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End of life influencing factors for Dual Active Bridge components in Flow Battery Application

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***Abstract*—This article discusses the various ways in which the stresses experienced by the IGBTs and diodes in a Dual Active Bridge (DAB) are asymmetric. This asymmetry can be between the two bridges or between IGBTs and diodes on both bridges. The terminal voltage, transformer ratio and the power through the DAB are varied to discuss the stresses. These asymmetrical stresses lead to devices' distinct temperatures. This unevenness of stresses can affect the lifetime of the devices employed. An analytical model of the DAB is used to analyse the currents and power losses in various devices. Some preliminary results of power losses in the devices are presented.**

***Index Terms*—Dual Active Bridge, Reliability, Lifetime, Thermal cycling**

I. Introduction

Global efforts are being made to embrace renewable energy sources, such as solar and wind power, in the fight against climate change and global warming. However, the energy through these sources is intermittent. There is a significant need to store the energy from these sources when the energy is surplus and use the stored energy during periods of energy deficits. Batteries are among the most popular energy storage methods, with Li-ion cells dominating the market. Even though this article holds true for these batteries, the focus of this article will be the reemerging technology of flow batteries. For a long-term sustainable energy future, the reliability of the power electronic converter is an important objective to go along with the emphasis on battery energy storage. It can ensure a long lifetime for the converter, which is not just cost-effective but environmentally sustainable.

Dual Active Bridge is a very popular isolated bidirectional DC-DC converter that is used in a host of applications. One is the grid integration of battery banks through multilevel converters like Cascaded H-bridges (CHB). Battery storage is connected on one side, and the other side is connected to a submodule of the CHB. Its soft switching capabilities add to its positives, leading to reduced switching losses [1].

This paper evaluates the factors affecting the end of life of devices of the DAB, operated with the single phase shift modulation. A Flow-battery V_2, connected on one side and the DC bus of a CHB submodule V_1, connected on the other [2]. The asymmetrical nature of the stresses on devices in various operating situations is explored. Which impacts the lifetime of the devices unevenly. The lifetime of a component or a converter depends on the number of thermal cycles it experiences. In a converter, the thermal cycles are basically governed by the changes in power losses over time [3, 4]. For the DAB (Dual Active Bridge), the power losses can change due to changes in power transfer, voltage or the converter going in and out of ZVS operation. Overall, this article focuses on variations of the losses, which impact the reliability of the devices and the converter [5].

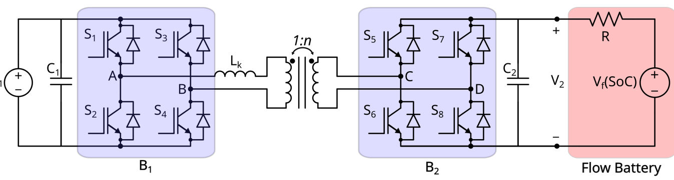


Fig. 1: Dual Active Bridge converter

Section II illustrates an analytical model of a DAB, which is used in the calculation of power losses as discussed in Section III. Section IV discusses the various operating conditions and how the stresses on the devices change as parameters such as power or voltage change. Finally, Section V concludes the article.

II. A simple model of the Dual Active Bridge

A DAB is a bidirectional DC-DC converter, originally proposed in [1] and [6], as shown in Fig. 1. This paper analyses the DAB with the input bridge (B_1) being connected to the submodule of the CHB. The secondary or the output bridge (B_2) is connected to a battery bank. However, this analysis will also hold if the positions of these two were swapped and for other possible cases also discussed.

