1. Mykola LUKIANOV, 2. Ievgen VERBYTSKYI, 3. Natalia STRZELECKA, 4. Ryszard STRZELECKI

Gdańsk University of Technology, Faculty of Electrical and Control Engineering (1), National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Dept. of Electronic Devices and Systems (2), Gdynia Maritime University, Faculty of Electrical Engineering (3)
ORCID: 1. 0000-0001-8930-9992; 2. 0000-0001-7275-5152; 3. 0000-0002-5976-6903; 4. 0000-0001-9437-9450

doi:10.15199/48.2023.11.23

Power converter interface for urban DC traction substations - solutions and functionality

***Abstract**. This paper focuses on extending an urban DC traction substation functionality by means of an additional power converter interface (PCI). In particular, by enabling bidirectional energy exchange between LV DC traction grid, AC grid and V2G chargers. Among other things, the presented material compares general attributes of the most promising DC/DC converters that can be used in a PCI, meet the requirements of galvanic isolation and can operate in a wide voltage range. Based on the literature, the application suitability of typical PCI structures and isolated DC/DC converters was made. In addition, the principles of power flow in the power converter interface that connects an AC grid, DC traction grid, V2G chargers and PV source are discussed.*

***Streszczenie.** Niniejszy artykuł koncentruje się na zagadnieniach związanych z rozszerzeniem funkcjonalności miejskich podstacji trakcyjnych prądu stałego za pomocą dodatkowych interfejsów energoelektronicznych, w szczególności umożliwiających dwukierunkową wymianę energii między trakcją, siecią i ładowarkami V2G. W prezentowanym materiale porównano między innymi ogólne atrybuty połączeń przetwornic DC/DC i aktywnych prostowników rewersyjnych, spełniających wymagania separacji galwanicznej i pracy w pełnym zakresie zmian napięcia trakcyjnego. Na podstawie literatury scharakteryzowano również przydatność typowych izolowanych przetwornic DC/DC. Ponadto omówiono zasady przepływu mocy w interfejsie łączącym sieć AC, trakcję DC, ładowarkę V2G i źródło PV. (**Interfejs energoelektroniczny dla miejskich podstacji trakcyjnych DC - rozwiązania i funkcjonalność**).*

Keywords: Power converter interface, EV charger, V2G EV charging, urban LV DC traction grid, renewable energy sources.
Słowa kluczowe: Interfejs energoelektroniczny, ładowarka samochodu V2G, trakcja DC, odnawialne źródła energii.

Introduction

Public and personal electric transport development can help to reduce environmental pollution in highly urbanized areas [1]. However, the rapid development of electric transport requires additional infrastructure installation, which is associated with additional economic expenses. To reduce the installation cost, different systems may be combined together, sharing the equipment. For example, EV charging stations can be connected to existing substations, sharing the same infrastructure with other consumers. Although this creates an additional load on the equipment, smart charging algorithms can be used, that adjust EV chargers power consumption depending on the substation load [2]. As a result, the existing electrical infrastructure can be utilized without any risk of overloading.

This article discusses the connection of EV charging stations to the urban tram/trolleybus networks in proximity to traction substations. The choice of LV DC traction grids is associated with their high prevalence within cities and their potential expansion in the future. In addition, a connection of EV charging equipment to LV DC networks can potentially bring benefits for the traction transport and substation equipment, solving problems of traction vehicles braking energy recuperation, DC line voltage instability and substation peak load shaving [3].

A typical structure of a substation, feeding a catenary section is shown in Fig. 1, which consists of a MV to LV transformer with a consequent 12-pulse rectifier. In a default case, when no additional equipment is installed, power consumption from the substation and voltage at the catenary directly depends on the tram movement profile (Fig. 2 (a)). Two particular moments are worth mentioning. The first one is the beginning of the movement with a high acceleration speed. It results in peak power consumption from the substation, which increases stress on the equipment and requires the installation of components with redundancy to withstand peak power loads [4]. The second one is a vehicle deceleration, which is accompanied by the release of vehicle braking energy to the LV DC line with a resulting voltage increase (Fig. 2 (b)). Usually, braking energy is dissipated in resistors, using braking choppers that are installed on the trams. However, it is associated with unwanted power loses and reduces transport efficiency by up to 30% [5, 6].

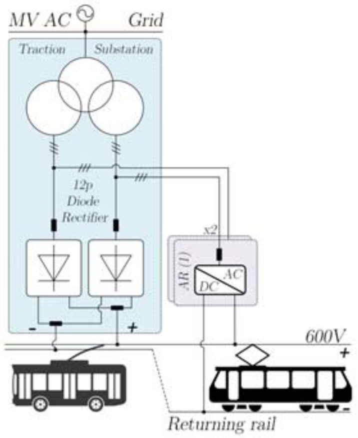

Fig.1. Typical substation reversible converter connection scheme.

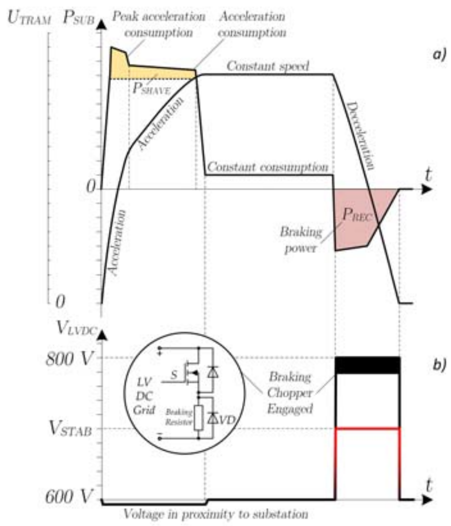

Fig.2. Power consumed by tram from substation P_{SUB}, which depends on its speed profile U_{TRAM} a); and voltage at LV DC catenary in proximity to the substation V_{LVDC} b).

One possible solution that allows transferring braking energy from the DC line back to the AC grid is an Active Rectifier (AR), installed in parallel with the substation diode bridge (fig. 1) [7]. Using such a reversible DC/AC converter allows to stabilize the voltage at the LV DC line as well as increases the efficiency of all traction vehicles in proximity to the substation. However, conventional AR has several problems:

— Low utilization;

The functions of AR are limited to braking energy recuperation, which occurs only for some time during the day. All other times, when there is no public transport nearby (which is the case at night) AR does not provide any significant functions.

