Input-series-output-parallel (ISOP) DAB converters

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This note presents a control strategy for an input-series output-parallel (ISOP) dual active bridge (DAB). This system can be used in applications where the input voltage is relatively high and the output voltage is relatively low, such as high-speed train power systems or industrial drives [1].

First, the topology and the proposed control strategy are going to be explained in detail, where the balancing of the input capacitors is the main challenge. Finally, the experimental implementation on the B-Box RCP is introduced using ACG SDK on Simulink, and experimental results are shown.

More information regarding the DAB modulation techniques and control can be found in TN116 and TN115, respectively.

Topology of the ISOP DAB

The ISOP DAB system offers modularity, scalability, and efficient bidirectional power flow. It is composed of two DABs connected in series at the input and in parallel at the output. The DABs are bidirectional DC-DC converters that consist of two identical full-bridge modules connected through a transformer on the AC side. The leakage inductance and any additional inductance placed at the primary or at the secondary are represented by the inductor L_{tot}. The system is represented in Figure 1, where V_{dc_s0} and V_{dc_s1} represent the voltages at the input series connection, V_{dc_p0} and V_{dc_p1} refer to the voltages at the output parallel connection, I_{dc0} and I_{dc1} are the output currents, I_{dc_LV} is the total current at the output and I_{p0} and I_{p1} are the currents in the output winding of the transformer.

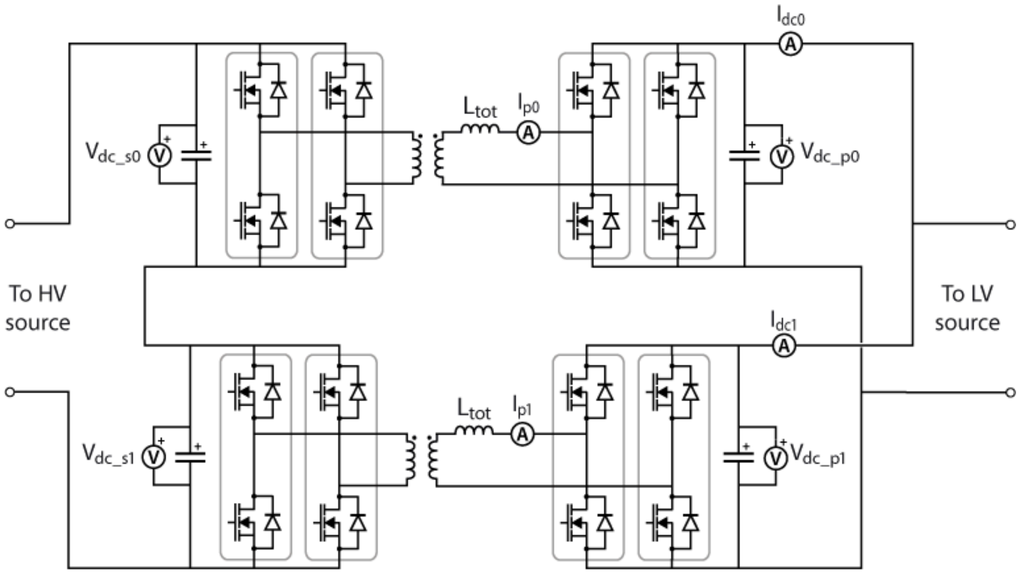


Figure 1. ISOP DAB converter schematic

When using this configuration, it is important to ensure a proper input voltage sharing between the modules connected in series, so the two capacitors are balanced. Without an appropriate balancing scheme, the voltages on the input capacitors could not be the same [1]. The unbalancing of the input capacitor voltages can be a consequence of parameter mismatches such as the capacitor or the series resitors, leading to unequal power sharing and, therefore, voltage imbalances.

Control strategy

In an ISOP DAB system, the series connection of modules at the input ensures equal input currents, while the parallel connection at the output maintains equal output voltages. However, achieving equal input voltages and output currents is not inherently guaranteed. Nonetheless, if the input voltages of the modules are balanced, their output currents will also be nearly equal, and vice versa [1]. Therefore, the considered balancing strategy focuses on balancing the input voltages.

