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Input parallel output parallel (IPOP) dual active bridge converter

***Abstract**. Isolated dual active bridge (DAB) converters can be connected in parallel to increase power and reliability. However, undesirable phenomena like common mode circulating currents can appear. In the literature, this problem is presented mainly theoretically, based on simulation models in which all parasitic parameters do not occur. The aim of this work is to verify experimentally the common mode current (CMC) in a 25kW input parallel output parallel (IPOP) DAB converter. The results of measurements in converters with and without EMI filters are presented. In addition, the influence of the operating conditions of these systems on the level of CMC currents was checked.*

***Streszczenie.** Izolowane przekształtniki o topologii podwójnego mostka aktywnego mogą być łączone równolegle w celu zwiększenia mocy i niezawodności. Niekorzystnym zjawiskiem są krążące prądy zaburzeń wspólnych. W literaturze problem ten jest przedstawiany głównie teoretycznie, w oparciu o modele symulacyjne, w których nie występują wszystkie elementy pasożytnicze. Celem tej pracy jest analiza prądu zaburzeń wspólnych w równolegle połączonych przekształtnikach o mocy znamionowej 25 kW na podstawie wyników eksperymentalnych. Przedstawiono wyniki pomiarów w przekształtnikach z filtrami EMI i bez nich. Ponadto sprawdzono wpływ warunków pracy tych układów na poziom prądu zaburzeń wspólnych. (**Badania równoległe połączonych przekształtników o topologii podwójnego mostka aktywnego**)*

Keywords: dual active bridge, common mode current, IPOP, EMI, parasitic
Słowa kluczowe: podwójny mostek aktywny, prąd zaburzeń wspólnych, IPOP, EMI, pojemności pasożytnicze

Introduction

The research focuses on galvanically isolated, bidirectional DC//DC converters, which are the basic and essential components in electric energy exchange, including energy storage systems and renewable energy sources. They should enable highly energy-efficient conversion of electrical energy and control of its flow between the source and the load or between two direct current circuits containing energy sources with different, changing voltage levels. One of the topologies that fulfil all the requirements is the dual active bridge (DAB) [1]. Therefore, it can be the main building component of larger DC structures called DC microgrids [2, 3]. Creating large-scale power systems usually involves connecting the converters in parallel (Fig.1) [4,5]. The properties and control methods of this converter have been the subject of many scientific works [6–8]. The unique features of this system, such as high energy efficiency, high power density and galvanic isolation, have made it successfully used in modular systems, where the converter outputs and inputs are connected in parallel (IPOP) [9]. Thanks to this, the power of the entire system is sharing between individual modules, which allows for reducing power losses, increasing the effective ripple frequency and increasing reliability, thanks to the possibility of redundant operation [10–12]. In addition, the appropriate control strategy, it is also possible to optimize the energy efficiency of the entire system [13]. However, the parallel operation of converters is associated with the occurrence of additional circulating currents, which can cause increased losses in power switches and in magnetic elements, causing various types of interference and undesirable effects [14]. Firstly the causes of CMC occurrence, its paths in the circuit, its influence on converter work and possible mitigation methods. Next, the experimental results of single and parallel work of DAB converters are presented.

Causes of common mode current in DAB

The cause of CMC is common mode voltage, which excites the parasitic capacitances (Fig.2) that create paths for uncontrolled current flow [15–19]. The values of parasitic capacitances are crucial in generating common mode currents in power converters. Usually examined are DC link to the ground (C_{ix},C_{ox}) and converter leg midpoint to ground capacitances (C_{xg}) which result from semiconductor switches and PCBs construction. Also important is HF transformer interwinding capacitance C_{ps} [17, 18], which links galvanically isolated full-bridges of the converter. DC link capacitances C_{dcx} and transformer intra-winding capacitances (C_p and C_s) are less important [15, 18]. The significant fact is that the modulation scheme also plays a role in creating paths for CMC. The simplest Single Phase Shift (SPS) modulation, in theory, provides zero CMC [18], which in reality can not be achieved because of hardware discrepancies between converters or lack of synchronization. Sometimes converters are interleaved intentionally [5] to achieve lower ripples or can be controlled by separate control units. More sophisticated modulation schemes like dual (DPS), extended (EPS) or triple phase shift (TPS) are utilized to improve the converter's performance create also paths for CMC [18, 19].