— Due to the absence of energy accumulators, AR cannot provide peak power shaving.

As a result, this article proposes and analyses power converter interface structures and their functionality, which provides energy exchange between LV DC grid, AC grid and connected EVs. Proposed PCI: increases AR functionality and utilization; provides DC line voltage stabilization and transport braking energy recuperation (P_{REC} in fig. 2); reduces substation peak power load during traction transport rapid acceleration by providing peak power shaving (P_{SHAVE} in fig. 2).

Proposed PCI structures

In order to expand AR converter functions without introducing changes to its structure, it is possible to use it as an AC port in a power converter interface (Fig. 3). PCI is required in order to ensure all the requirements needed for normal system operation, such as:

— Isolated DC port for the EVs connection [8];

EV charging station standards require galvanic isolation from energy sources. Thus, isolation must be provided both from the MV AC network and from the LV DC grid.

— Galvanic isolation between AR and LV DC grid;

Usually, AR does not have galvanic isolation [9]. Thus, in a conventional connection (Fig. 1) its operation is possible only when the voltage at the LV DC line is higher than at the AC side (during transport braking), i.e., when a diode bridge is not in a conductive state. Galvanic isolation allows it to operate independently from a 12-pulse rectifier.

— AR DC side voltage must be constantly higher than AC side voltage for active rectifier operation;

Procuring the abovementioned functions is possible by applying various connection schemes with the formation of different numbers of DC-buses, using different converter topologies. The schemes considered in this article are presented in Fig. 3.

As a result, in addition to braking energy recuperation, usage of one of the proposed PCI structures allows AR to provide next functions:

— Work regardless of the voltage on the LV DC line;

— Active power filtering (APF) functions that improve the quality of electricity consumed from the AC network. (From this point of the article AR is going to be called APF);

— Provide energy exchange between the AC network and the DC loads/sources (during day and night) that are connected to the DC-bus (bidirectional EVs, renewable energy sources, storage batteries etc.), which is particularly important in V2G applications;

—

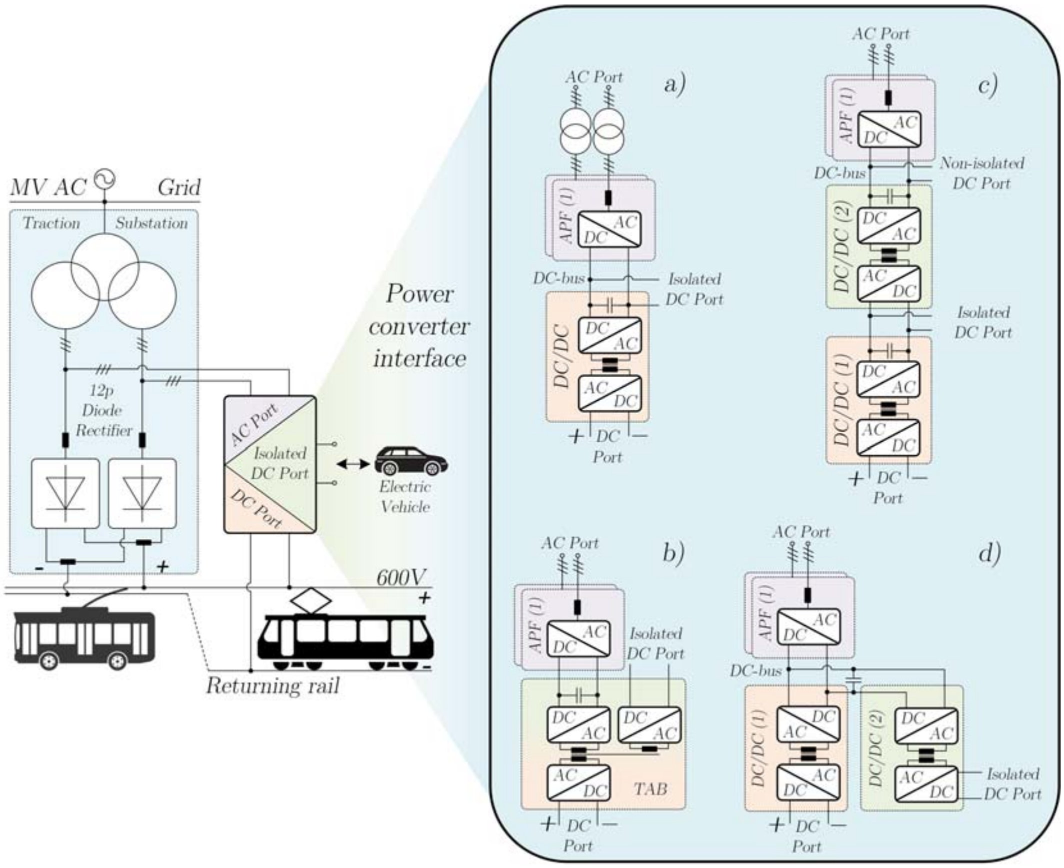

Fig.3. Possible connection schemes of power converter interface, connected to LV DC traction grid.

Table 1. Connection scheme comparison.

Name	Description
a. DC/DC converter with isolated APF	- Single isolated DC bus for EV chargers, PV generation and batteries connection; - Transformer has high efficiency and relatively low price; - **3-phase low-frequency transformer has low power density;**
b. Triple Active Bridge converter (TAB)	- Single magnetic core used to connect all sources; - Two DC busses - non-isolated DC bus and isolated DC/AC output for EV chargers, PV generation and batteries connection; - **Complicated control;**
c. Two series DC/DC converters	- Two DC busses - non-isolated DC bus and isolated DC/AC output for EV chargers, PV generation and batteries connection; - Voltage of DC busses can have different values, which adds versatility to the circuit; - **Two DC buses require more DC-bus capacitors installed**.
d. Two isolated DC/DC converters	- Two DC buses - non-isolated DC bus and isolated DC/AC output for EV chargers, PV generation and batteries connection;

Additionally, the abovementioned PCI schemes, due to the presence of bidirectional EV chargers, connected to the system DC-bus, provide substation peak power shaving [10]. A comparison of described solutions together with their main characteristics is provided in Table 1.