To address this, the proposed control scheme regulates the distribution of output currents in the DABs to balance the input voltages. This control scheme is based on [2] and [3] and is illustrated in Figure 2, where $V^*_{dc\_p}$ represents the desired reference at the output, ϕ_0 and ϕ_1 are the phase shift of each DAB and k is the balancing factor.

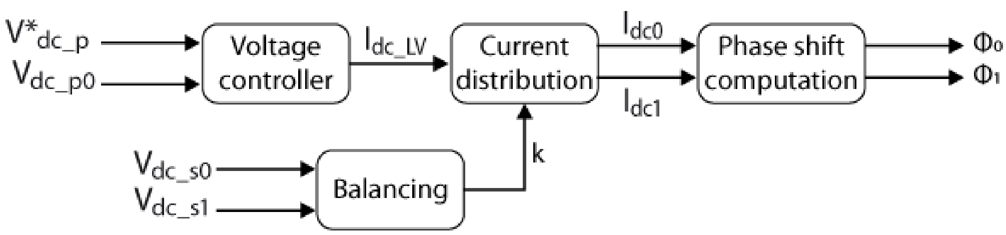
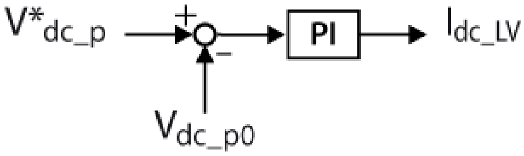


Figure 2. Control scheme

As it can be observed, the control scheme consists of four main blocks: a voltage controller, a balancing stage, a current distribution stage, and the calculation of the phase shift. Each block is detailed below.

Voltage controller

The voltage controller regulates the output voltage of the DABs. Since the outputs are connected in parallel, both DABs maintain equal output voltages. The controller's block diagram is shown below and includes a typical PI controller designed using the Symmetrical Optimum method. The controller's output determines the total current flowing through the LV side, which must be distributed between the two DABs to ensure balanced input voltages.



Balancing factor

The balancing factor, k, is calculated so the input voltages of the DABs stay equally balanced. It must be inside the range $[0, 1]$ and is given by [2]:

$$k = 0.5 + K\left(\frac{V_{dc\_s0} - V_{dc\_s1}}{V_{dc\_s0} + V_{dc\_s1}}\right) sign(I_{dc\_LV})$$

where K is a gain that adjusts the amount of balancing, either increasing or decreasing its effect, and is value is selected empirically. The sign of the current allows reversing the effect of the voltage difference based on the direction of the current, ensuring that the voltage balancing works correctly in both power flow directions.

Current distribution

The total current flowing through the LV side, I_{dc_LV}, is the sum of the currents at the output of each DAB, I_{dc0} and I_{dc1}. This relationship is given by the equation:

$$I_{dc_{LV}} = I_{dc0} + I_{dc1}$$

where the output currents of the DABs are determined as follows:

$$I_{dc0} = kI_{dc\_LV}$$
$$I_{dc_1} = (1 - k)I_{dc\_LV}$$

When $k = 0.5$, the total current I_{dc_LV} is equally distributed between the two DAB outputs. However, if $k \neq 0.5$, each DAB can contribute a different amount of power, leading to an unequal distribution of currents. This flexibility enables the balancing of the input voltages.

