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Bidirectional DC-DC Converter for Battery Energy Storage Systems with Support to the Balance of Bipolar DC Microgrids

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Abstract. In the context of the more electrical aircraft, *DC* microgrids are beginning to become very significant. For this kind of microgrid, there are various conceivable configurations. However, one of the configurations that has been considered is bipolar *DC* microgrids. Thus, the design of the power electronic converters should take into consideration the particularity of this microgrid in order to maintain their balance. Thus, a new power converter to interconnect batteries to the bipolar *DC* microgrids is presented. This converter is designed in order to take into consideration the balance or unbalance of the bipolar microgrid. Thus, in the case of the microgrid be unbalanced, the converter will only use one of the poles in order to support the balance of the microgrid. The proposed converter will be tested by simulation, but also through a laboratory prototype.

Keywords. More electrical aircraft, storage systems, *DC* microgrids; bipolar *DC* microgrid

1. Introduction

The electric infrastructure in aircraft plays a critical role in powering and controlling various systems essential for safe and efficient flight operations. The *AC* infrastructure has been the standard for this kind of application. However, in recent years, this scenario has changed, and *DC* infrastructure has started to become a reference [1,2]. In the case of the so-called more electric aircraft, this kind of infrastructure becomes even more important [2-6]. Regarding the *DC* infrastructure, there are two main configurations: the unipolar and the bipolar [7,8]. However, regarding aircraft, the bipolar infrastructure has been adopted in several aircraft, like, for example, the Boeing

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787 or the NASA N3-X [9]. This kind of infrastructure allows for a better reliability system, a lower voltage regarding the reference.

As mentioned before, bipolar *DC* microgrids presents some advantages over unipolar *DC* microgrids, such as, increased reliability and lower voltage face to the reference. However, it can suffer problems related with the unbalance between the positive and negative poles. This problem appears due to the fact that typically only one pole is used to interconnect the generators, loads and storage systems. It is extremely difficult to ensure that the generated power is exactly the same as the consumed power at each of the poles. To attenuate or eliminate this problem, multiport converters or voltage balancers have been adopted [8-10]. In the case of the multiport converters, they have been used in generators and loads. For example, in the generators, the injected power into the \ microgrid will be done in accordance with the state of the microgrid [11-14]. Thus, if the bipolar *DC* microgrid is balanced, then the injected power will be exactly the same for both poles. However, if there is an unbalance, then the generated power will be injected only in the pole with less voltage level. In the case of the loads, will be exactly the inverse, i.e, it is used the pole with higher voltage level [15-17]. Due to their specific characteristics, these systems only require a power converter with a unidirectional *DC-DC* converter.

Unlike generators and loads, battery storage systems require a bidirectional *DC-DC* converter. Thus, some solutions adapted to the bipolar *DC-DC* microgrids have been developed. One of the solutions was presented by [18], in which is used a combination of two bidirectional converters, namely the Boost Sepic. Another solution that is based on a modified SC *DC-DC* converter was presented in [19]. The Buck-Boost three-level bidirectional converter is another solution that was adapted to this particular infrastructure [20]. A derived topology from this last one, but that incorporates full-bridge three-level Buck Boost voltage balancer with coupled inductor was also presented in [21]. In [22] is presented another solution that is based on the interleaved switched capacitor converter. However, all these topologies do not consider the problem associate to the change of the voltage gain when there is a transition from the balance to the unbalance mode and vice versa. In fact, this gives rise to an important variation of the duty cycle that could originate instabilities in the system. Besides that, many of the topologies presents some limitation in their static voltage gain. This work proposes a new power converter topology to be used as interface between a battery storage system and a bipolar *DC* microgrid. The proposed converter allows to modify the behavior of his structure taking into consideration if the bipolar *DC* microgrid is balanced or not. In this way, it is minimized the difference between the static voltage gain for these two different grid conditions. In fact, the topology allows for a high static voltage gain for the condition with more demand, namely the balanced condition.