Converters topology selection

In addition to the system features described in Table 1, PCI converter topologies play an important role in the system design, as they directly affect PCI installation cost, efficiency and size. In this chapter, promising and popular isolated DC/DC converters, such as Dual Active Bridge (DAB), Semi-DAB, Three-Phase DAB (TP-DAB), Tripple Active Bridge (TAB), Series Resonant Converter (SRC), High-Frequency Inverting Converter (HFIC) are compared in terms of price, efficiency, frequency and semiconductors used. Because of the standard structure of the APF (Typical 3-Phase VSI), and its market availability, its topology is not considered in the comparison.

According to current trends in power electronics, the efficiency and price of the converter are the decisive criteria when choosing converters. It is clear, that high efficiencies can be achieved using more advanced components and topologies (for example interleaved topologies are widely used to increase efficiency). As a result, high-efficiency topologies usually have higher costs. Thus, in order to define cost-effective solutions, converters comparison should be done in two planes simultaneously - price and efficiency plane.

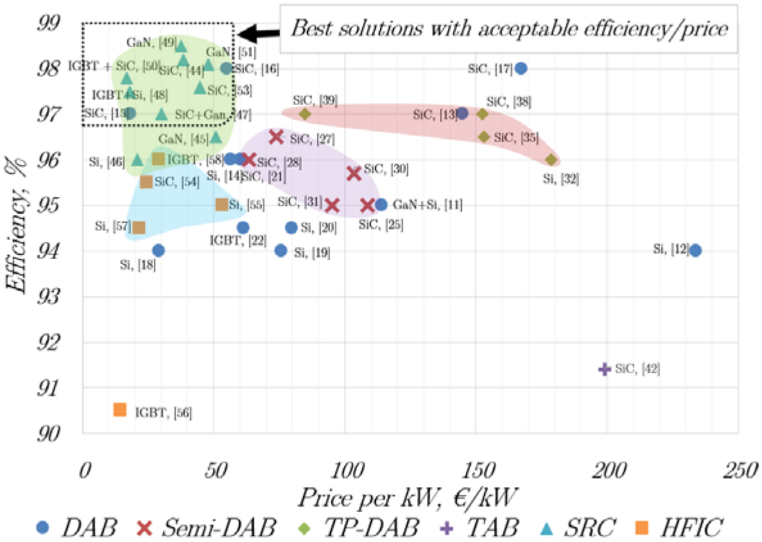

Fig.4. Comparison of converters price per kW / efficiency relation.

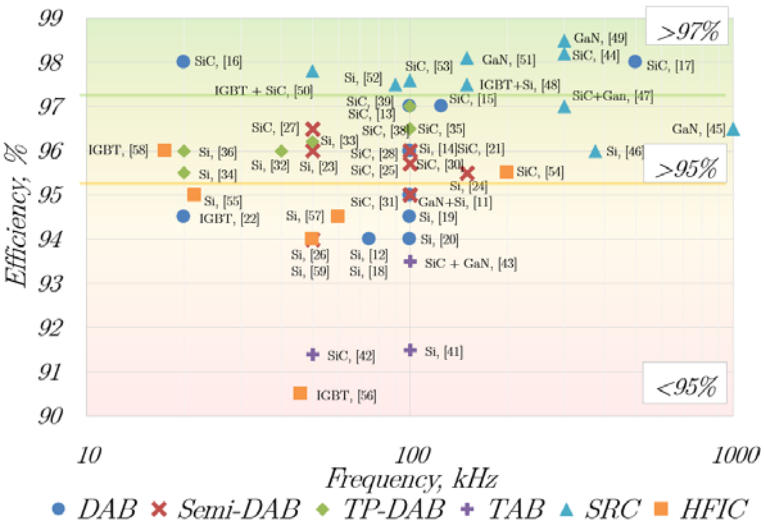

Fig.5. Comparison of converters switching frequencies.

Figure 4 shows that the most effective solutions (>97%) are SRC [44, 47-51, 53], DAB [15-17] and TP-DAB [38, 39]. Their high efficiency can be explained by the utilization of ZVS (Zero Voltage Switching) and ZCS (Zero Current Switching), as well as active bridges at the input and output. The next in terms of efficiency are Semi-DAB [27, 28] and HFIC [58] with an efficiency of more than 96%. Semi-DAB shows lower efficiency due to the use of two diodes at the output bridge, which, although lowers the cost of the converter, reduces its efficiency and allows only unidirectional power flow. The HFIC, in its part, utilizes a full bridge diode rectifier at the output, which does not allow high-efficiency values to be achieved. Among all converters, TAB has the lowest efficiency. This can be explained by the converter circulating powers from port to port through a magnetic core in terms of unequal ports load. However, an important advantage of TAB is that it does not need an additional converter in order to provide galvanic isolation between 3 ports. It also isolates all sources using only one magnetic core. When it comes to a converters price, solutions like SRC [44, 47-51, 53] and DAB [15, 16] have the lowest prices. Worth noting that in order to reduce the cost of converters, SRC solutions in [48, 50] use both relatively cheap IGBT transistors and Si/SiC, which allows them to achieve acceptable efficiency at a lower cost. As a result, the most cost-effective solutions, with efficiency >97% and price per kW < 50 € are most SRC converters and some DABs.

Another important parameter to consider, comparing converter topologies, is their operating switching frequency, since it directly affects converter efficiency, power density, and cost. Fig. 5 shows that converters with efficiency over 97% use mainly SiC components. At high frequencies, GaN transistors are also used. However, in general, the use of GaN transistors is not currently a common practice. Also, some solutions like DAB (150kHz) [48] and SRC (50kHz) [50], which have high efficiency and high switching frequency use a combination of high-frequency IGBT and SiC/Si transistors. In converters such as HFIC [55, 58], the lower frequency is used in order to increase efficiency, which is a trade-off, that leads to an increased size of the converter.

