Effect of Battery to EDLC Power Ratio in ATBM Control Strategy for Grid Fluctuation Compensation

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The current trend in power generation is to increase the amount of renewable energy sources. In order to attenuate the fluctuation a hybrid energy storage system is used. In a previous work a high efficiency control system called ATBM was introduced. This work is an experimental analysis of the effect of the power ratio on the efficiency and working time of the system. A 1kW experimental setup is built in order to understand the effect of the power ratio between the Lithium battery pack and the supercapacitor (EDLC) pack.

Keywords：エネルギー蓄電、エネルギー制御、バッテリー、EDLC、ATBM
(Energy storage, energy control, battery, EDLC, ATBM)

1. Power stabilization problem

Renewable power generation sources, such as mega solar, are on the rise, as well as microgrids. Due to the ever-changing weather, the nature of renewable sources is quite unpredictable (1)-(4). The produced power can suddenly change due to different weather conditions, and this affects the power grid. In order to make the grid stable, one solution is the connection of energy storage systems to the grid. In this and in the previous work (5), the system being analyzed is a hybrid energy storage system, as shown in Fig. 1.

Lithium batteries are used for their high energy density, allowing for long periods of stabilization, and EDLCs for their high power density, allowing for short but high power periods. These two storage devices are connected to a DC/DC converter each, essentially having two parallel branches which can be controlled separately. The two DC/DC converters boost the voltage of the storage devices to a DC bus, which is connected to a DC/AC stage. Finally, this stage is directly connected to the power grid for power fluctuation attenuation.

The reference of the system is created using a ROC (Rate Of Change) limiter or a low pass filter. The power which cannot be stabilized naturally by the grid becomes the power reference of the attenuation system. The PV generation, limited power and power to be attenuated are as shown in Fig. 2.

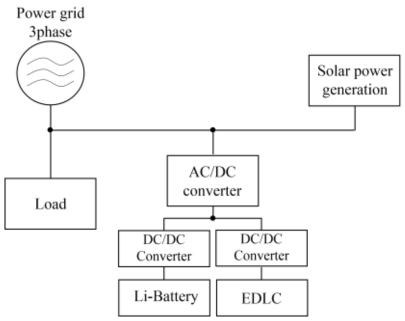

Fig. 1: Stabilization system connected to the grid and PV generation plant

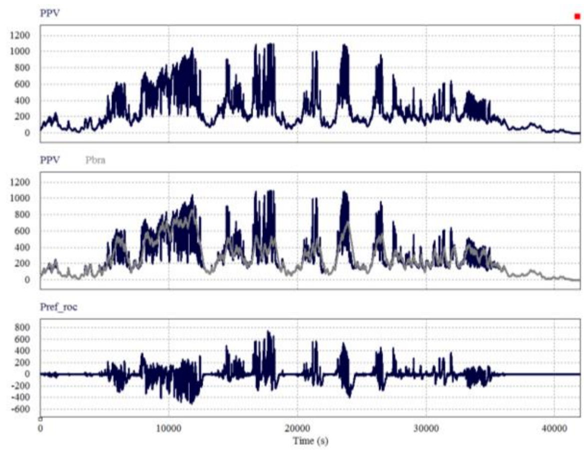

Fig. 2: PV power generation, filtered power and power to be attenuated

2. Conventional power division methods

As previously mentioned, the system is hybrid. This means that the battery branch and EDLC branch are separate and can be controlled independently. This allows for different control strategies in order to decide where the power should be supplied form, battery or EDLC. The two main conventional methods are FDAM and ADAM (6).

- FDAM (Frequency Division Allotment Method):

This power division method is based on frequency using just a low pass filter Fig. 3. The high frequency component is supplied by the EDLC, and the low frequency component is supplied by the battery.

This method has been used for a long time. However, in the current era is not relevant anymore. The current lithium batteries have a much higher response capability than lead acid batteries, so high that there is no point in dividing the reference into frequency. The lithium batteries are not limited in terms of frequency, thus this method is obsolete.