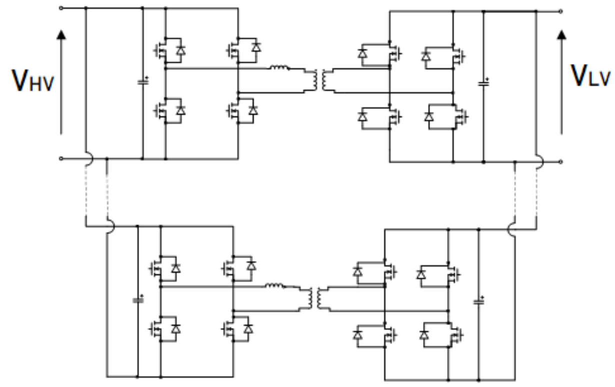

Fig. 1. Input parallel output parallel (IPOP) dual active bridge

Outcome of common mode current in DAB

The CMC can have unfavourable effects, the most of which is increased electromagnetic interference (EMI) [16-18]. Recharging capacitance during the switching of power semiconductors results in uncontrolled current spikes. The phenomenon gains importance when fast-switching SiC semiconductor switches are used. The other negative result is narrowing the soft-switching achievable range, which can deteriorate power efficiency [16].

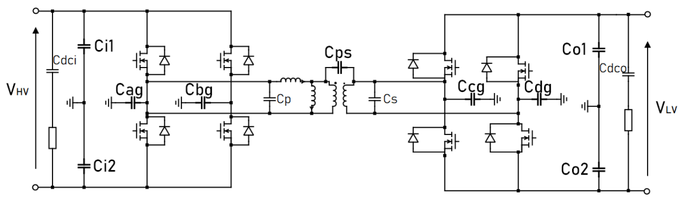

Fig. 2. DAB scheme with parasitic capacitances

Common mode current model

When CMC current in DABs is concerned usually a subject is the current flowing in path "a" (Fig.3). To model this, switches in the DAB CM model are replaced by current and voltage ideal sources, and superposition theory can be used to analyze them separately [15] [18] [20]. The path is the most important because of potential impact of CMC on conducted EMI. Nevertheless, [21] point out paths which exist only in HF AC circuit of one or both sides of the converter (path "b": in Fig.3). This common mode circulating current (CMCC) can not be suppressed by input and output EMI filters and can be crucial when radiated EMI is concerned.

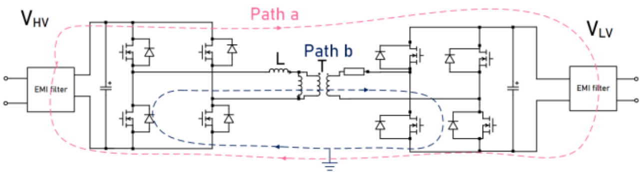

Fig. 3. CMC paths in DAB converter

Experimental results

The experimental results have been evaluated with the setup shown in (Fig.4a). Converters were integrated into the rack cabinet, and Itech 6018B-800-75 DC power supplies were used. DAB converters which parameters are listed in (Tab.1) are fully integrated into the case and consist of: power and control PCB board, HF inductor and transformer, EMI filters, cooling system and communication modules (Fig.4b). Crucial components and its models are presented in Fig. 5. Each converter is independent, in matters of control and EMI filtering.

Table 1. Experimental DAB model parameters

Parameter	Value
HV/LV voltage	760V/150V – 575V
rated power	25kW
HF transformer ratio	8:5
nominal power efficiency	98 %
switching frequency	50kHz
modulation type	EPS
semiconductor switches	CAB011M12FM3/CAB008M12GM3
DC line EMI filter	FN 2200-50/75-34