2. Proposed Bidirectional Converter for the Bipolar DC Microgrid

To ensure the balancing support of the bipolar *DC* microgrids, their interconnection to storage systems is crucial. Hence, we propose a bidirectional *DC-DC* converter for linking a bipolar *DC* microgrid. This converter, featured in Fig. 1, boasts a high voltage step-up/down ratio while requiring only two capacitors and three inductors. It facilitates energy transfer between the storage system in a way that supports the balance of the bipolar structure's. For example, if the positive pole's voltage exceeds the negative one, energy transfer from bipolar to the storage system occurs solely from the positive pole. Moreover, the input/output voltage ratio varies depending on whether the bipolar microgrid is in a balanced state or not.

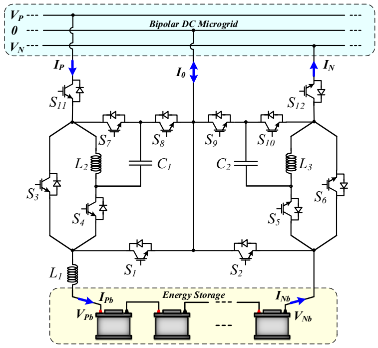

Figure 1. Proposed bidirectional *DC-DC* converter for the interconnection of a bipolar *DC* microgrid to a storage system.

The functionality of the proposed solution in unbalanced mode, transferring power between the storage system and the bipolar *DC* microgrid, is depicted in Figs. 2 to 7. The first two illustrate the scenario where the positive pole's voltage is lower than the negative pole's. Here, to balance the grid, energy transfer occurs solely from the storage systems to the positive pole of the bipolar *DC* microgrid, or from the negative pole to the storage system. Upon analyzing the resulting circuits, it becomes apparent that they mirror the classical Buck-Boost converter topology, as evidenced in Figs. 2 and 3. Consequently, the voltage relationship between the microgrid voltages, contingent on the power flow direction, is determined by these relationships:

$$V_{PO} = \frac{1}{1-\delta} V_{PNb} \qquad\qquad V_{PNb} = -\,\delta\, V_{ON} \tag{1}$$

Figs. 4 and 5 depict the operation of the solution in the scenario where the negative pole exhibits a higher voltage than the positive pole. Once more, the resulting circuits align with the classical Buck-Boost converter, establishing the same voltage relationship between the microgrids as before, namely:

$$V_{ON} = -\frac{1}{1-\delta} V_{PNb} \qquad\qquad V_{PNb} = \delta\, V_{PO} \tag{2}$$

The operation of the proposed solution in balanced mode from the storage system to the bipolar *DC* microgrid and vice versa is illustrated in Figs. 6 and 7. This figure showcases the operation when the energy transfer occurs from the storage system to the positive pole of the bipolar *DC* microgrid. Upon analyzing the resulting circuit, it becomes evident that it shares the same topology as the quadratic converter [23]. Consequently, the voltage relationship between the microgrid voltages is determined by equation (3). It's worth noting that in this scenario, the energy transfer occurs to both poles, resulting in the converter output voltage being doubled. Hence, the circuit changes to a quadratic configuration to mitigate significant changes in the converter duty cycle when there a change from unbalanced to balanced mode.

$$V_{PN} = \frac{1}{\left(1-\delta\right)^2} V_{PNb} \tag{3}$$

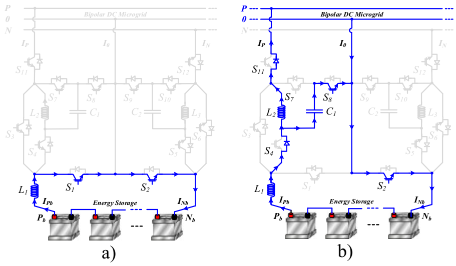

Figure 2. Operation of the proposed solution in unbalanced mode using positive pole from storage system to the bipolar *DC* microgrid a) Boost mode with switches *ON*, b) Boost mode with switches *OFF*.

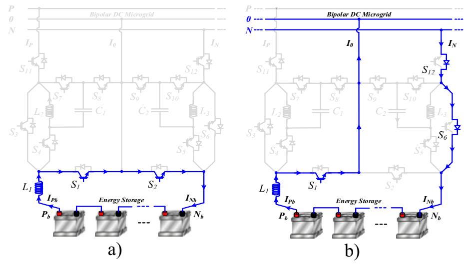

Figure 3. Operation of the proposed solution in unbalanced mode using negative pole from storage system to the bipolar *DC* microgrid a) Boost mode with switches *ON*, b) Boost mode with switches *OFF*.