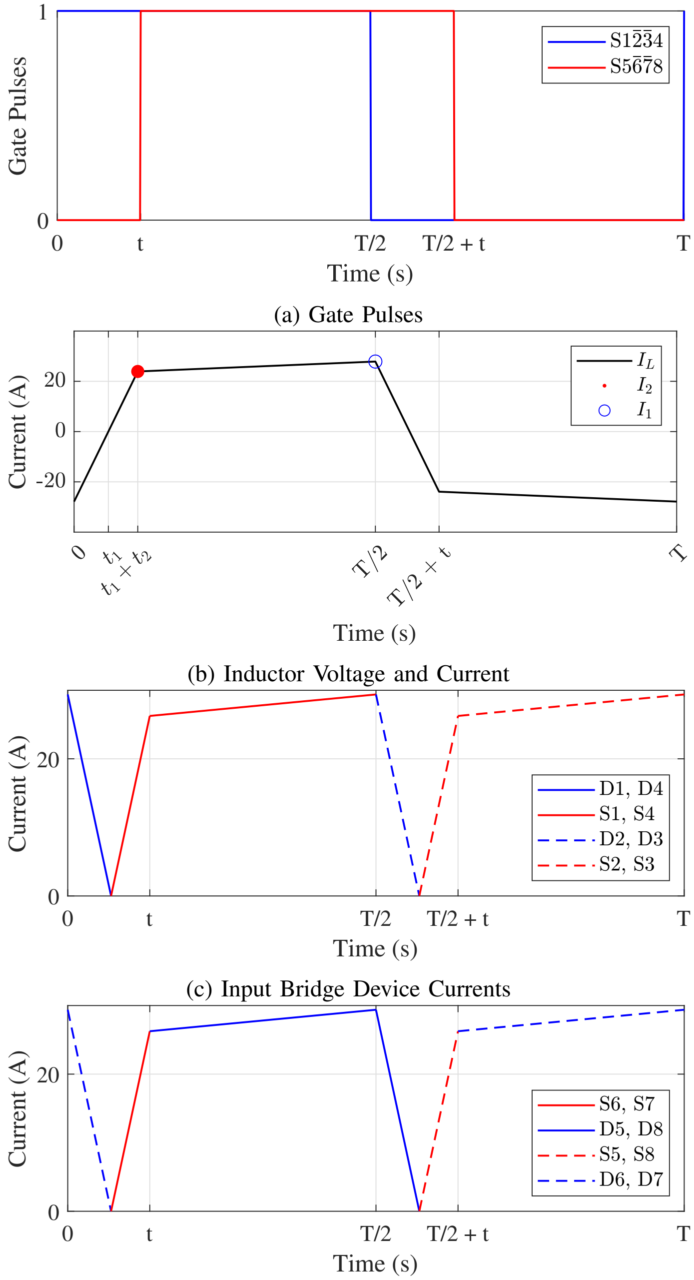
With simple phase shift modulation control of the DAB, there is only one independent control variable, which is the phase shift between the two H-Bridges. Both bridges ideally have a 50% duty cycle. The gate signals to the switches can be seen in the Fig. 2a.

With V_1 as the input voltage, V_2 as the output DC voltage of the converter, and V_2' as the secondary voltage referred to the primary. Further analysis has only been shown for the first half-cycle. The currents for the second half-cycle can be inferred from the same analysis.

Using the inductor current-voltage relationship to evaluate the currents through the inductor [7, 8]. (1) and (2) show the inductor relationship from 0 to t and from t to $\frac{T}{2}$, respectively.

$$V_1 + V_2' = L\frac{I_1 + I_2}{\frac{T}{2}d} \tag{1}$$

$$V_1 - V_2' = L\frac{I_1 - I_2}{\frac{T}{2}(1-d)} \tag{2}$$



(a) Gate Pulses

(b) Inductor Voltage and Current

(c) Input Bridge Device Currents

(d) Output Bridge Device Currents

Fig. 2: Inductor waveforms for single phase shift modulation

where T is the time period of the wave and d is the phase difference between the bridges, which can be defined by

$$d = \frac{\phi}{\pi} \tag{3}$$

where ϕ is the phase shift between the two bridges in radians. A positive d refers to the power flow from the primary to secondary and a negative d refers to power flow from the secondary to the primary. Solving (1) and (2), the currents I_1 and I_2 and the time instants t_1 and t_2, shown in the Fig. 2b, can be calculated as