- ADAM (Amplitude Division Allotment Method)

This method was first introduced in (6). The power reference is divided by its amplitude so that the battery provides power until a certain limit, after which the EDLC supplies the rest. This method has been shown to improve converter efficiency.

However, both the ADAM and FDAM do not take the characteristic differences of lithium batteries and EDLC into account in order to create a comprehensive control method. In addition, they are not able to control the energy inside the storage devices. If the energy of the EDLC is low (as its capacity is usually much lower than the battery´s capacity) there is no control which recharges the EDLC in order to keep it from reaching 0% SOC.

There is a need for a control system which is able to take advantage of the different characteristics of these two technologies in order to achieve a higher efficiency. There is a need too for storage energy balancing for shutdown prevention. On a previous work (5) the ATBM was proposed a as a solution.

3. Optimum Voltage Range (OVR)

3.1 Power loss analysis

The OVR method developed in this paper follows the next line of thought: Both the battery side and the EDLC side of the system have an energy storage device and a converter connected. These have characteristic power losses, and can be controlled independently. On the one hand, the battery´s losses are related to the equivalent series resistance (ESR) (7)-(8), while the converter has it´s switching and conducting losses. On the other hand, the EDLC´s losses are related to the ESR as well as to the self-discharge phenomenon (9)-(10), plus the converter losses.

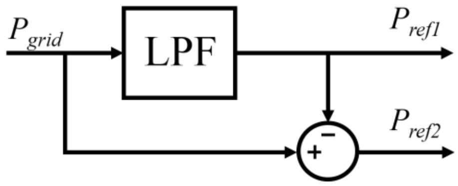

Fig. 3: FDAM block diagram

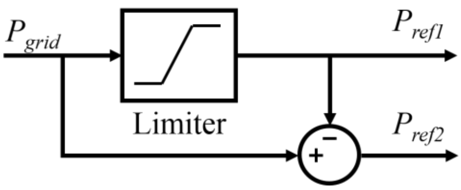

Fig. 4: ADAM block diagram

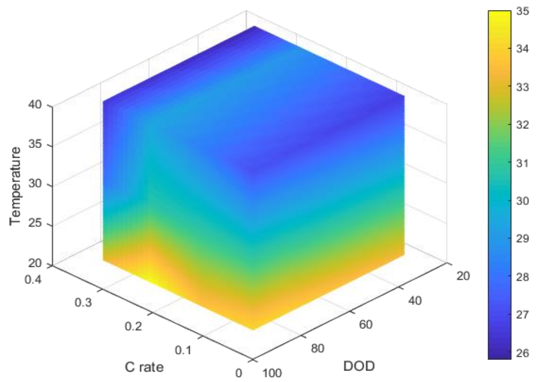

Fig. 5: Battery ESR relation with temperature, C rate and DOD.

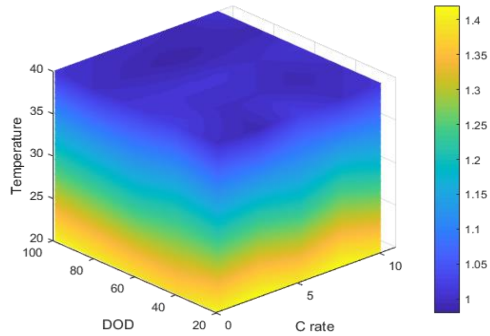

Fig. 6: EDLC ESR relation with temperature, C rate and DOD.

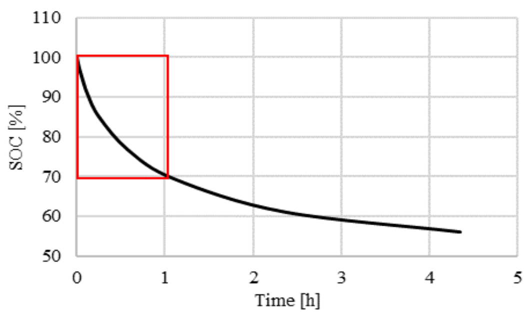

Fig. 7: EDLC self-discharge trend in a 4-hour period from 100% SOC.