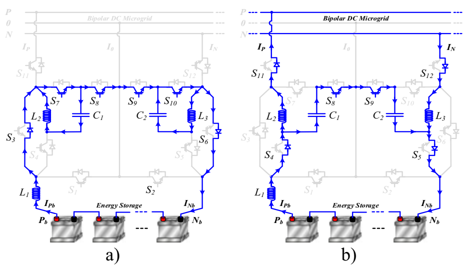

Figure 4. Operation of the proposed solution in balanced mode from storage system to the bipolar *DC* microgrid a) Boost mode with switches ON, b) Boost mode with switches OFF.

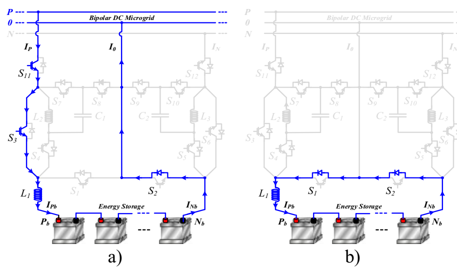

Figure 5. Operation of the proposed solution in unbalanced mode using positive pole from the bipolar DC microgrid to the storage system a) Buck mode with switches *ON*, b) Buck mode with switches *OFF*.

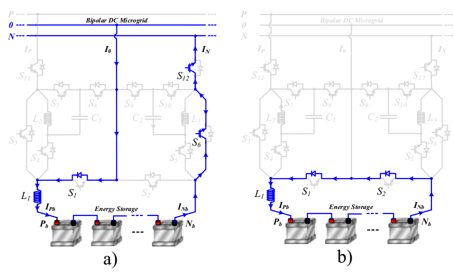

Figure 6. Operation of the proposed solution in unbalanced mode using negative pole from the bipolar DC microgrid to the storage system a) Buck mode with switches *ON,* b) Buck mode witches *OFF*.

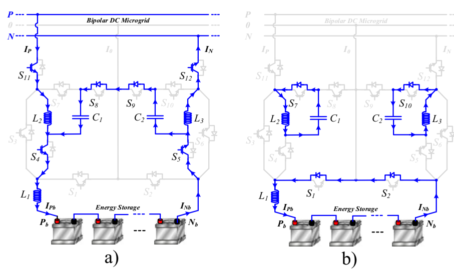

Figure 7. Operation of the proposed solution in balanced mode from the bipolar *DC* microgrid to the storage system a) Buck mode with switches *ON,* b) Buck mode with switches *OFF*.

The idea behind using quadratic or classical Buck-Boost modes is to reduce significant duty cycle fluctuations when the two-pole balancing converter switches from balanced to unbalanced modes and vice versa. For the classical Buck-Boost, quadratic *Buck-Boost,* and classical Buck-Boost with half output voltage (converter operating in Boost in unbalanced mode). It's worth mentioning that during unbalanced operation of the bipolar *DC* microgrid, only one pole is utilized, resulting in the converter on the bipolar DC microgrid side receiving approximately half the voltage (as only one pole is engaged). However, when the bipolar *DC* microgrid achieves balance, the voltage applied to the converter on this side doubles. This leads to significant fluctuations in the duty cycle to maintain the desired static voltage gain. Therefore, it becomes evident that the transition of the duty cycle from the conventional Buck or Boost mode, where only half of the voltage is present on one side, to the quadratic mode, is much less pronounced compared to the conventional mode with full voltage on one side.