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

$$t_1 = \frac{nV_1 + (2d-1)V_2}{4f(nV_1+V_2)} \tag{5}$$

$$I_2 = \frac{nV_1(2d-1) + V_2}{4fLn} \tag{6}$$

$$t_2 = \frac{(2d-1)nV_1 + V_2}{4f(nV_1+V_2)} \tag{7}$$

The IGBT and diode currents in the input and output bridges are shown in Fig. 2c and 2d with different colours. With these currents known, the average and RMS currents [9] through all the diodes and the IGBTs were evaluated as shown below

$$I_{avg-IGBT-B_1} = \frac{2I_2t_2f + (I_1+I_2)(1-d)}{4} \tag{8}$$

$$I_{avg-Diode-B_1} = \frac{I_1t_1f}{2} \tag{9}$$

$$I_{avg-IGBT-B_2} = \frac{I_2t_2f}{2n^2} \tag{10}$$

$$I_{avg-Diode-B_2} = \frac{2I_1t_1f + (I_1+I_2)(1-d)}{4n^2} \tag{11}$$

$$I_{RMS-IGBT-B_1} = \sqrt{\frac{(1-d)(I_1^2+I_1I_2+I_2^2)+2I_2^2t_2f}{6}} \tag{12}$$

$$I_{RMS-Diode-B_1} = \sqrt{\frac{I_1^2t_1f}{3}} \tag{13}$$

$$I_{RMS-IGBT-B_2} = \sqrt{\frac{I_2^2t_2f}{3n}} \tag{14}$$

$$I_{RMS-Diode-B_2} = \sqrt{\frac{(1-d)(I_1^2+I_1I_2+I_2^2)+2I_1^2t_1f}{6n}} \tag{15}$$

III. Modelling of Power Losses

The conduction losses of an IGBT are modelled as shown [10]

$$P_{cond-IGBT} = V_{drop}I_{avg} + I_{RMS}^2R \tag{16}$$

where V_{drop} is the forward voltage drop of the IGBT, and R is its on-state resistance.

The switching loss of an IGBT depends on the switching current and whether the DAB is in ZVS mode or not. As all the IGBTs are the same, the turn-on switching losses of all the IGBTs can be calculated as shown below

$$P_{sw-on-IGBT} = \begin{cases} 0 & \text{if } I_1, I_2 > 0 \\ 4fE_{on} & \text{if } I_1 < 0 \text{ or } I_2 < 0 \end{cases} \quad (17)$$

Similarly, the turn-off switching losses of all the IGBTs can be calculated as

$$P_{sw-off-IGBT} = 8fE_{off} \quad (18)$$

where f is the frequency of operation of the DAB.

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

$$P_{cond-Diode} = V_{drop}I_{avg} + I_{RMS}^2 R \quad (19)$$

and the switching loss of the anti-parallel diode can be expressed as

$$P_{switch-Diode} = E_{off}f \quad (20)$$

IV. Asymmetry in stresses of the devices

There are many cases of asymmetry and variations of stresses on the devices of both the H-Bridges. These stresses also change as the power or voltage changes. Many of these cases will be discussed in this section.

Source V_1 is the DC terminal of a multilevel grid-connected AC-DC converter, and hence the voltage of this terminal is assumed to be constant. Source V_2 is either connected to a constant DC source, an EV charger or a flow battery. One notable aspect of flow battery features is the significantly greater voltage variation than that of Li-ion cells. Note that the power losses specified in this article are the cumulative losses of the specified device in the specified bridge.