Using the pulsing current method for calculating the ESR of the battery and the EDLC at different operating conditions, the results shown in Fig. 5 and Fig. 6 were obtained. The ESR of the battery changes mostly with the temperature, while the ESR of the EDLC is quite smaller and almost does not change. With the ESR, the conduction losses of the battery and EDLC pack can be calculated as:

$$P_{loss} = I^2 ESR \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

However, the EDLC´s power loss is also dictated by the self-discharge phenomenon. Fig. 7 shows the results of the self-discharge tests. The higher the voltage the higher the power loss.

In addition, power converters were created in order to carry out experimental power loss analysis. The converters are the same as in (5), one 300 W and a 500 W, buck boost converters. As the power loss in the DC/AC stage does not change regardless of the control method, this stage was omitted in the power loss analysis.

The converter experiment results can be seen in Fig. 8 and Fig. 9. As the high side is connected to the DC bus, is always at 120 V, while the low side fluctuates from 30 V to 50 V. The results show that the efficiency decreases as the conversion ratio increases.

3.2 Determining the OVR

With the data obtained from the power-loss analysis, using simulations, it was possible to determine the OVR of the system. It is divided into the battery OVR and EDLC OVR. This was achieved by creating models of the analysed parts in PSIM and observing the change in power loss which incurred at different voltage levels.

The battery side´s efficiency is higher when the voltage of the device is high. This supports the prediction made when testing the battery. The battery´s ESR does not change much with the voltage, but the lower the voltage, the higher the current for the same power reference. This increases the power losses of the battery, and as shown in Fig. 10, the efficiency of the converter decreases with the voltage. Thus, it is possible to determine that the OVR of the battery side is around 46 V to 50 V.

As regards the EDLC side, the opposite effect can be seen. The lower the voltage the higher the efficiency. This happens due to the self-discharge of the EDLC. This effect is so strong that, although the converter has a lower efficiency at low voltages, the converter losses are shadowed by it. The EDLC pack was not tested at a lower voltage than 33 V due to the fact that the current would be too high for the designed converter. Thus, it is possible to determine that the OVR of the battery side is around 33 V to 42 V.