3. Testing through simulation experiments

The suggested converter undergoes initial testing through simulation experiments showing their capability to interconnect battery storage systems to a bipolar *DC* microgrid. Passive components include an inductor L_1 with a value of 1 mH, inductors L_2 and L_3 each with a value of 6 mH, and capacitors (C_1 and C_2) with a value of 47 µF. The bipolar *DC* microgrid voltages are specified as $V_{DC\_bipolar}$ = ±170 V. The voltage of the batteries are $V_{bat} = 64\ V$. To guarantee the desired energy transfer, a hysteretic current controller is employed. These tests were done using the simulator Matlab/Simulink. The results, depicting the transfer of energy from the bipolar DC microgrids to the batteries, are illustrated in Fig. 8. These outcomes are derived from a scenario where the bipolar *DC* microgrid is initially unbalanced (where support is required for the negative pole, utilizing solely this pole to accommodate increased load). However, at t = 0.5 s, a sudden change to balanced mode occurs in the bipolar DC microgrid. Consequently, the converter shifts from a single to a double-pole operation. However, at t = 0.501 s there is a sudden change in the current reference (that charges the batteries) from 16 A to 10 A. The results show that the system maintains its operation, changing only the amplitude of the currents. On the other hand, at t = 0.502 s there is another sudden change in the condition of the *DC* bipolar microgrid, namely, becoming again unbalanced (but now the support is required for the negative pole, utilizing solely this pole to accommodate increased load). This result shows that change, and that the current injected into the batteries is not affected. Fig. 9 displays the outcomes of a new test where the energy is transferred again from the bipolar *DC* microgrids to the batteries, considering now that initially, the bipolar *DC* microgrid is unbalanced in an inverse situation (where support is required for the positive pole, utilizing solely this pole to accommodate increased load). However, at t = 0.5 s, a sudden new change in the unbalanced mode occurs (now support is required for the negative pole, utilizing solely this pole to accommodate increased load). The result shows that this did not affect the current that is injected into the batteries. A sudden change in the current reference (that charges the batteries) from 16 A to 10 A happens at t = 0.501 s. The results show that the system maintains its operation, changing only the amplitude of the currents. On the other hand, at t = 0.502 s there is another sudden change in the condition of the *DC* bipolar microgrid, namely, for the inverse situation of the unbalanced mode (the support is now required for the positive pole, utilizing solely this pole to accommodate increased generation). This result shows that change, and that the current supplied by the batteries is not affected. Another test was conducted with the bipolar *DC* microgrid unbalanced and taking into account the transference of energy in both directions (beginning from the bipolar to the unipolar and then an inversion). The results are displayed in Fig. 10, where it is feasible to verify that the batteries current reverse at t = 0.501 s.

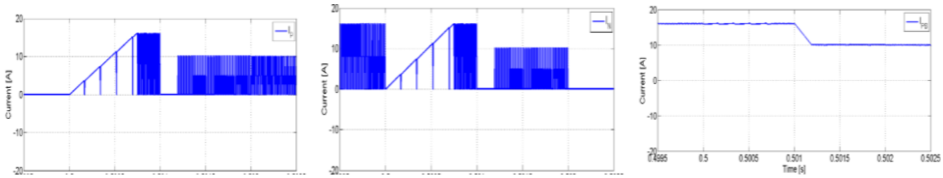

Figure 8. Simulation results considering that the energy is transferred from the batteries to the bipolar *DC* microgrids in unbalanced mode.

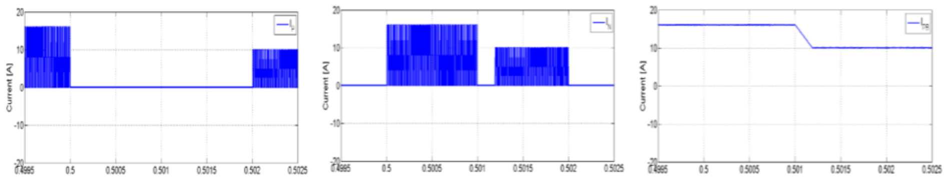

Figure 9. Simulation results considering that the energy is transferred from the batteries to the bipolar *DC* microgrids in unbalanced mode.

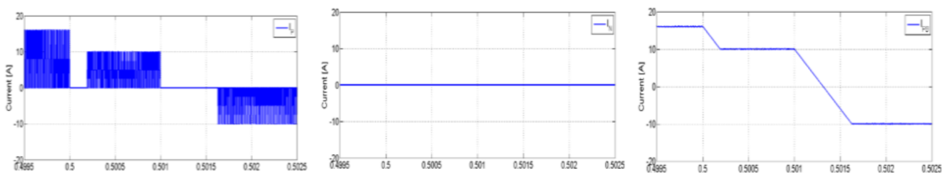

Figure 10. Simulation results considering that the energy is transferred from the batteries to the bipolar *DC* microgrids in unbalanced mode.