A. Constant voltage on both terminals, $V_1 = V_2$, n=1 and constant power

In this case, $V_1 = V_2$ and the transformer ratio (n) is 1 (V_o/V_i). The devices used in both bridges are identical. The voltages remain constant, and the power transfer through the DAB is constant, too. It can be seen from Fig. 2c that for the IGBTs in B_1, conduct for most of the cycle and the diode conducts for a short time. On the other hand Fig.2d shows that in B_2 the diode conducts for a significantly more time compared to the IGBTs. With this the current magnitudes through the devices are also different as shown in Table I. This difference will lead to more conduction losses in IGBTs in B_1. The switching losses will be significantly different as the reverse recovery losses of the diode and the switching losses of the IGBTs follow different characteristics. Overall, the losses likely contribute to more stresses for the IGBTs in B_1 and the diodes in B_2, which can be observed from Table I.

For bidirectional power transfer, the bridge B_2 becomes the input bridge in case of reverse power transfer, and B_1 becomes the output bridge. During such operation, the current in the devices of bridge B_2 will look similar to Fig. 2c and the device currents in B_1 will look similar to Fig. 2d. Hence, the losses occurring in the bridge B_2 in the reverse power flow will look like the losses in the bridge B_1 earlier (during forward power transfer). This way the IGBTs and the diodes on both the sides will be subjected to similar losses over this power cycle (forward + reverse power transfer), hence similar thermal stresses. Leading to similar damage and lifetime.

TABLE I: DAB currents and power losses for the four device types, as discussed in the cases of Section IV. Note that the losses shown for a device are cumulative losses of all the devices of the specified type in the specified bridge

Parameter	Case IV-A	Case IV-B	Unit
L_k	0.1	0.4	mH
B_1 IGBT I_{RMS}	16.1	8.1	A
B_1 Diode I_{RMS}	3.2	1.6	A
B_2 IGBT I_{RMS}	3.2	3.22	A
B_1 Diode I_{RMS}	16.1	16.1	A
B_1 IGBT P_{loss}	196.5	182	W
B_1 Diode P_{loss}	1.3	0.59	W
B_2 IGBT P_{loss}	173.5	174.4	W
B_2 Diode P_{loss}	23.4	41.9	W

B. Constant voltage on both terminals, $V_1 > V_2$, n≠1 and constant power

For a different case, where the design requirements are such that the input and output voltage are unequal, say V_1 is 1000V, and V_2 is 500V. The transformer ratio (n) is kept at 0.5. In such a case, the devices in both bridges will have different ratings as they deal with different current and voltage levels. As the devices have different ratings, their failure rates will be different [11]. The higher RMS and average current values in B_2 will lead to higher conduction losses in its devices, assuming equal resistances (However, this depends on the specific device chosen). Coupled with the different failure rates of devices, the asymmetrical losses lead to different rates of failure and lifetimes.

$$I_2' = \frac{I_2}{n} \quad (21)$$

For bidirectional power transfer, the current in B_2 will always be higher, be it forward or reverse power transfer. This will always result in a higher conduction loss in the devices in the bridge B_2. This leads to higher thermal losses on this bridge. Hence, as explained earlier, the stresses in the devices for both bridges will differ.

C. Constant voltage on one terminal, variable voltage on the other, n=1 and constant power

Here, V_2 is a flow battery, and the voltage varies on this terminal. For explanation, a DAB is designed with parameters shown in Table II. During the discharge of the flow battery, V_2 varies, say, from 550V to 330V, while during charge, the voltage V_2 varies from, say, 380V to 600V.

The voltage range during the charge is higher than the voltage during the discharge, which can be understood from the simple flow battery model shown in Fig. 1. During discharge the output voltage V_o is expressed in (22), here I is the current

TABLE II: Design parameters of the Dual Active Bridge

Parameter	V_i	V_o	P	f	n	L
Values	500 V	500 V	10 KW	20 KHz	1	0.1 mH

through the resistor. During charge V_o is expressed as (23). The voltage drop across the internal resistance is responsible for the increase in the voltage during battery charge.

$$V_o = V_f - IR \tag{22}$$

$$V_o = V_f + IR \tag{23}$$

Assuming a constant power, as the voltage during the charge is higher, the currents are relatively smaller than the discharge currents. During charge, IGBTs in B_1 conduct for a longer time than diodes and diodes conduct for a longer time in B_2. Which results in higher RMS currents for these devices. Hence, the conduction losses are higher in the devices with a longer conduction time. As the current during the charge is a bit lower, the conduction losses are lower relative to when the battery discharges.

