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Optimal design methodology for Dual Active Bridge for Flow battery application

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***Abstract*—The Dual Active Bridge (DAB) is a popular DC-DC converter for bidirectional power transfer in applications such as the re-emerging technology of flow batteries. For such applications, it is essential to design the DAB for the wide voltage range operation of batteries, specifically focusing on its non-linear characteristics. The existing design methods utilise an optimisation algorithm to minimise the losses of the DAB at various equidistant voltage points in the voltage range. The resulting design is less efficient as it gives too much weight to insignificant operating points. This article proposes a new method that uses the flow battery characteristics to determine the operating points at which minimisation should be performed. The proposed method is validated with simulation results.**

***Index Terms*—Optimization, Dual Active Bridge, Reliability, Efficiency, Design, Flow Battery**

I. Introduction

With the growing portfolio of renewable energy sources today, the composition of wind and solar sources in the overall energy mix has increased. Due to their intermittent nature, a focus on energy storage mediums such as batteries has emerged. In a similar pursuit, this paper will focus on the re-emerging technology of Flow batteries for grid energy storage [1].

For this application, a bidirectional converter to manage the power flow of the Flow battery with a grid-connected AC/DC converter is necessary. A Dual Active Bridge (DAB) is a popular DC/DC converter topology with the additional benefit of galvanic isolation. However, the design of such a DAB is not straightforward because of the non-linearly changing voltage of the battery during charge and discharge. The DAB has to perform efficiently with minimum switching and conduction losses throughout the different operating points arising from the variable voltage. Generally, for applications with constant voltages on both terminals, the transformer ratio (n) is simply the ratio of the output voltage (V_o) with the input voltage (V_i). On the other hand, such a simple solution is hard to find for a battery application due to the variable voltage.

The design of the DAB to deal with power transfer with a battery has caught the attention of some researchers [2, 3, 4]. [2] proposes to optimise the operation of the DAB at different power levels along with voltage variation on both terminals. However, the focus is on reducing peak current or back power flow. [3] focused on decreasing losses for the whole voltage range but only did it considering constant power (CP) operation. Only the terminal connected to the battery had voltage variations. [4] considered constant current (CC) and constant voltage (CV) both, as the operational power decreases considerably during CV. The general idea in these papers is to minimise the losses at various voltages in the battery cycle using an optimisation algorithm. However, all three have divided the operating voltage range into linear equidistant points, and the losses at those points have been minimised. This does not consider the battery's non-linear characteristics, which is fundamental to this application. Equidistant points give the same weight to the power losses in the usable range of the battery and those at the end of charge or discharge.

This paper proposes a new design process that reflects the battery's characteristics. The proposed method leads to more points in the usable region of the battery, which is the voltage range where the battery operates for a significant part of its cycle. This is done by dividing the voltage range into equal parts with respect to the battery's state of charge (SoC). Hence, the operating points thus obtained to undergo minimisation are concentrated along the usable region of the flow battery. The resulting DAB design will be more efficient compared to the method discussed in the literature. The total energy loss throughout the operation is reduced as well. This can also lead to less device stress and a longer lifetime.

This paper is organised as follows. Section II describes the analytical model of the DAB used to evaluate the current through the devices and the corresponding power losses. Section III describes the proposed optimisation problem and its significance. Section IV describes the results obtained with the proposed method and compares it with the previous method. Section V provides concluding remarks.

II. Dual Active Bridge Converter

The DAB is a bidirectional DC/DC converter initially proposed by Kheraluwala et al. [5, 6] as shown in Fig 1. This paper analyses the DAB converter with bridge B_1 connected to the constant voltage source and the bridge B_2 connected to the flow battery stack.

A. Simple model of the DAB

Single-phase shift (SPS) modulation is used in this work and is the most widely used control algorithm for DABs. Fig. 2 illustrates the basic characteristics of the converter using SPS, including the phase-shifted gate pulses and the inductor current. The phase shift of the converter d is defined as (1)

$$d = \frac{\phi}{\pi} \quad (1)$$

The currents I_1 and I_2, as defined in Fig. 2b are inductor currents at the instant when the bridges B_1 and B_2 switch,