Considering the pros and cons of each converter described above, it can be concluded that the DAB converter is the most suitable for applications where bidirectional power flow together with high efficiency is required. In the presented PCI, it can be used both as a DC/DC(1) and DC/DC(2). TP-DAB bridge looks more suitable for high-power applications due to a power distribution between phases, which results in lower current stress on components. However, the increased number of transistors leads to an increased price and a more complex control system. TAB, due to its low efficiency at partial loads, looks suitable only for solutions, where ports are loaded equally, which allows achieving higher efficiency. SRC, because of its poor regulation characteristics is not suitable for LV DC grid interfaced converter DC/DC(1) due to significant DC catenary line voltage fluctuations, which leads to low SRC efficiency. However, in EV applications, SRC is widely used in two-stage topologies in combination with classical buck or buck/boost converters. Two stages allow to expand SRC regulation range in order to match different EV voltage levels (400V and 800V batteries). As a result, in the proposed PCI, SRC can be used to provide galvanic isolation between the DC bus and EVs with a consequent buck converter for EV charging. HFIC has the poorest functionality (not bidirectional, as a result, no peak shaving), lowest power density and relatively low efficiency. Thus, its usage in the PCI is not recommended. All of the above can be summarized in Table 2.

Table 2. DC/DC topologies comparison.

Name	Features
DAB	- Medium price - High efficiency - High efficiency/price ratio
Semi-DAB	- Medium price (Lower than DAB) - High efficiency (Lower than DAB) - **Unidirectional energy flow**
TP-DAB	- High price (Higher than DAB) - High efficiency (Higher than DAB) - **Preferable for high-power applications (Power splits between phases)**
TAB	- **Low efficiency (when ports are loaded unequally)** - Higher power density than two separate DABs
SRC	- Low price - High efficiency - High operation frequency leads to high power density - High efficiency/price ratio - **Regulation range is low**
HFIC	- Cheap - Relatively low efficiency - **Low operation frequency leads to low power density** - **Unidirectional energy flow**

PCI power flow

Power flow management plays a crucial role in a PCI operation. Due to the existence of different elements of a system like MV grid, LV DC grids and EV chargers (fig. 6), optimal control of such system is a separate research task and widely discussed in the literature [60-62, 63]. However, in [60-62] energy exchange only between batteries and the AC grid takes place. In [63] optimal control of reversible substations and wayside storage devices is considered for a metro DC line. Nevertheless, the authors do not take into account renewable energy sources. In contrary to mentioned researches, this section discusses the basic power exchange principle between all system elements - MV AC grid, LV DC traction grid, EV batteries and renewables. The integration of renewable sources into such a system seems reasonable, as it follows the green energy development trend and potentially reduces the load on a substation by partially powering the line. In addition, when there is no transport operating on the traction line, generated energy is stored in EV batteries or transmitted back to the AC grid, which creates different options for renewables management.

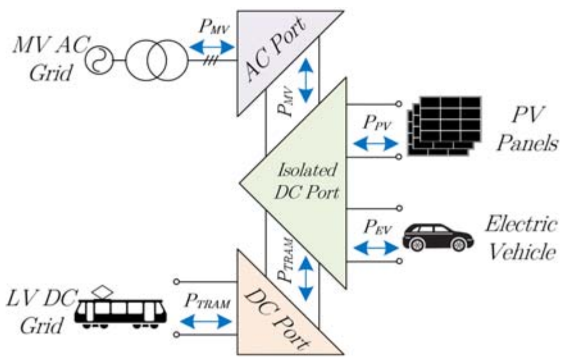

Fig.6. Power converter interface power flow.

PCI system power flow in a simplified form is described using formula (1). **Positive power** flows are considered **in the direction of the isolated DC port**.

$$(1)\quad \begin{aligned} &\pm P_{TRAM} \pm P_{MV} \pm P_{EV}^{mode} + P_{PV} = 0 \\ &P_{PV} = f(Irradiance, Temperature) \end{aligned}$$

where: P_{TRAM} – tram power consumption/recuperation, P_{MV} – power consumed from grid/transferred back to grid, P_{EV}^{mode} – EV charger power depending on mode, P_{PV} – PV panels generation power.

In formula (1) "±" means bidirectional power flow possibility. Thus, when the energy generated by solar panels and consumed by EVs are both equal to zero ($P_{PV}=0$, $P^{mode}_{EV}=0$), power consumed from the MV grid during tram movement and recuperated during tram braking entirely depends on tram consumption and generation ($P_{MV}=P_{TRAM}$). In the case of non-zero EVs and PV powers, the AC port manages only the mismatch between P^{mode}_{EV} and P_{PV}. That means, that when all generated by PV energy is used to charge EVs ($P_{PV}=P^{mode}_{EV}$), the same $P_{MV}=P_{TRAM}$ relation takes place. In addition, it means that when EV chargers are consuming power from the DC port, but PV generation does not fully satisfy this demand ($P_{PV} < P^{mode}_{EV}$), EV chargers consume missing power from the MV grid, creating additional load on an AC port and, consequently, on the substation. In particular, this is important during tram acceleration, when the substation is already significantly loaded. As a result, to reduce overload on an AC port and substation during peak load events, EV chargers should operate in smart charging mode.

Overall, there are several EV charger modes, which result in a different system behavior:

— Mode 1. Non-intelligent unidirectional charging:

$$Mode\ 1: \quad P_{EV}^{unidirectional} = P_{EV}^{\max},$$

where $P_{EV}^{unidirectional}$ – power consumption during non-intelligent charging, P^{max}_{EV} – maximal power consumption of installed EV chargers.

Non-intelligent EV charging is a simple EV charging method that does not consider the substation load. This mode results in an increased load on a substation, which leads to faster equipment aging. Applying such mode with a high-power charging stations is not recommended.

— Mode 2. Intelligent unidirectional charging:

$$Mode\ 2: \quad P_{EV}^{smart} = \pm P_{MV}^{\max} \pm P_{TRAM} + P_{PV}, \\ [0 \le P_{EV}^{smart} \le P_{EV}^{\max}]$$

where P_{EV}^{smart} – power during smart EV charging, P^{max}_{MV} – power limit, overcoming which, EV chargers reduce power.

