolation capacitors, for instance C_a and C_b, have been sized with a value of 10 μF in order to make their voltage drop negligible and not introduce a negative DC offset which would consequently limit the voltage conversion ratio of the converter [24].

III. SIMULATION TESTS

According to the reported specifications, a set of simulation tests has been carried out under different solar radiation conditions, to estimate the correct converter behaviour.

TABLE 1: SYSTEM SPECIFICATIONS

BESS	V_{BESS} = 215 V	
	E_{BESS} = 5 kWh	
PV STRING	@ 1000 W/m^2	Isc = 4 A Voc = 480 V Pmax = 1.43 kW
	@ 500 W/m^2	Isc = 2 A Voc = 460 V Pmax = 690 W
	@ 100 W/m^2	Isc = 0.4 A Voc = 415 V Pmax = 150 W
INVERTER	V_{dc} = (150 ÷ 450) V $I_{dc.INV.max}$ = 10 A	

Under AM 1.5 irradiance, the PV is providing its full power and mainly supplies the inverter. The compensation current is thus positive and the S-PPP converter is recharging the BESS, whereas the inverter input voltage is increasing with the increasing BESS state of charge. If the PV module irradiance gets lower, the BESS charging power reduces accordingly.

A working stall point is reached whenever the inverter sinks enough power from PV so that the BESS is neither recharging nor discharging as the compensation current is zero. Whenever the inverter sinked power gets higher to move the system working point above this stall, be it due to a higher sinked inverter power or due to a reduced PV irradiance, the BESS shall fill the power gap and keeping the PV in MPPT as well.

Accordingly, as the compensation current goes negative under these working conditions, the BESS discharges to supply the S-PPP which in turn injects current in the inverter node, thus providing the current missing difference and filling the power gap.

The S-PPP proposed converter has been simulated according to a pulsed square wave with a 500 kHz switching frequency, 50% duty-cycle with a 2.5% dead time, which is required to avoid current shoot-throughs due to the switching operation.

In Fig. 5 voltage and current waveforms of the insulation capacitances are shown, according to the gate signals applied on MOSFETs S1-S4-S5-S8 (green colour) and S2-S3-S6-S7 (red colour). Fig. 5a) refers to the BESS in discharging mode, since the grid requires power from

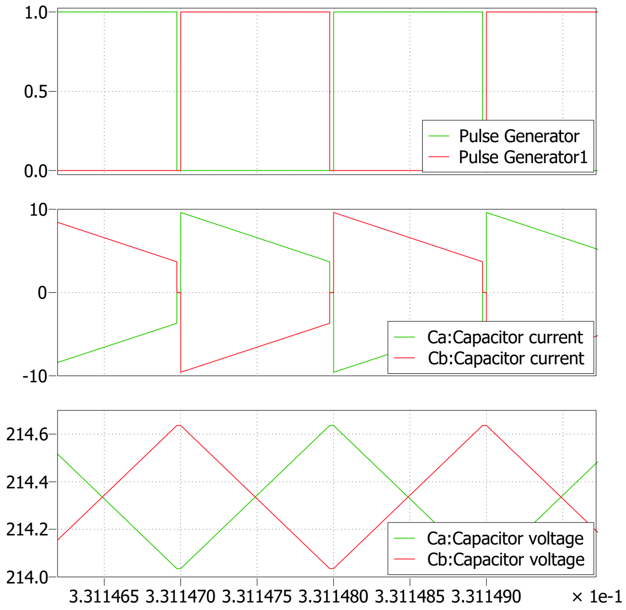

Fig. 5a): Simulation plots during BESS discharging state ($I_{dc,INV}$ = 10 A; solar irradiance = 1000 W/m^2)