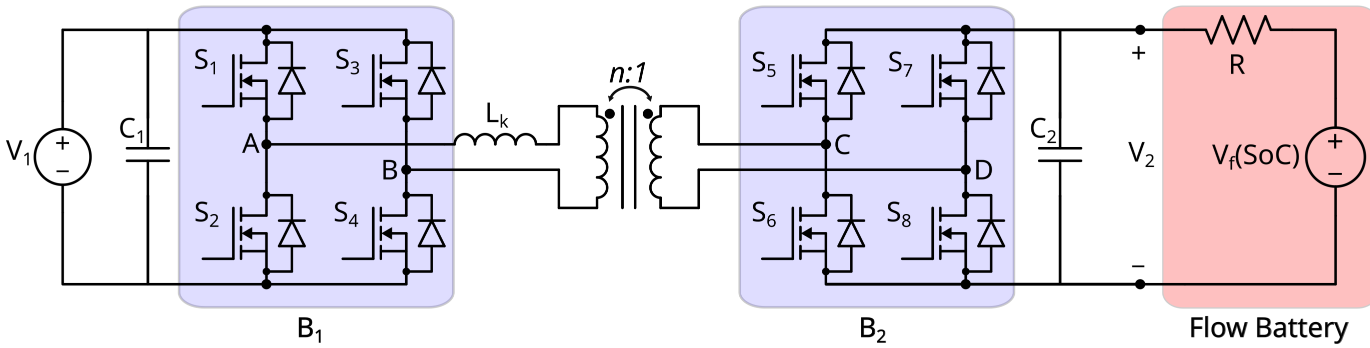


Fig. 1: Dual Active Bridge converter with the terminal V_2 connected to a flow battery.

respectively. Their values and the time instants are calculated as shown below

$$I_1 = \frac{nV_1 - V_2(1-2d)}{4fLn} \tag{2}$$

$$t_1 = \frac{nV_1 + (2d-1)V_2}{4f(nV_1 + V_2)} \tag{3}$$

$$I_2 = \frac{nV_1(2d-1) + V_2}{4fLn} \tag{4}$$

$$t_2 = \frac{(2d-1)nV_1 + V_2}{4f(nV_1 + V_2)} \tag{5}$$

The average and RMS currents for the MOSFET and the diode of both bridges are calculated separately [7, 8], as shown below. This ensures that the calculation of device losses in the next part is accurate.

$$I_{avg-IGBT-B_1} = \frac{2I_2 t_2 f + (I_1 + I_2)(1-d)}{4} \tag{6}$$

$$I_{avg-Diode-B_1} = \frac{I_1 t_1 f}{2} \tag{7}$$

$$I_{avg-IGBT-B_2} = \frac{I_2 t_2 f}{2n^2} \tag{8}$$

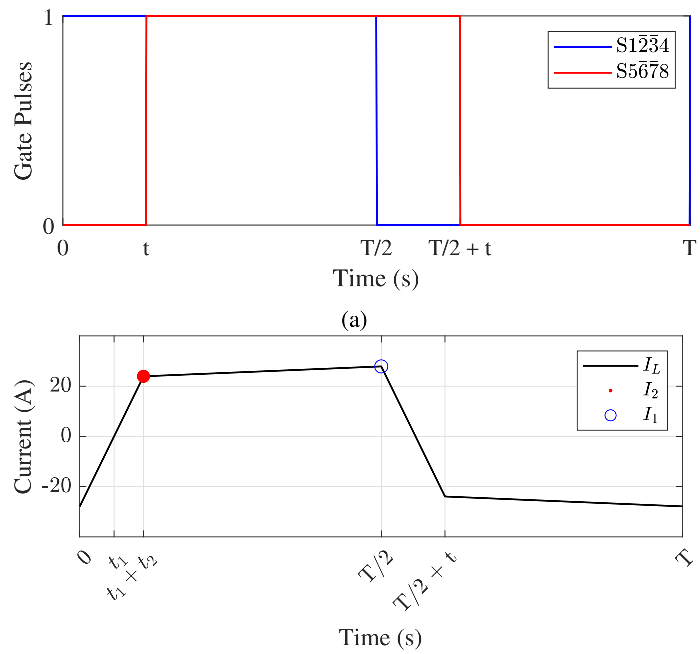
$$I_{avg-Diode-B_2} = \frac{2I_1 t_1 f + (I_1 + I_2)(1-d)}{4n^2} \tag{9}$$

$$I_{RMS-IGBT-B_1} = \sqrt{\frac{(1-d)(I_1^2 + I_1 I_2 + I_2^2) + 2I_2^2 t_2 f}{6}} \tag{10}$$

$$I_{RMS-Diode-B_1} = \sqrt{\frac{I_1^2 t_1 f}{3}} \tag{11}$$

$$I_{RMS-IGBT-B_2} = \sqrt{\frac{I_2^2 t_2 f}{3n}} \tag{12}$$

$$I_{RMS-Diode-B_2} = \sqrt{\frac{(1-d)(I_1^2 + I_1 I_2 + I_2^2) + 2I_1^2 t_1 f}{6n}} \tag{13}$$