Intelligent charging is an EV charging that is controlled correspondingly to the substation load. During peak consumption from the substation, EV chargers decrease charging power to reduce peak load. However, there is no peak shaving due to unidirectional power flow. That means that when power consumed by tram is higher than substation power limit ($P_{TRAM} > P^{max}_{MV}$) it is impossible to limit substation power at level of P^{max}_{MV} using unidirectional smart charging.

— Mode 3. Intelligent bidirectional charging:

$$Mode\ 3: \quad P_{EV}^{bidirectional} = \pm P_{MV}^{\max} \pm P_{TRAM} + P_{PV}, \\ [-P_{EV}^{\max} \le P_{EV}^{bidirectional} \le P_{EV}^{\max}]$$

where $P_{EV}^{bidirectional}$ – power during bidirectional EV charging.

Bidirectional intelligent EV charging allows providing peak shaving to reduce maximum substation load, when $P_{TRAM} > P^{max}_{MV}$. Power deficit is supplied from EV batteries (if enough cars with bidirectional power flow are present).

Conclusions

The proposed PCI with a dedicated DC port can be beneficial for both electric transport and LV DC grids development due to a wide range of functions – LV DC grid voltage stabilization, traction transport braking energy recuperation, substation peak load shaving and APF functions. Additionally, a dedicated DC-bus with a stabilized voltage simplifies the integration of EV chargers and renewable energy sources into the urban grids. The review of possible PCI connection schemes and DC/DC converters shows that the solution in Fig. 3 (a), with two DAB converters, provides necessary functions and galvanic isolation with a relatively high efficiency of over 97%. Other connection schemes seem to be more complex and have drawbacks, which limit their efficiency and implementation. Described system power flow shows that in the case of proper EV chargers and PV generation management, increased load on a substation can be mitigated, and in the case of bidirectional EV chargers operation, peak power shaving can be achieved.

Worth mentioning, that it is preliminary research, the aim of which is to define solutions and topologies that have practical potential. The further research task is to simulate described PCI work in real-time in order to investigate the dynamic behavior of the system and define system power levels using real tram parameters and behavior. The authors would be grateful for any comments and suggestions regarding this study.

Acknowledgments: *This research was funded by the: EU Horizon 2020 Framework Programme Project: 955614— SMARTGYsum—H2020-MSCA-ITN-2020*

Authors*: mgr inż. Mykola Lukianov, Gdańsk University of Technology, Department of Power Electronics and Electrical Machines, Narutowicza 11/12, 80-233 Gdańsk, Poland, E-mail: mykola.lukianov@pg.edu.pl; prof. dr hab. inż. Ievgen Verbytskyi, Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute, Department Of Electronic Devices and Systems, Peremohy Ave 37, 03056 Kyiv, Ukraine, E-mail: verbytskyi.ievgen@gmail.com; dr inż., docent Natalia Strzelecka, Gdynia Maritime University, Faculty of Electrical Engineering, Morska St. 81-87, 81-225 Gdynia, Poland, E-mail: n.strzelecka@we.umg.edu.pl, prof. dr. hab. inż. Ryszard Strzelecki: ryszard.strzelecki@pg.edu.pl, Gdańsk University of Technology, Department of Power Electronics and Electrical Machines, Narutowicza 11/12, 80-233 Gdańsk, Poland.*

REFERENCES

[1] United Stated Environmental Protection Agency, "Power Plants and Neighboring Communities", U.S. Census Bureau's American Community Survey (ACS) 2014-2018, USA, 2022. Accessed: Feb. 8, 2023. [Online]. Available: https://www.epa.gov/airmarkets/power-plants-and-neighboring-communities

[2] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii and I. Batarseh, "A Comprehensive Review of Power Converter Topologies and Control Methods for Electric Vehicle Fast Charging Applications," in IEEE Access, vol. 10, pp. 40753-40793, 2022, doi: 10.1109/ACCESS.2022.3166935.

[3] P. Cheng, H. Kong, J. Ma and L. Jia, "Overview of resilient traction power supply systems in railways with interconnected microgrid," in CSEE Journal of Power and Energy Systems, vol. 7, no. 5, pp. 1122-1132, Sept. 2021, doi: 10.17775/CSEEJPES.2020.02110.

[4] R. Martins, P. Musilek, H. C. Hesse, J. Jungbauer, T. Vorbuchner and A. Jossen, "Linear Battery Aging Model for Industrial Peak Shaving Applications," 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Palermo, Italy, 2018, pp. 1-6, doi: 10.1109/EEEIC.2018.8494584.

[5] L. Streit and J. Talla, "Energy storage savings depended on recuperation ratio in traction," 2016 ELEKTRO, Strbske Pleso,