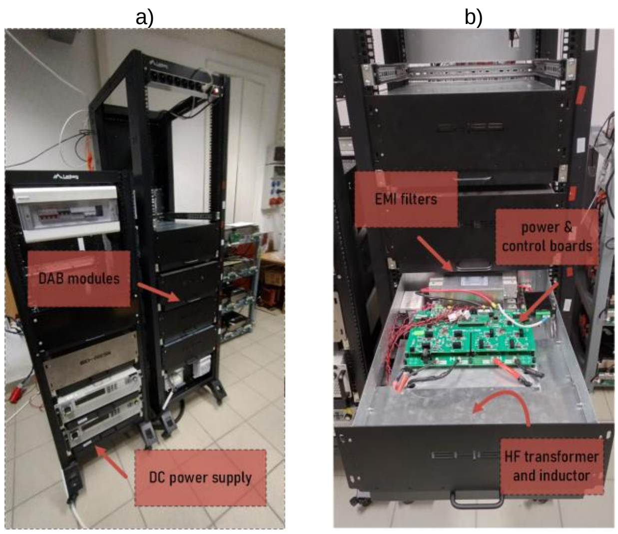

Fig. 4. (a) Experimental setup (b) DAB converter

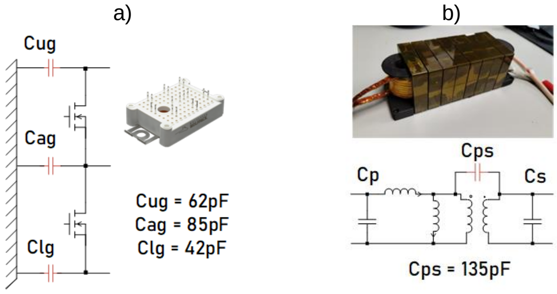

Fig. 5. Parasitic capacitances of (a) SiC transistor module and (b) high-frequency transformer.

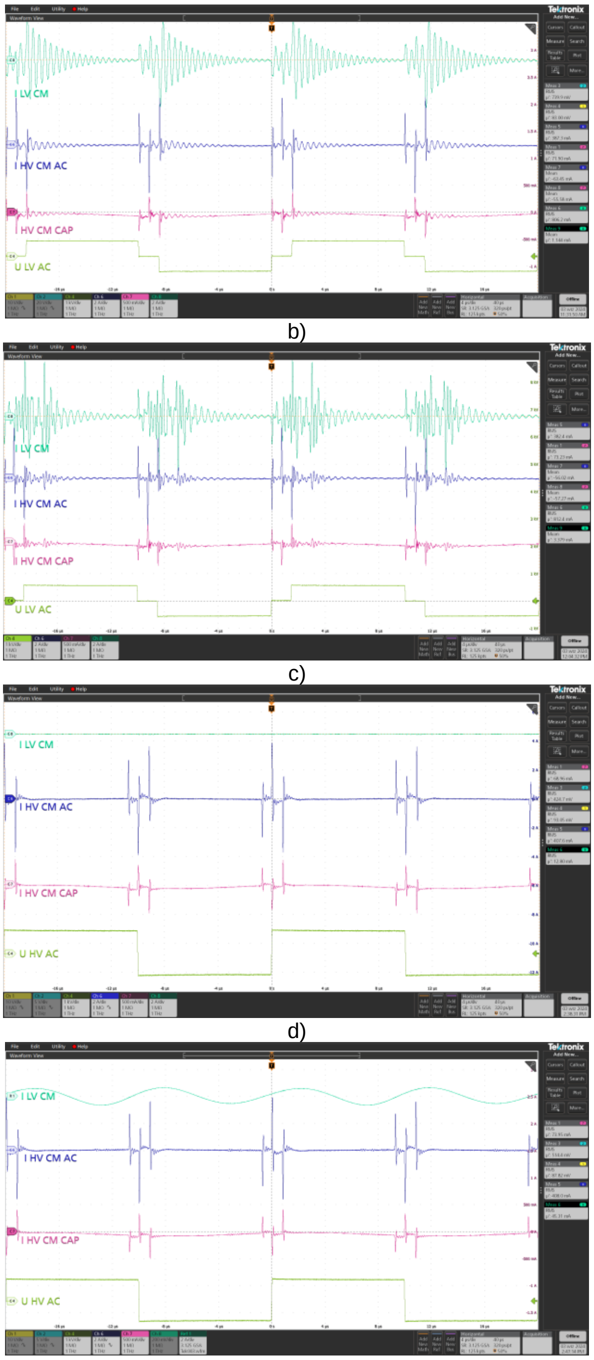

Fig. 6. Experimental results of measuring CMC (a) single DAB without filter (b) parallel DAB without filters (c) single DAB with filter (d) parallel DAB with filters

Analysed cases

In Fig.7 are shown schemes of experimental testes circuit and related oscillograms in Fig.6. Experimental research focused on the impact of paralleling converters on common mode currents. CMC which were measured are marked in (Fig.7).

A single converter was examined at first as a reference point (Fig.7a). CMC in all of the three points of measurement are observed. Nevertheless, the level and character of the disturbance are different. $I_{LV\ CM}$ disturbance has longer time constant than the two others. $I_{HV\ CM\ AC}$ and $I_{HV\ CM\ CAP}$ have rather impulse characters. However, their level differs (Tab.2).