The currents at the switching instants, I_1 and I_2 and the RMS currents in the devices for discharge of flow battery are shown in Fig. 3a and for charge, they are shown in Fig. 3b. As can be clearly observed, all the current values are higher for discharge compared to charge. Hence, the B_1 IGBT and B_2 diode experience more conduction and switching losses during discharge. When charging the B_1 Diode and B_2, IGBT experiences relatively lower conduction and switching losses. Over the converter's lifetime, the devices' asymmetrical losses will accumulate, leading to an asymmetrical lifetime.

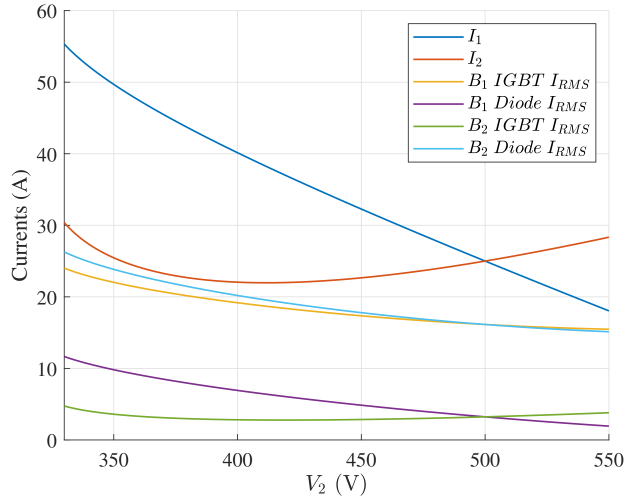
It's also possible to assume V_2 as an EV battery. Hence, only forward power transfer to charge the battery is possible. This case is similar to IV-A for forward conduction but with variable V_2. However, the power losses experienced are much higher as the voltage variations lead to higher power losses and more stresses on B_1 IGBT and B_2 Diode.

D. *Constant voltage on one terminal, variable voltage on the other, n≠1 and constant power*

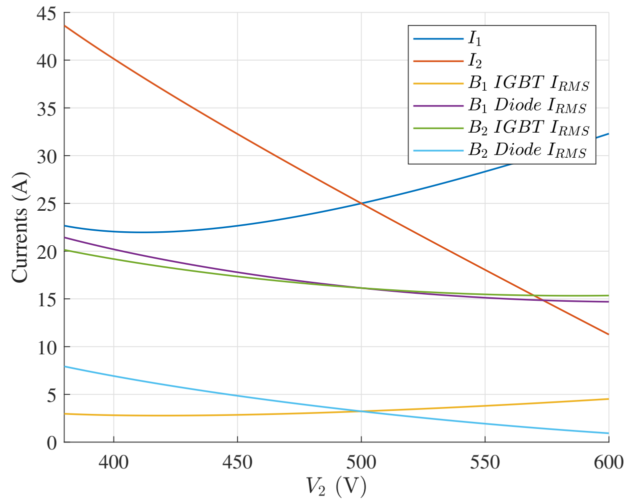
Similar to the last section. But often, the requirements demand the input and output voltages of the DAB to be dissimilar, as discussed in section IV-B. For V_1 = 1000V, the flow battery voltage ranges remain the same as quoted in section IV-C and n=0.5. Naturally, the currents in B_2 are higher by a factor of 2. The device ratings on both the bridges are different. The effects of voltage variations and different current magnitudes lead to asymmetrical stresses.