(a)

(b)

Fig. 2: (a) DAB Gate Pulses. (b) Leakage inductor current. Note: $t = t_1 + t_2$.

B. Power loss model

An approximate loss model is used in this work, focusing on the losses in the semiconductor devices used in the converter. The conduction losses of a MOSFET are modelled as shown

$$P_{cond-MOSFET} = I_{RMS}^2 R \tag{14}$$

where R is the on-state resistance of the MOSFET used. The switching loss of a Power MOSFET depends on the switching current and whether the DAB is in ZVS mode. The turn-on loss of all the MOSFETs is evaluated based on the ZVS region, as shown in (15)

$$P_{sw-on-MOSFET} = \begin{cases} 0 & \text{if } I_1, I_2 > 0 \\ 4fE_{on} & \text{if } I_1 < 0 \text{ or } I_2 < 0 \end{cases} \tag{15}$$

where f is the DAB's operation frequency, E_{on} is the turn-ON switching energy. The devices on both bridges are the same: C3M0030090K SiC MOSFET from Wolfspeed. The turn-off loss of all the MOSFETs is calculated as shown in (16)

$$P_{sw-off-MOSFET} = 8fE_{off} \tag{16}$$

Similarly, the conduction loss in the anti-parallel diode to the MOSFET can be expressed as

$$P_{cond-Diode} = V_{drop}I_{avg} + I_{RMS}^2 R \tag{17}$$

III. Optimal Design of the DAB

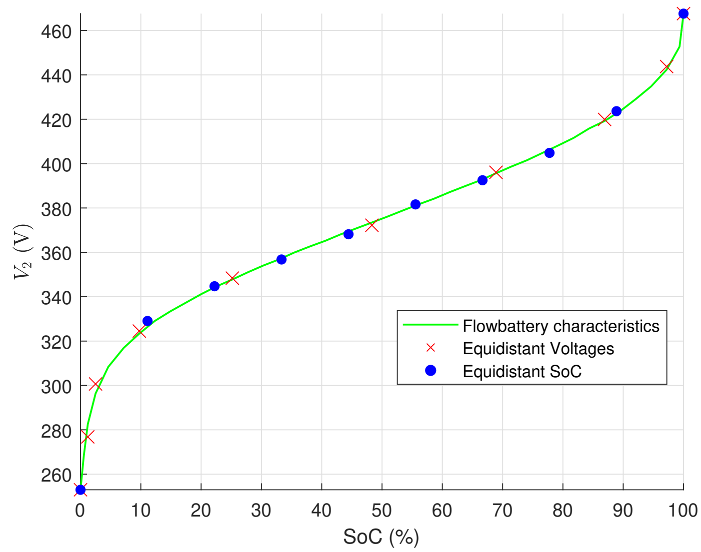
The objective is to design a DAB with the least energy losses during power transfer to and from the flow battery. To maximise the energy transfer through the DAB, the overall efficiency of the DAB during the charge and discharge of the Flow battery should be enhanced.

The flow battery characteristics shown in 4 and 3 have been taken from [9]. It's usual for many such cells of flow batteries to be connected in series to achieve a higher voltage and capacity. For this work, the voltages were multiplied by 550, denoting the number of cells in the series. However, a similar analysis can be made for different numbers of series cells.