Slovakia, 2016, pp. 370-373, doi: 10.1109/ELEKTRO.2016.7512099.
[6] Jisheng Hu, Yukun Zhao and Xiaojing Liu, "The design of regeneration braking system in light rail vehicle using energy-storage Ultra-capacitor," 2008 IEEE Vehicle Power and Propulsion Conference, Harbin, 2008, pp. 1-5, doi: 10.1109/VPPC.2008.4677708.
[7] ABB Sp. z o.o, "ABB Electrification – Distribution Solutions, DC Traction Power Supply", ABB, Poland, 2020. Accessed: Feb. 8, 2023. [Online].Available:https://library.e.abb.com/public/98a2116cd4364d8e9ebd168cabd44c48/ABB_DC%20TPS_EN_V1_16_9_2020-05-07_Handout.pdf
[8] Electrically propelled road vehicles - Safety specifications. Part 3 - Protection of persons against electric shock, International Standard ISO 6469-3, December 2011. [Online]. Available: https://cdn.standards.iteh.ai/samples/45479/4dd589196f204a21a2ae18c1638e8197/ISO-6469-3-2011.pdf
[9] F. Hao, G. Zhang, J. Chen, Z. Liu, D. Xu and Y. Wang, "Optimal Voltage Regulation and Power Sharing in Traction Power Systems With Reversible Converters," in IEEE Transactions on Power Systems, vol. 35, no. 4, pp. 2726-2735, July 2020, doi: 10.1109/TPWRS.2020.2968108.
[10] T. U. Solanke et al., "Optimal design of EV aggregator for real-time peak load shaving and valley filling," 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India, 2020, pp. 1-5, doi: 10.1109/PEDES49360.2020.9379637.
[11] F. Xue, R. Yu and A. Q. Huang, "A 98.3% Efficient GaN Isolated Bidirectional DC–DC Converter for DC Microgrid Energy Storage System Applications," in IEEE Transactions on Industrial Electronics vol. 64, no. 11, pp. 9094-9103, Nov. 2017, doi:10.1109/TIE.2017.2686307.
[12] A. K. Bhattacharjee and I. Batarseh, "Optimum Hybrid Modulation for Improvement of Efficiency Over Wide Operating Range for Triple-Phase-Shift Dual-Active-Bridge Converter," in IEEE Transactions on Power Electronics, vol. 35, no. 5, pp. 4804-4818, May 2020, doi: 10.1109/TPEL.2019.2943392.
[13] D. Chen, J. Deng, W. Wang and Z. Wang, "A Dual-Transformer-Based Hybrid Dual Active Bridge Converter for Plug-in Electric Vehicle Charging to Cope With Wide Load Voltages," in IEEE Transactions on Industrial Electronics, vol. 70, no. 2, pp. 1444-1454, Feb. 2023, doi: 10.1109/TIE.2022.3158013.
[14] F. Krismer and J. W. Kolar, "Accurate Power Loss Model Derivation of a High-Current Dual Active Bridge Converter for an Automotive Application," in IEEE Transactions on Industrial Electronics, vol. 57, no. 3, pp. 881-891, March 2010, doi: 10.1109/TIE.2009.2025284.
[15] S. A. Assadi, H. Matsumoto, M. Moshirvaziri, M. Nasr, M. S. Zaman and O. Trescases, "Active Saturation Mitigation in High-Density Dual-Active-Bridge DC–DC Converter for On-Board EV Charger Applications," in IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 4376-4387, April 2020, doi: 10.1109/TPEL.2019.2939301.
[16] H. Akagi, S. Kinouchi and Y. Miyazaki, "Bidirectional isolated dual-active-bridge (DAB) DC-DC converters using 1.2-kV 400-A SiC-MOSFET dual modules," in CPSS Transactions on Power Electronics and Applications, vol. 1, no. 1, pp. 33-40, Dec. 2016, doi: 10.24295/CPSSTPEA.2016.00004.
[17] Y. Park, S. Chakraborty and A. Khaligh, "DAB Converter for EV Onboard Chargers Using Bare-Die SiC MOSFETs and Leakage-Integrated Planar Transformer," in IEEE Transactions on Transportation Electrification, vol. 8, no. 1, pp. 209-224, March 2022, doi: 10.1109/TTE.2021.3121172.
[18] A. Rodríguez, A. Vázquez, D. G. Lamar, M. M. Hernando and J. Sebastián, "Different Purpose Design Strategies and Techniques to Improve the Performance of a Dual Active Bridge With Phase-Shift Control," in IEEE Transactions on Power Electronics, vol. 30, no. 2, pp. 790-804, Feb. 2015, doi: 10.1109/TPEL.2014.2309853.
[19] F. Krismer and J. W. Kolar, "Efficiency-Optimized High-Current Dual Active Bridge Converter for Automotive Applications," in IEEE Transactions on Industrial Electronics, vol. 59, no. 7, pp. 2745-2760, July 2012, doi: 10.1109/TIE.2011.2112312.
[20] Y. -W. Cho, W. -J. Cha, J. -M. Kwon and B. -H. Kwon, "High-Efficiency Bidirectional DAB Inverter Using a Novel Hybrid Modulation for Stand-Alone Power Generating System With Low Input Voltage," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4138-4147, June 2016, doi: 10.1109/TPEL.2015.2476336.