E. *Variable power transfer*

The power through the DAB has been kept constant in all the cases discussed from IV-A to IV-D. In all those cases, power change can lead to drastic changes in the stresses on the devices. The earlier sections are again discussed here for a variable power case.



(a) DAB currents as the flow battery discharges from 550V to 330V

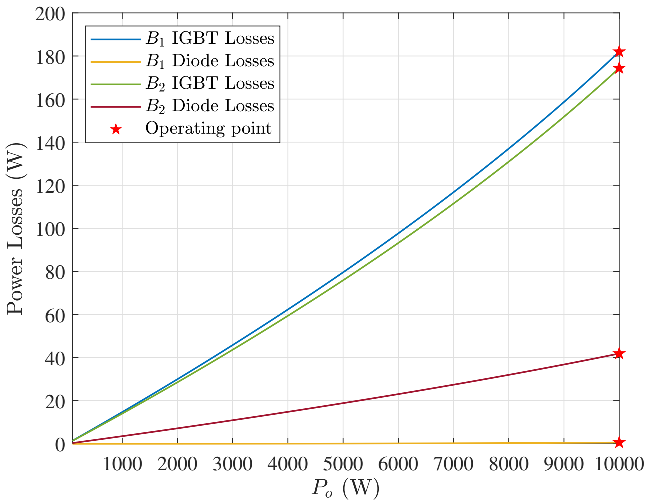


(b) DAB currents as the flow battery charges from 380V to 600V

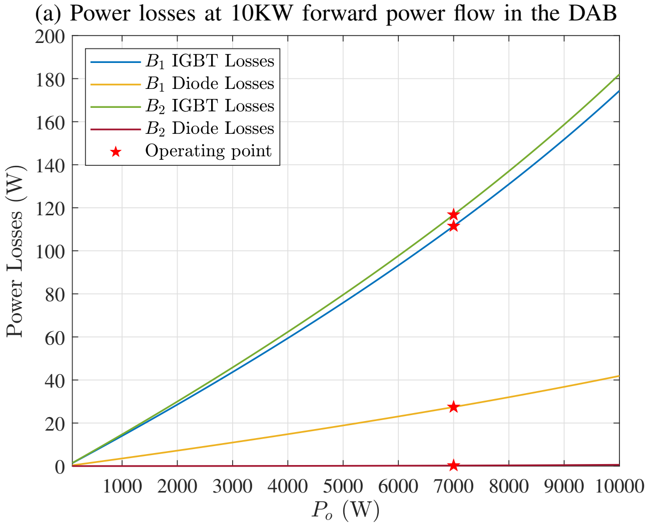
Fig. 3: DAB currents when the flow batteries charge or discharge.

For the case of constant voltages, as discussed in sections IV-A and IV-B, let's say the power in the forward direction, say 10 KW, is higher than in the reverse direction, say 7KW. Leading to higher current magnitudes in the forward power transfer. As shown in Fig. 4a, the IGBTs in B_1 and diodes in B_2 will experience more stresses than diodes in B_1 and IGBTs in B_2 shown in Fig. 4b.

For the case of variable voltages, as discussed in sections IV-C and IV-D, let's say the power at the time of charging the battery is higher, say 10KW, than the power at the time of discharging, say 7KW. Leading to higher current magnitudes during the charging of the flow battery. Similar to the previous case and illustrated in Fig. 5a, the peak power losses experienced by IGBTs in B_1 and Diode in B_2 will be more than the peak power losses Diodes in B_1 and IGBTs in B_2 as shown in Fig. 5b.