Phase shift computation

The power transfer between the input and the output of a DAB is given by:

$$P = \frac{nV_{dc\_p}V_{dc\_s}}{2\pi^2 f_{sw} L_{tot}}\phi(\pi - |\phi|)$$

where f_{sw} is the switching frequency and n is the turn ratio of the transformer. Considering that $P = V_{dc_p} I_{dc_p}$, the equation can be expresed as:

$$I_{dc\_p} = \frac{nV_{dc\_s}}{2\pi^2 f_{sw} L_{tot}}\phi(\pi - |\phi|)$$

Therefore, the phase shift ϕ of each DAB can be calculated using the next equation:

$$\phi = \frac{\pi}{2}\left(1 - \sqrt{\frac{8f_{sw}L_{tot}|I_{dc\_p}|}{nV_{dc\_p}}}\right) sign(I_{dc\_p})$$

Implementation of the ISOP DAB

Experimental setup

The model of the ISOP DAB system can be downloaded from the next link:

TN151_ISOP_DABDownload

The DABs used for the experimental tests are built using the following components:

- A B-Box RCP controller.
- 2 full bridge converters per DAB. Each full bridge converter consists of two imperix PEB8038 modules.
- A transformer rack containing one high-frequency transformer (SIRIO135822) per DAB. Each transformer has four leakage inductors (74437429203470) connected in parallel at each terminal, resulting in a total of 32 leakage inductors across all DABs. Note that the inductance value has been selected based on TN119.

The ISO DAB setup and the inside of the transformer box are depicted in the next picture.

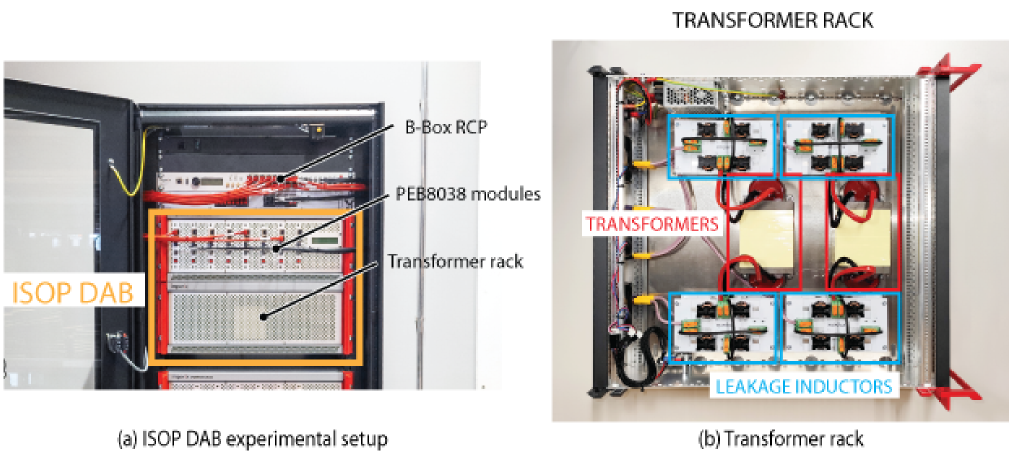


Figure 3. Experimental setup and transformer rack

The operating conditions are:

Parameter	Value
Rated DAB power P	10 kW
Input voltage V_{dc_s}	400 V
Output voltage V_{dc_p}	400 V
Transformer turn ratio n	1
Total leakage inductance L_{tot}	47 µH

Parameter	Value
Switching frequency f_{sw}	20 kHz
Balancing gain K	10

ISOP DAB parameters

Experimental results

To validate experimentally the discussed control strategy for the ISOP DAB converters, a DC source at 800V has been connected to the HV side and a current source at the LV side, so the voltage at the output can be controlled. The startup procedure for the DABs is based on the soft-start procedure explained in TN115.

In Figure 4, the precharge and soft-start of the system can be observed. The first step is to precharge the input series capacitors, followed by the soft-start process to charge the output parallel capacitors. Additionally, in the zoomed-in section, the effect of the balancing factor can be seen. For testing purposes, the balancing is switch off at t = 200 ms by setting K = 0, leading to a balancing factor of $k = 0.5$ and, consequently, an equal distribution of the currents at the output of the DABs. As a result, the input voltages become unbalanced. As can be observed, a steady state is achieved during the unbalance, which is due to the small difference between the different modules [4]. When the balancing is reactivated, the two input voltages are balanced again, demonstrating the correct functioning and usefulness of the proposed balancing startegy.