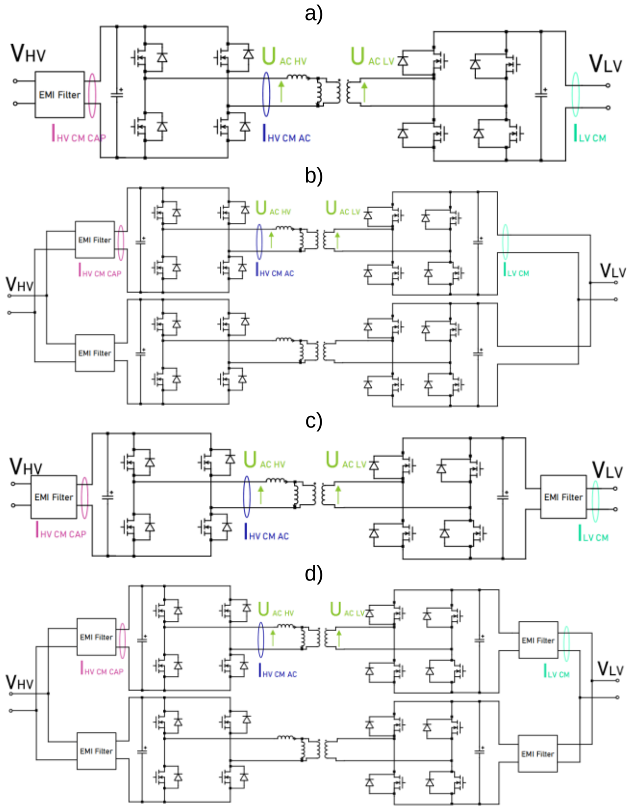

Fig. 7. Schemes of experimentally analyzed cases (a) single DAB without filter (b) parallel DAB without filters (c) single DAB with filter (d) parallel DAB with filter

Examining $U_{LV\ AC}$ trace clearly shows that impulses of current are the result of recharging parasitic capacitances during semiconductor devices switching. $I_{LV\ CM\ RMS}$ values were analysed, whereas $I_{HV\ CM\ AC}$ and $I_{HV\ CM\ CAP}$ peak-to-peak values were taken under consideration. Parallel work of two converters (Fig.7b) results in change of CMC values, however the increase is not more than 10%.

Table 2. Common mode current measurements

Case	Common mode current		
	$I_{LV\ CM\ RMS}$ [A]	$I_{HV\ CM\ AC\ pk\text{-}pk}$ [A]	$I_{HV\ CM\ CAP\ pk\text{-}pk}$ [mA]
(a)	808	7,07	0,85
(b)	894	7,5	0,78
(c)	12	7,8	0,93
(d)	427	7,87	0,91

Including EMI filter in low voltage side of single converter (Fig.7c) results in suppressing $I_{LV\ CM}$ because of closing the CMC conduction path through C_y capacitors of EMI filter, whereas when two filter are connected in parallel in $I_{LV\ CM}$ 2nd harmonic of switching frequency emerges (Fig.7d).

Impact of low side voltage level on $I_{LV\ CM}$

Observed in (Fig.7d) switching frequency second harmonic RMS value depends on the voltage level of DC circuit (Tab.3). and flows in the path "c" marked in Fig.8

Table 3. I LV CM depending on low voltage level

VHV [V]	V LV [V]	ILV CM RMS [mA]
760	400	36
760	450	97
760	550	330

Conclusion

In this paper, CMC in IPOP dual active bridge converters was discussed. The reasons and effects of CMC were described. The starting point was CMC in DAB. An experimental model of two IPOP DABs was presented. CMC measured in single and parallel DAB were compared with and without EMI filters. Besides well-known in literature paths of CMC in single DAB another one was described (Fig.8). The voltage and load dependence of the current in the path were verified.

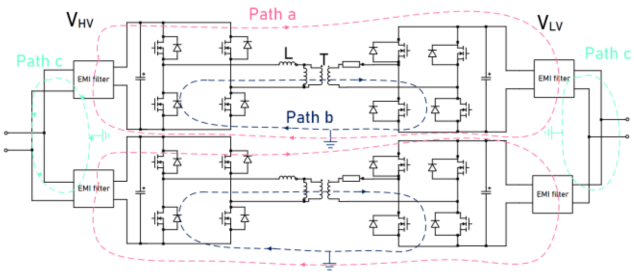

Fig. 8. Scheme of examined CMC paths in parallel DABs

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