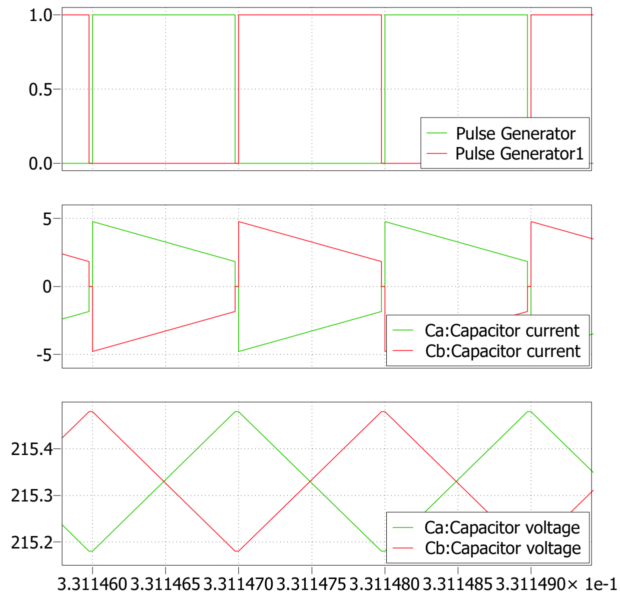

Fig. 5b): Simulation plots during BESS discharging state ($I_{dc,INV}$ = 1 A; solar irradiance = 1000 W/m^2)

both PV and BESS; the compensation current (see Fig. 1) is negative and therefore when S1-S4-S5-S8 conduct, which is when I_{Ca} is positive. Fig. 5b) refers to the BESS in recharging mode, since the current required from the grid-connected inverter is lower, thus allowing the BESS to go out of the discharging mode and be recharged from the PV; the compensation current is thus positive when S1-S4-S5-S8 conduct, which is when I_{Ca} is negative.

IV. Conclusions

This work proposed the idea of the Series Partial Power Processing (S-PPP) as solution to integrate a Battery Energy Storage System (BESS) with a PV module in order to continuously supply the grid-connected inverter. The PPP consists of processing less power than a full power processing and therefore allows to increase the overall power transfer efficiency.

To implement the S-PPP concept, an isolated Switched Capacitor power converter based on a Dual Active Bridge based on Capacitive Power Transfer (CPT) was proposed. According to the regulation of the compensation current, defined as the difference between the PV current and the BESS current, the converter is capable to properly regulate the DC-link voltage supplying the solar inverter while recharging the battery stack if the load power is low.

Simulation tests have been performed on the proposed converter, assessing the correct operation of the system during both BESS charging and discharging modes, while considering a PV string capable to provide 1430 W under full irradiance conditions, a BESS nominal voltage equal to 215 V and a solar inverter assumed to operate with a minimum voltage of 150 V and a maximum current of 10 A.

The proposed application looks forward on a system analysis relying on the experimental assessment which will be made on a laboratory prototype, taking into account the use of emerging semiconductor technologies capable to switch at minimum of 500 kHz, thus giving compactness to the system.

Moreover, among the known works in literature there is a lack of control in step-down and step-up power conversion, due to the design challenges which aim at achieving high conversion efficiency.

Therefore, a comprehensive analysis will be carried out in the near future, regarding the control of the proposed circuital solution. Finally, a system capable of handling 3 kW, to be compliant with standard commercial households' PV systems, will be realized and measurements on the converter prototype will be carried out to assess the proposed results.

Acknowledgment

This work was realized with the contribution of: Italian Ministry of University and Research; PON R&I 2014-2020 FSE REACT EU, Action IV.6, research contract regulated by DM 1062/2021; PRIN 2017, Advanced power-trains and -systems for full electric aircrafts, prot. no.: 2017MS9F49; RPLab (Rapid Prototyping Laboratory - University of Palermo); project REACTION (first and euRopEAn siC eighT Inches pilOt liNe), co-funded by the ECSEL Joint Undertaking under grant agreement No 783158; SDES (Sustainable Development and Energy Savings) Laboratory UNINETLAB of University of Palermo, Laboratory of Electrical APplications LEAP - of University of Palermo; Electrical Drives Laboratory of University of Palermo; Aerospower Lab, School of Aerospace Engineering, Sapienza, University of Rome.

REFERENCES

[1] A. O. Di Tommaso, F. Genduso, R. Miceli and C. Nevoloso, "Fast procedure for the calculation of maximum slot filling factors in electrical machines," 2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER), 2017, pp. 1-8, doi: 10.1109/EVER.2017.7935906.

[2] R. Leuzzi et al., "High-Speed Machines: Typologies, Standards, and Operation Under PWM Supply," 2018 AEIT International Annual Conference, 2018, pp. 1-6, doi: 10.23919/AEIT.2018.8577297.