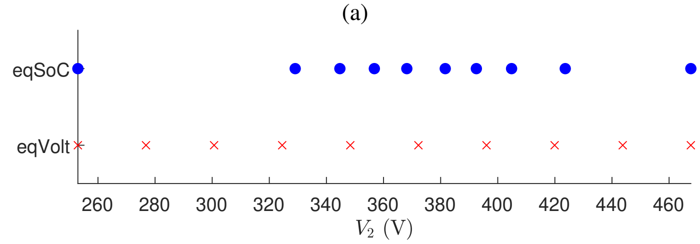
The previous work on the design of DAB for working with a battery such as an EV charger [3, 4], has divided the battery voltage variation into equal parts according to the voltage, as shown by the "Equidistant Voltage" points in Fig 3 and 4. Further, they calculate and minimise the norm of losses or inductor currents at these points. During discharge, the points bunch up closer to the start of the operation, as seen in Fig. 3a. Hence, to minimise losses, they have focused heavily on the losses at the start. In contrast, the losses during the rest of the operation are covered by fewer points. Similarly, for charge, as shown in Fig. 4a, several points bunch up closer to the 100% SoC mark. This leaves fewer points for the usable region of the battery and leads to a higher weightage to the losses at the extreme. A total of ten points is just chosen for the ease of explanation. However, this explanation will hold true for a division with even more points.

The proposed design method, the "Equidistant SoC", has been shown with blue points in Fig 3 and 4. This equally divides the curve into distinct parts with respect to the SoC of the battery. It can be seen that the operating points found with this method cover the usable region of the battery operation. In the charge operation, most points are between the 320V to 420V range and between 400V to 510V in the discharge. Fig 3b and 4b show the projection of operating points of both methods on the voltage axis. They better describe how significantly the shift in operating voltages occurs with these two optimisation methods.

To evaluate the total energy losses, the power losses at the first operating point are multiplied by the time duration between the first and second operating points, and so on. This process is done reverse for the discharge, i.e. the first operating point is at 100% SoC. It is noted here that the losses calculated at the final point during discharge (at 0% SoC) and charge (at 100% SoC) will be multiplied by zero time as the discharge ends at that time, and no further losses are expected.



(a)



(b)

Fig. 3: (a) Illustration of flow battery discharge characteristics. The points on the curve marked with × denote the equidistant voltages, which divide the curve into equal parts by voltages and the points marked as "Equidistant SoC" divide the curve into equal parts according to the SoC of the battery. (b) Both groups of points are projected on the voltage axis and shown as such to show the differences in the operating points with both methods. "eqSoC" refers to the "Equidistant SoC" and "eqVolt" refers to the "Equidistant Voltages".

The proposed optimisation problem has been formulated with the power loss vector,

$$\vec{P}_{loss} = [P_{loss_1}\ P_{loss_2} \cdot ..\ P_{loss_n}] \tag{18}$$

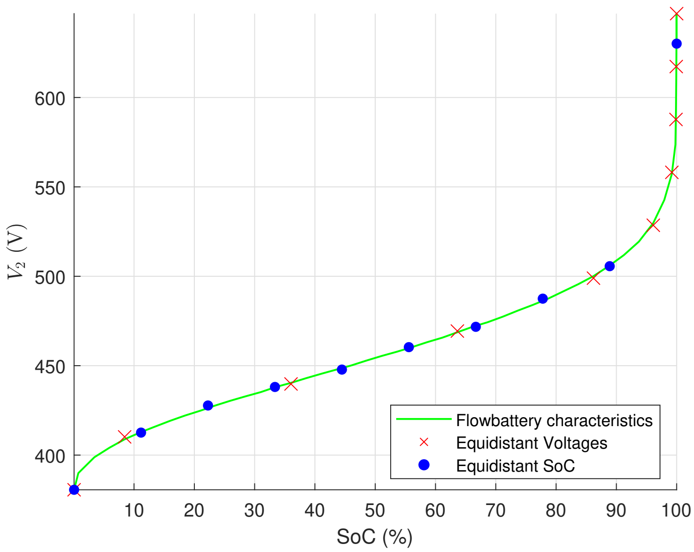
the norm of which is to be minimised.

$$Minimise \quad ||\vec{P}_{loss}|| \tag{19}$$

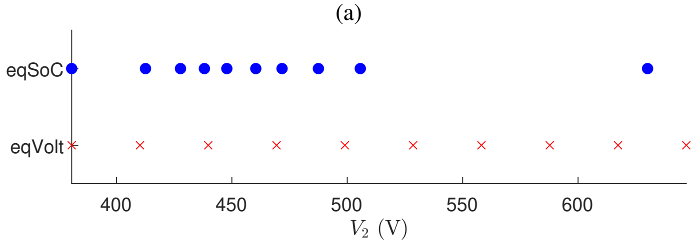
with the following constraint

$$d_{\min} \leq d \leq d_{\max} \tag{20}$$

(20) lists the only constraint on the optimisation algorithm. This means that all the operating points are to be kept within



(a)



(b)

Fig. 4: (a) Illustration of flow battery charge characteristics. (b) Both groups of points are projected on the voltage axis and shown as such to show the differences in the operating points with both methods. The labels are the same as described in Fig. 3.

the possible DAB range of phase shift. Here, d_{min} and d_{max} are kept at -0.5 and 0.5.