[21] Y. Yan, H. Bai, A. Foote and W. Wang, "Securing Full-Power-Range Zero-Voltage Switching in Both Steady-State and Transient Operations for a Dual-Active-Bridge-Based Bidirectional Electric Vehicle Charger," in IEEE Transactions on Power Electronics, vol. 35, no. 7, pp. 7506-7519, July 2020, doi: 10.1109/TPEL.2019.2955896.
[22] G. G. Oggier, G. O. GarcÍa and A. R. Oliva, "Switching Control Strategy to Minimize Dual Active Bridge Converter Losses," in IEEE Transactions on Power Electronics, vol. 24, no. 7, pp. 1826-1838, July 2009, doi: 10.1109/TPEL.2009.2020902.
[23] D. Sha, F. You and X. Wang, "A High-Efficiency Current-Fed Semi-Dual-Active Bridge DC–DC Converter for Low Input Voltage Applications," in IEEE Transactions on Industrial Electronics, vol. 63, no. 4, pp. 2155-2164, April 2016, doi: 10.1109/TIE.2015.2506625.
[24] X. Gao, H. Wu and Y. Xing, "A Multioutput LLC Resonant Converter With Semi-Active Rectifiers," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 5, no. 4, pp. 1819-1827, Dec. 2017, doi: 10.1109/JESTPE.2017.2719683.
[25] P. Ma, D. Sha and K. Song, "A Single-Stage Semi Dual-Active-Bridge AC–DC Converter With Seamless Mode Transition and Wide Soft-Switching Range," in IEEE Transactions on Industrial Electronics, vol. 70, no. 2, pp. 1387-1397, Feb. 2023, doi: 10.1109/TIE.2022.3156172.
[26] F. Wu, Z. Wang and S. Luo, "Buck–Boost Three-Level Semi-Dual-Bridge Resonant Isolated DC–DC Converter," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 5, pp. 5986-5995, Oct. 2021, doi: 10.1109/JESTPE.2020.3041094.
[27] D. Sha, J. Zhang and Y. Xu, "Improved Boundary Operation for Voltage-Fed Semi-DAB With ZVS Achievement and Nonactive Power Reduction," in IEEE Transactions on Industrial Electronics, vol. 64, no. 8, pp. 6179-6189, Aug. 2017, doi: 10.1109/TIE.2017.2682026.
[28] D. Sha, J. Zhang and T. Sun, "Multimode Control Strategy for SiC mosfets Based Semi-Dual Active Bridge DC–DC Converter," in IEEE Transactions on Power Electronics, vol. 34, no. 6, pp. 5476-5486, June 2019, doi: 10.1109/TPEL.2018.2866700.
[29] F. Hoffmann, J. -L. Lafrenz, M. Liserre and N. Vazquez, "Multiwinding based Semi-Dual Active Bridge Converter," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 2142-2149, doi: 10.1109/APEC39645.2020.9124525.
[30] M. A. H. Rafi and J. Bauman, "Optimal Control of Semi-Dual Active Bridge DC/DC Converter With Wide Voltage Gain in a Fast-Charging Station With Battery Energy Storage," in IEEE Transactions on Transportation Electrification, vol. 8, no. 3, pp. 3164-3176, Sept. 2022, doi: 10.1109/TTE.2022.3170737.
[31] D. Sha, D. Chen, S. Khan and Z. Guo, "Voltage-Fed Three-Phase Semi-Dual Active Bridge DC–DC Converter Utilizing Varying Operating Modes With High Conversion Efficiency," in IEEE Transactions on Power Electronics, vol. 34, no. 10, pp. 9447-9458, Oct. 2019, doi: 10.1109/TPEL.2018.2890340.
[32] Z. Wang and H. Li, "A Soft Switching Three-phase Current-fed Bidirectional DC-DC Converter With High Efficiency Over a Wide Input Voltage Range," in IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 669-684, Feb. 2012, doi: 10.1109/TPEL.2011.2160284.
[33] H. Chen, S. Ouyang, J. Liu and X. Li, "An Asymmetrical Phase-Shift Scheme of Three-Phase Dual Active Bridge With Minimum Current Root-Mean-Square Value Control," in IEEE Transactions on Power Electronics, vol. 37, no. 12, pp. 14343-14361, Dec. 2022, doi: 10.1109/TPEL.2022.3192781.
[34] J. Hu, Z. Yang, S. Cui and R. W. De Doncker, "Closed-Form Asymmetrical Duty-Cycle Control to Extend the Soft-Switching Range of Three-Phase Dual-Active-Bridge Converters," in IEEE Transactions on Power Electronics, vol. 36, no. 8, pp. 9609-9622, Aug. 2021, doi: 10.1109/TPEL.2021.3055369.
[35] L. M. Cúnico, Z. M. Alves and A. L. Kirsten, "Efficiency-Optimized Modulation Scheme for Three-Phase Dual-Active-Bridge DC–DC Converter," in IEEE Transactions on Industrial Electronics, vol. 68, no. 7, pp. 5955-5965, July 2021, doi: 10.1109/TIE.2020.2992961.