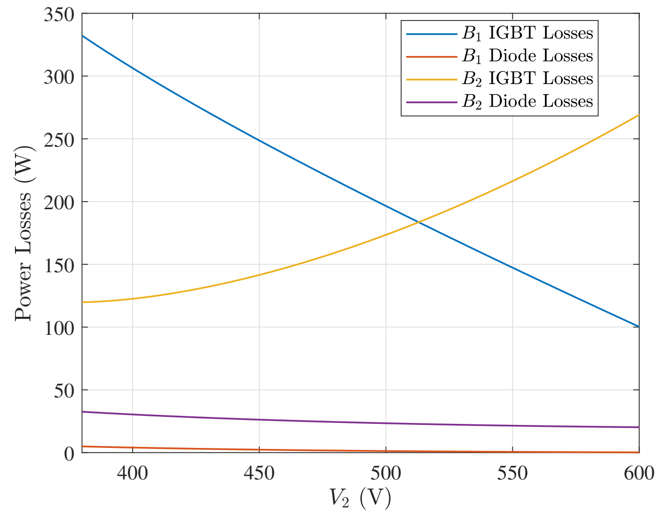


(a) Power losses at 10KW forward power flow in the DAB

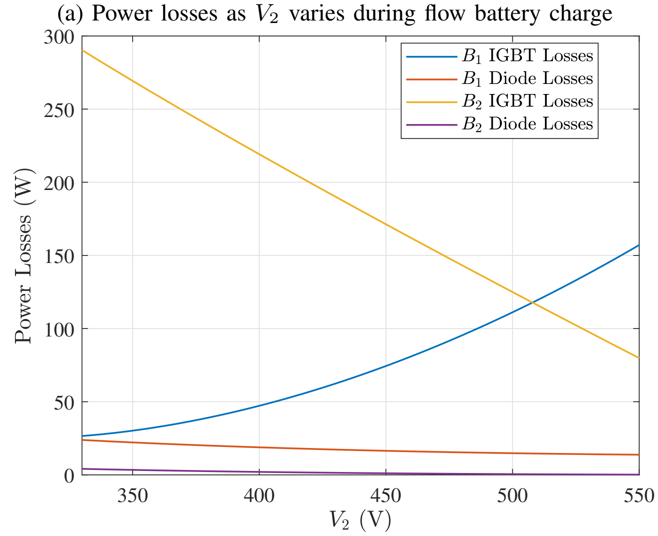


(b) Power losses at 7KW reverse power flow in the DAB

Fig. 4: Power losses at different operating points, highlighted by the star mark. Note n=1.



(a) Power losses as V_2 varies during flow battery charge



(b) Power losses as V_2 varies during flow battery discharge

Fig. 5: Power losses as the flow battery voltage varies at different charging power and discharging power levels. Note n=1.

If the power is allowed to be reduced at the end of charge or discharge, the phase shift between the bridges will reduce to a small value. This likely pushes the operating points outside of the Zero Voltage Switching (ZVS) range of the DAB. This increases the switching losses considerably, further increasing the temperatures.

The overall lifetime of the devices depends on the thermal cycles they experience. If the converter and the battery are always operating with either charge or discharge, the minimum junction temperature will be higher than the ambient temperature, depending on the losses at that operating point. However, if the battery is allowed to rest after the charge and discharge, and the minimum junction temperature reaches the ambient temperature, the thermal stresses on the devices will be considerably higher. The CIPS reliability model [12, 13] shows the relevance of minimum junction temperature ($T_{j_{min}}$) and the peak-to-peak temperature fluctuation (ΔT_j).

V. Conclusion

This paper discusses the asymmetric stresses that the devices of the DAB experience. Discusses the effects of variation of terminal voltage, transformer ratio and the power output of the DAB on power losses. Some preliminary results of power losses and current variations are shown to highlight the asymmetric stresses. These power losses and variations over time lead to the thermal cycling of devices, which is the main cause of the failure of devices in the long term. However, the stresses experienced by the devices are not uniformly distributed to all the devices equally. Highlighting which is the main focus of this work.

These factors can eventually be a part of the design process of the DAB. The selection of the leakage inductance, transformer ratio, device voltage and current ratings can be enhanced to achieve a more reliable DAB converter.

ACKNOWLEDGMENT

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