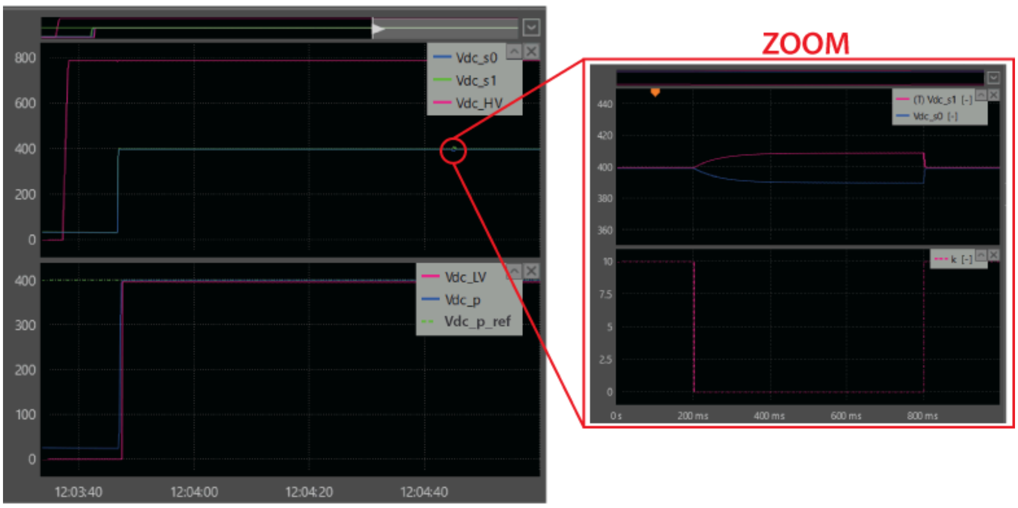
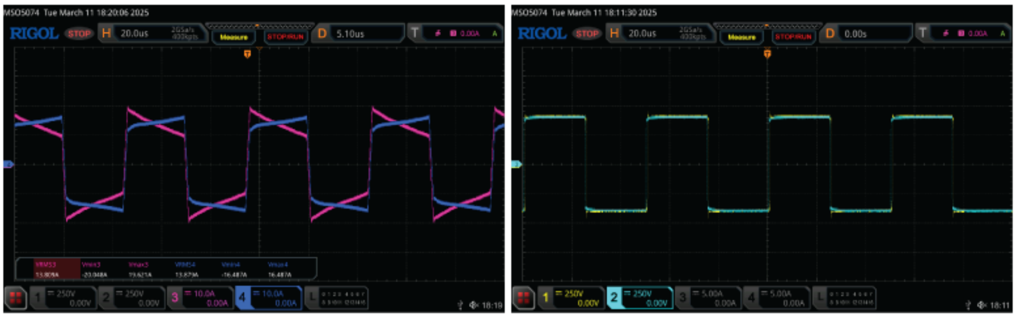


Figure 4. Soft start and balancing experimental results

Finally, Figure 5 shows the currents and the voltages at the input and output of the transformer. As can be observed, the voltages at the primary and secondary have a square waveform as expected. Regarding the currents, the slope observed at the top and bottom of each period is due to the small difference between the primary and secondary voltages and the current flowing through the magnetization inductance of the transformer.



(a) Transformer currents

(b) Transformer voltages

Figure 5. Transformer currents and voltages

References

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[2] "Input-Series/Output-Parallel Dual Active Bridge." Available at: https://www.plexim.com/sites/default/files/demo_models_categorized/tic2000/isop_dual_active_bridge.pdf.

[3] Barrade, P., Coulinge, E., & Rufer, A. (2015). *Control of a modular DC-DC converter dedicated to energy storage. 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe).* doi:10.1109/epe.2015.7309134

[4] Zumel, P., Ortega, L., Lazaro, A., Fernandez, C., & Barrado, A. (2013). Control strategy for modular Dual Active Bridge input series output parallel. 2013 IEEE 14th Workshop on Control and Modeling for Power Electronics (COMPEL). doi:10.1109/compel.2013.6626418