[3] 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, doi: 10.1109/TIE.2014.2308132.

[4] L. Schirone and M. Macellari, "Design of high-efficiency non-insulated step-up converters", in IET Power Electronics, vol. 8, no. 5, pp. 743-749, May 2015, doi: 10.1049/iet-pel.2014.0554.

[5] N. Kim and B. Parkhideh, "PV-Battery Series Inverter Architecture: A Solar Inverter for Seamless Battery Integration With Partial-Power DC–DC Optimizer," in IEEE Transactions on Energy Conversion, vol. 34, no. 1, pp. 478-485, March 2019, doi: 10.1109/TEC.2018.2873664.

[6] H. Jeong, H. Lee, Y. Liu and K. A. Kim, "Review of Differential Power Processing Converter Techniques for Photovoltaic Applications," in IEEE Transactions on Energy Conversion, vol. 34, no. 1, pp. 351-360, March 2019, doi: 10.1109/TEC.2018.2876176

[7] N. M¨uller, S. Kouro, P. Zanchetta and P. Wheeler, "Bidirectional partial power converter interface for energy storage systems to provide peak shaving in grid-tied PV plants," 2018 IEEE International Conference on Industrial Technology (ICIT), 2018, pp. 892-897, doi: 10.1109/ICIT.2018.8352296

[8] 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, vol. 8, no. 3, pp. 3934-3945, Sept. 2022, doi: 10.1109/TTE.2022.3170286.

[9] J. Zhao, K. Yeates and Y. Han, "Analysis of high efficiency DC/DC converter processing partial input/output power," 2013 IEEE 14th Workshop on Control and Modeling for Power Electronics, 2013, pp. 1-8, doi: 10.1109/COMPEL.2013.6626440.

[10] 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, doi: 10.1109/TPEL.2007.915182.

[11] 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, doi: 10.1109/TPEL.2012.2235084.

[12] D. Cao, S. Jiang and F. Z. Peng, "Optimal design of multilevel modular switched-capacitor dc-dc converter," 2011 IEEE Energy Conversion Congress and Exposition, 2011, pp. 537-544, doi: 10.1109/ECCE.2011.6063816.

[13] K. Kesarwani and J. T. Stauth, "Resonant and multi-mode operation of flying capacitor multi-level DC-DC converters," 2015 IEEE 16th Workshop on Control and Modeling for Power Electronics, 2015, pp. 1-8, doi: 10.1109/COMPEL.2015.7236511.

[14] 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, doi: 10.1109/TPEL.2017.2690324.

[15] 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, doi: 10.1109/ECCE.2016.7855401.

[16] 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, doi: 10.1109/ECCE.2015.7309945.

[17] 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, doi: 10.1109/JESTPE.2019.2936231.

[18] H. Zhang, F. Lu, H. Hofmann, W. Liu and C. C. Mi, "A Four-Plate Compact Capacitive Coupler Design and LCL-Compensated Topology for Capacitive Power Transfer in Electric Vehicle Charging Application," in IEEE Transactions on Power Electronics, vol. 31, no. 12, pp. 8541-8551, Dec. 2016, doi: 10.1109/TPEL.2016.2520963.

[19] 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, doi: 10.1109/JESTPE.2015.2505622.

[20] D. Shmilovitz, S. Ozeri and M. M. Ehsani, "A resonant LED driver with capacitive power transfer," 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, 2014, pp. 1384-1387, doi: 10.1109/APEC.2014.6803487.

[21] 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, doi: 10.1109/APEC.2012.6166152.

[22] Y. Li, L. Gu, A. Hariya, Y. Ishizuka, J. Rivas-Davila and S. Sanders, "A Wide Input Range Isolated Stacked Resonant Switched-Capacitor dc-dc Converter for High Conversion Ratios," 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics, 2018, pp. 1-7, doi: 10.1109/COMPEL.2018.8459936.

[23] 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, doi: 10.1109/JESTPE.2019.2936231.

[24] P. Granello, F. Pellitteri, R. Miceli and L. Schirone, "Highly Efficient Capacitive Galvanic Isolation for EV Charging Stations," 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2022, pp. 389-394, doi: 10.1109/SPEEDAM53979.2022.9842217.