4. Testing through simulation experiments

Additionally, experimental findings were acquired to validate the converter's simulation behavior. The same parameters used for the simulation testing were applied to the laboratory prototype. The initial test was conducted under the testing condition in which the energy is transferred from bipolar *DC* microgrids to the batteries. Fig. 11 presents the findings. This result illustrates the bipolar *DC* microgrid's shift from a balanced to an imbalanced state. These results show that energy is transferred solely from the negative pole, and then from both poles the negative. It is also possible to see that there is a change in the batteries current reference. Besides that, that change is accompanied with a change in the bipolar *DC* microgrid, namely from unbalanced to balanced. It is also possible to see that these changes do not originate perturbations in the system. Another laboratory test to verify the simulation results where the one in which the energy is transferred again from the bipolar *DC* microgrids to the batteries, considering now that initially, the bipolar *DC* microgrid is unbalanced in an inverse situation. The result of this test is presented in Fig. 12, being possible to see that a sudden new change in the unbalanced mode occurs. However, this did not affect the current that is injected into the batteries. This result also shows that a sudden change in the current reference (that charges the batteries). Even with this change the system maintains its operation, changing only the amplitude of the currents. On the other hand, it is also possible to see that there is another sudden change in the condition of the *DC* bipolar microgrid, namely, for the inverse situation of the unbalanced. Despite that, the current supplied by the batteries is not affected. A laboratory test with the bipolar *DC* microgrid unbalanced and taking into account the transference of energy in both directions is displayed in Fig. 13. The results confirms that reverse in the batteries current.

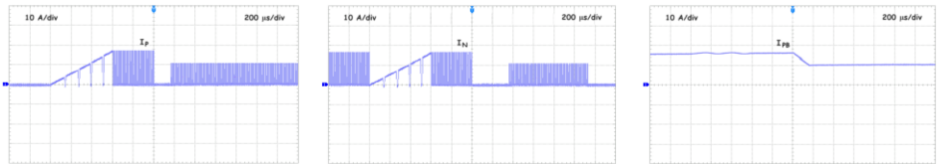

Figure 11. Experimental results considering that the energy is transferred from the batteries to the bipolar *DC* microgrids in unbalanced mode.

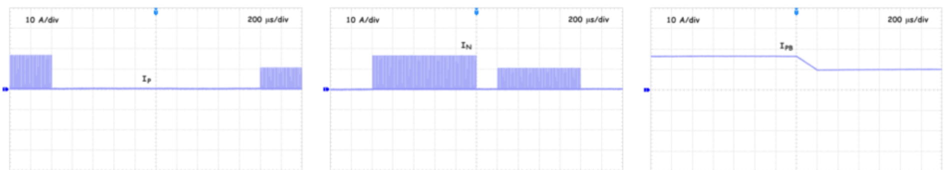

Figure 12. Experimental results considering that the energy is transferred from the batteries to the bipolar *DC* microgrids in unbalanced mode.

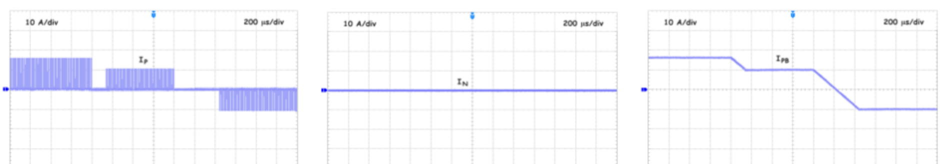

Figure 13. Experimental results considering that the energy is transferred from the batteries to the bipolar *DC* microgrids in unbalanced mode.

5. Conclusions

This study addresses the challenge of interconnecting a storage system to a bipolar *DC* microgrid infrastructure. This kind of infrastructure can suffer from voltage unbalances between the two poles, and a classical power converter to interconnect to a storage system can aggravate this problem. Thus, to eliminate or attenuate this problem, a novel bidirectional *DC-DC* converter with a high voltage step up/down capability was introduced. In this way, the solution enables energy transfer in a manner that facilitates voltage balance in the bipolar *DC* microgrid. In case of balance the converter uses both poles. However, under unbalance condition, the converter will only use one of the poles in order to in order to help the balance of the microgrid.

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