[36] J. Huang, Z. Li, L. Shi, Y. Wang and J. Zhu, "Optimized Modulation and Dynamic Control of a Three-Phase Dual Active Bridge Converter With Variable Duty Cycles," in IEEE Transactions on Power Electronics, vol. 34, no. 3, pp. 2856-2873, March 2019, doi: 10.1109/TPEL.2018.2842021.
[37] N. H. Baars, J. Everts, C. G. E. Wijnands and E. A. Lomonova, "Performance Evaluation of a Three-Phase Dual Active Bridge DC–DC Converter With Different Transformer Winding Configurations," in IEEE Transactions on Power Electronics, vol. 31, no. 10, pp. 6814-6823, Oct. 2016, doi: 10.1109/TPEL.2015.2506703.
[38] L. M. Cúnico and A. L. Kirsten, "Single-Phase Operating Modes for DC–DC Three-Phase Dual-Active-Bridge With YΔ Transformer," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 4, pp. 4845-4853, Aug. 2022, doi: 10.1109/JESTPE.2022.3142686.
[39] D. Chen, D. Sha and T. Sun, "Three Phase Current-Fed Semi Dual Active Bridge DC–DC Converter With Hybrid Operating Mode Control," in IEEE Transactions on Power Electronics, vol. 35, no. 2, pp. 1649-1658, Feb. 2020, doi: 10.1109/TPEL.2019.2919530.
[40] G. Waltrich, M. A. M. Hendrix and J. L. Duarte, "Three-Phase Bidirectional DC/DC Converter With Six Inverter Legs in Parallel for EV Applications," in IEEE Transactions on Industrial Electronics, vol. 63, no. 3, pp. 1372-1384, March 2016, doi: 10.1109/TIE.2015.2494001.
[41] C. Zhao, S. D. Round and J. W. Kolar, "An Isolated Three-Port Bidirectional DC-DC Converter With Decoupled Power Flow Management," in IEEE Transactions on Power Electronics, vol. 23, no. 5, pp. 2443-2453, Sept. 2008, doi: 10.1109/TPEL.2008.2002056.
[42] J. Li, Q. Luo, T. Luo, D. Mou and M. Liserre, "Efficiency Optimization Scheme for Isolated Triple Active Bridge DC–DC Converter With Full Soft-Switching and Minimized RMS Current," in IEEE Transactions on Power Electronics, vol. 37, no. 8, pp. 9114-9128, Aug. 2022, doi: 10.1109/TPEL.2022.3157443.
[43] S. Dey, A. Mallik and A. Akturk, "Investigation of ZVS Criteria and Optimization of Switching Loss in a Triple Active Bridge Converter Using Penta-Phase-Shift Modulation," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 6, pp. 7014-7028, Dec. 2022, doi: 10.1109/JESTPE.2022.3191987.
[44] H. Li, Z. Zhang, S. Wang, J. Tang, X. Ren and Q. Chen, "A 300-kHz 6.6-kW SiC Bidirectional LLC Onboard Charger," in IEEE Transactions on Industrial Electronics, vol. 67, no. 2, pp. 1435-1445, Feb. 2020, doi: 10.1109/TIE.2019.2910048.
[45] P. He, A. Mallik, A. Sankar and A. Khaligh, "Design of a 1-MHz High-Efficiency High-Power-Density Bidirectional GaN-Based CLLC Converter for Electric Vehicles," in IEEE Transactions on Vehicular Technology, vol. 68, no. 1, pp. 213-223, Jan. 2019, doi: 10.1109/TVT.2018.2881276.
[46] S. -H. Ryu, D. -H. Kim, M. -J. Kim, J. -S. Kim and B. -K. Lee, "Adjustable Frequency–Duty-Cycle Hybrid Control Strategy for Full-Bridge Series Resonant Converters in Electric Vehicle Chargers," in IEEE Transactions on Industrial Electronics, vol. 61, no. 10, pp. 5354-5362, Oct. 2014, doi: 10.1109/TIE.2014.2300036.
[47] B. Li, F. C. Lee, Q. Li and Z. Liu, "Bi-directional on-board charger architecture and control for achieving ultra-high efficiency with wide battery voltage range," 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, USA, 2017, pp. 3688-3694, doi: 10.1109/APEC.2017.7931228.
[48] Z. U. Zahid, Z. M. Dalala, R. Chen, B. Chen and J. -S. Lai, "Design of Bidirectional DC–DC Resonant Converter for Vehicle-to-Grid (V2G) Applications," in IEEE Transactions on Transportation Electrification, vol. 1, no. 3, pp. 232-244, Oct. 2015, doi: 10.1109/TTE.2015.2476035.
[49] L. A. D. Ta, N. D. Dao and D. -C. Lee, "High-Efficiency Hybrid LLC Resonant Converter for On-Board Chargers of Plug-In Electric Vehicles," in IEEE Transactions on Power Electronics, vol. 35, no. 8, pp. 8324-8334, Aug. 2020, doi: 10.1109/TPEL.2020.2968084.
[50] C. Bai, B. Han, B. -H. Kwon and M. Kim, "Highly Efficient Bidirectional Series-Resonant DC/DC Converter Over Wide Range of Battery Voltages," in IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 3636-3650, April 2020, doi: 10.1109/TPEL.2019.2933408.
[51] G. Liu, Y. Jang, M. M. Jovanović and J. Q. Zhang, "Implementation of a 3.3-kW DC–DC Converter for EV On-Board Charger Employing the Series-Resonant Converter With Reduced-Frequency-Range Control," in IEEE Transactions on Power Electronics, vol. 32, no. 6, pp. 4168-4184, June 2017, doi: 10.1109/TPEL.2016.2598173.
[52] H. Haga and F. Kurokawa, "Modulation Method of a Full-Bridge Three-Level LLC Resonant Converter for Battery Charger of Electrical Vehicles," in IEEE Transactions on Power Electronics, vol. 32, no. 4, pp. 2498-2507, April 2017, doi: 10.1109/TPEL.2016.2570800.
[53] Texas Instruments, "Bidirectional, Dual Active Bridge Reference Design for Level 3 Electric Vehicle Charging Stations", Design Guide: TIDA-010054, June 2019 [Revised July 2022]. Accessed: Feb. 8, 2023. [Online]. Available: https://www.ti.com/tool/TIDA-010054
[54] B. Whitaker et al., "A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices," in IEEE Transactions on Power Electronics, vol. 29, no. 5, pp. 2606-2617, May 2014, doi: 10.1109/TPEL.2013.2279950.
[55] R. Huang and S. K. Mazumder, "A Soft Switching Scheme for Multiphase DC/Pulsating-DC Converter for Three-Phase High-Frequency-Link Pulsewidth Modulation (PWM) Inverter," in IEEE Transactions on Power Electronics, vol. 25, no. 7, pp. 1761-1774, July 2010, doi: 10.1109/TPEL.2010.2042180.
[56] D. S. Oliveira and I. Barbi, "A three-phase ZVS PWM DC/DC converter with asymmetrical duty cycle associated with a three-phase version of the hybridge rectifier," in IEEE Transactions on Power Electronics, vol. 20, no. 2, pp. 354-360, March 2005, doi: 10.1109/TPEL.2004.842996.
[57] M. C. Mira, Z. Zhang, A. Knott and M. A. E. Andersen, "Analysis, Design, Modeling, and Control of an Interleaved-Boost Full-Bridge Three-Port Converter for Hybrid Renewable Energy Systems," in IEEE Transactions on Power Electronics, vol. 32, no. 2, pp. 1138-1155, Feb. 2017, doi: 10.1109/TPEL.2016.2549015.
[58] S. Ikeda and F. Kurokawa, "Isolated and wide input ranged boost full bridge DC-DC converter with low loss active snubber," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, 2017, pp. 2213-2218, doi: 10.1109/ECCE.2017.8096433.
[59] D. Liu, Y. Wang, F. Deng and Z. Chen, "Triple-Phase-Shift Modulation Strategy for Diode-Clamped Full-Bridge Three-Level Isolated DC/DC Converter," in IEEE Access, vol. 8, pp. 2750-2759, 2020, doi: 10.1109/ACCESS.2019.2961788.
[60] A. Aldik, A. T. Al-Awami, E. Sortomme, A. M. Muqbel and M. Shahidehpour, "A Planning Model for Electric Vehicle Aggregators Providing Ancillary Services," in IEEE Access, vol. 6, pp. 70685-70697, 2018, doi: 10.1109/ACCESS.2018.2880443.
[61] V. Monteiro, J. G. Pinto and J. L. Afonso, "Operation Modes for the Electric Vehicle in Smart Grids and Smart Homes: Present and Proposed Modes," in IEEE Transactions on Vehicular Technology, vol. 65, no. 3, pp. 1007-1020, March 2016, doi: 10.1109/TVT.2015.2481005.
[62] G. R. Chandra Mouli, M. Kefayati, R. Baldick and P. Bauer, "Integrated PV Charging of EV Fleet Based on Energy Prices, V2G, and Offer of Reserves," in IEEE Transactions on Smart Grid, vol. 10, no. 2, pp. 1313-1325, March 2019, doi: 10.1109/TSG.2017.2763683.
[63] V. A. Kleftakis and N. D. Hatziargyriou, "Optimal Control of Reversible Substations and Wayside Storage Devices for Voltage Stabilization and Energy Savings in Metro Railway Networks," in IEEE Transactions on Transportation Electrification, vol. 5, no. 2, pp. 515-523, June 2019, doi: 10.1109/TTE.2019.2913355.