Furthermore, the previous work has constrained itself to the operating region where both the H-bridges experience Zero Voltage Switching (ZVS). It's possible that a small part of the operating points from the non-ZVS region will be included, and the overall efficiency will still be lower. Hence, no limitations are put on the operating region in the optimisation problem.

This optimisation has been performed using the python's publically available *scipy* library. In particular, the "L-BFGS-B" minimisation method has been used.

IV. Results

The optimisation has been performed for two cases: charge-only and charge and discharge. For the case of charge-only, only the operating points for charge characteristics of the battery were included to minimise losses. However, both the charge and discharge characteristics were considered in the second case. Table I lists the DAB parameters and operating conditions.

TABLE I

Parameter	Values
Terminal Voltage - V_1	500 V
Switching frequency - f	20 KHz
Constant Current	20 A
MOSFET	C3M0030090K Wolfspeed

TABLE II: Optimised parameters obtained from minimising the losses for battery charging operation by the two discussed methods.

Method	n	L (μH)	Energy Losses (Wh)
Equidistant SoC	1.05	11.8	15.44
Equidistant Voltages	1.16	12.5	16.34

Table II shows the optimised parameters obtained from the discussed methods. The proposed method reduces the energy losses by 5.5%. For the charge-only case, Fig. 5a illustrates the power loss characteristics of the DABs with optimised parameters obtained from both methods discussed earlier. It's interesting to notice that almost all of the markers (filled circles) in the case of Equidistant SoC have lesser power losses than the other method.

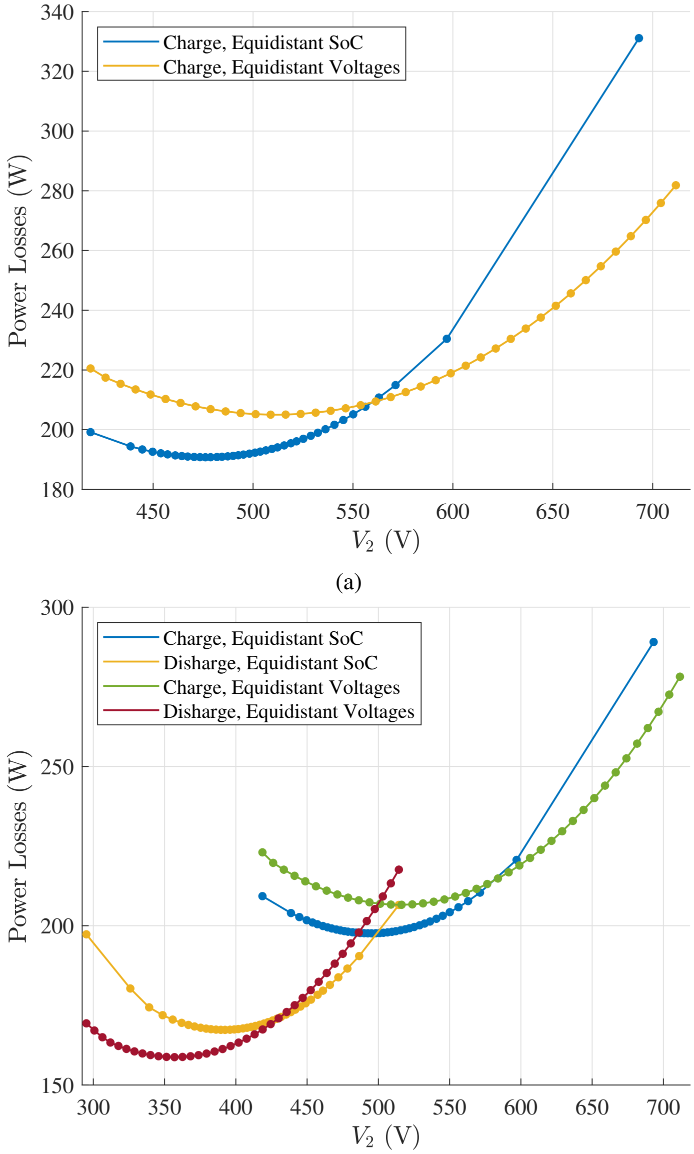
In the second case, where both the charge and discharge operating points were included for minimisation, the optimised parameters are shown in Table III. Fig. 5b illustrates the power losses of the DAB modelled with the optimised parameters obtained from minimising the power losses for charge and the discharge operations. The proposed optimisation method didn't result in lower losses throughout the operating range, as some points during the discharge resulted in higher losses. Moreover, the higher losses during the charge have been reduced considerably, while only a slight increase in losses is noticeable during the discharge.

V. Conclusion

This paper proposed a new design optimisation method based on the non-linear characteristics of flow batteries. The proposed method increases the number of operating points in the usable region of the battery in the minimisation function by dividing the SoC of the battery with multiple equidistant points. The proposed method was compared with the methods from the literature by simulation results with an analytical model of the DAB. The results show that the proposed method leads to lower power losses through most of the battery's operating region and overall lower energy losses. The proposed method may be more suitable for charging applications due to the higher increment in energy efficiency.

TABLE III: Optimised parameters obtained from minimising the losses for the battery charging and discharging operation by the two discussed methods.

Method	n	L (μH)	Energy Losses (Wh)
Equidistant SoC	1.11	12.2	29.00
Equidistant Voltages	1.17	12.6	29.47



(a)

(b)

Fig. 5: (a) Power losses of the DAB during the charge of the flow battery stacks, using the optimised system parameters calculated from the proposed and the previous methods. (b) Power losses of the DAB using the parameters obtained from both optimisation methods for the combined charge and discharge case. Note that the markers (filled circles) represent the operating points where the respective method calculated and minimised losses.

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References

[1] Yuriy V. Tolmachev. “Review—Flow Batteries from 1879 to 2022 and Beyond”. In: *Journal of The Electrochemical Society* 170.3 (2023), p. 030505. DOI: 10.1149/1945-7111/acb8de.

[2] N. Noroozi, A. Emadi, and M. Narimani. “Performance Evaluation of Modulation Techniques in Single-Phase Dual Active Bridge Converters”. In: *IEEE Open Journal of the Industrial Electronics Society* 2 (2021), pp. 410–427. DOI: 10.1109/OJIES.2021.3087418.

[3] Vishnu Mahadeva Iyer, Srinivas Gulur, and Subhashish Bhattacharya. “Optimal design methodology for dual active bridge converter under wide voltage variation”. In: *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*. 2017, pp. 413–420. DOI: 10.1109/ITEC.2017.7993306.

[4] Uddhav Surve et al. “Loss Minimization of Dual Active Bridge Converter Through Design Optimization in CC-CV Mode for Electric Vehicle Battery Charging Applications”. In: *2023 IEEE Industry Applications Society Annual Meeting (IAS)*. 2023, pp. 1–6. DOI: 10.1109/IAS54024.2023.10406857.

[5] M.H. Kheraluwala et al. “Performance characterization of a high power dual active bridge DC/DC converter”. In: *Conference Record of the 1990 IEEE Industry Applications Society Annual Meeting*. 1990, 1267–1273 vol.2. DOI: 10.1109/IAS.1990.152347.

[6] R.W.A.A. De Doncker, D.M. Divan, and M.H. Kheraluwala. “A three-phase soft-switched high-power-density DC/DC converter for high-power applications”. In: *IEEE Transactions on Industry Applications* 27.1 (1991), pp. 63–73. DOI: 10.1109/28.67533.

[7] Alberto Rodríguez et al. “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* 30.2 (2015), pp. 790–804. DOI: 10.1109/TPEL.2014.2309853.

[8] R.T. Naayagi and A.J. Forsyth. “Bidirectional DC-DC converter for aircraft electric energy storage systems”. In: *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*. 2010, pp. 1–6. DOI: 10.1049/cp.2010.0184.

[9] Wei Wang et al. “A new redox flow battery using Fe/V redox couples in chloride supporting electrolyte”. In: *Energy Environ. Sci.* 4 (10 2011), pp. 4068–4073. DOI: 10.1039/C0EE00765J. URL: http://dx.doi.org/10.1039/C0EE00765J.