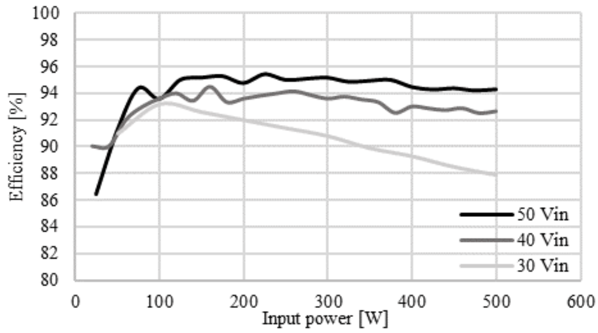

Fig. 8: Converter boost mode efficiency at 30, 40 and 50 Vin, 120 Vout

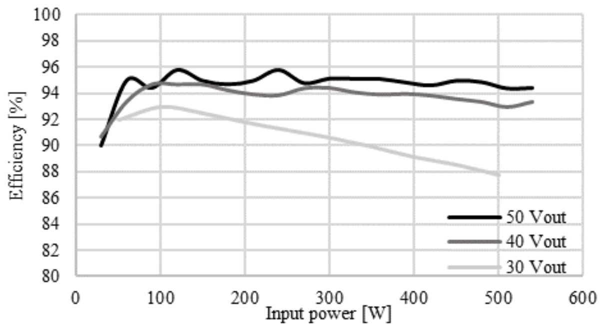

Fig. 9: Converter buck mode efficiency at 30, 40 and 50 Vin, 120 Vout

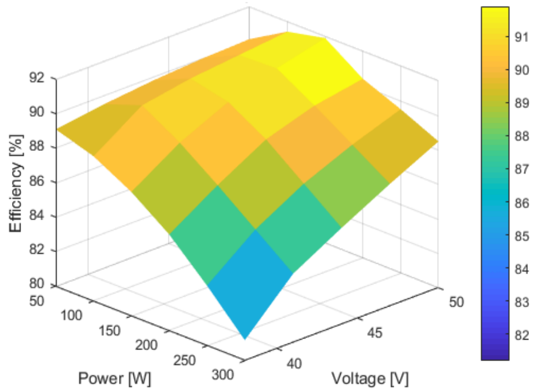

Fig. 10: Battery pack and battery side DC/DC converter combined efficiency at 38 V to 50 V (10% SOC to 95% SOC).

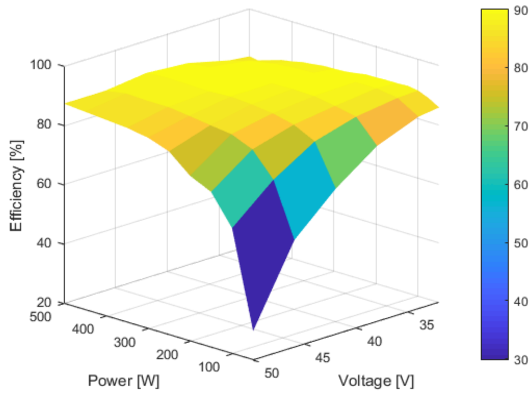

Fig. 11: EDLC pack and EDLC side DC/DC converter combined efficiency at 33 V to 50 V (39% SOC to 95% SOC).

4. Proposed power division method ATBM

The proposed control system tackles all the problems previously mentioned. The ATBM is based on OVR (Optimum voltage Range), which is a way to determine the highest efficiency range in battery branch and in the EDLC branch. The range is defined in the voltage of the storage devices.

In the case of the battery branch, the higher the battery´s voltage, the lower the current, and thus lower conduction losses. This translates into higher efficiency at high voltage or SOC. In the case of the EDLC branch, due to the self-discharge phenomenon, it was show that the EDLC pack should be kept at a medium voltage level. In consequence, the ATBM is based on maintaining the voltage of the storage devices inside their OVR, shown with red dotted lines in Fig. 13 and Fig. 14.

The ATBM has three modes:

- Synchronous: In order to decrease the conduction losses of the battery branch, the battery and EDLC are used at the same time. In (5) the ratio is 1:3, this means that one third of the power is given by the EDLC and two thirds by the battery. The objective of this paper is to test different power ratios in order to understand the effect on efficiency and working time.
- Overpower: In the case that the battery hits its power limit, the rest of the power is given by the EDLC due to its higher power density.
- Capacitor recovery mode: This mode ensures that the EDLC is charged faster when its SOC is lower that the OVR. When the voltage of the EDLC goes below the dotted line, as soon as the power reference changes to positive (charging), the EDLC is charged twice as fast as the battery. This enables the system to extend its working time by avoiding low SOCs.

The figures 12 to 14 describe an example of the ATBM, where the system starts in synchronous mode, then changes to overpower when the battery´s power limit is exceeded. As the voltage of the EDLC is very low, the system waits for charging reference, where it changes to capacitor recovery mode. When the EDLC´s voltage recovers to the OVR range, the synchronous mode is resumed.

5. Power ratio experiments

The aim of this paper is to assess how much of an impact the power ratio has on the total efficiency of the system. For this, a 1 kW scale experiment setup is built (Fig. 15). The characteristics of the system are shown in Table 1.

The setup is comprised of a battery pack, an EDLC pack, two DC/DC converters and an emulated DC bus. The grid power reference is emulated in the DC bus.

Three experiments were carried out with different power ratios:

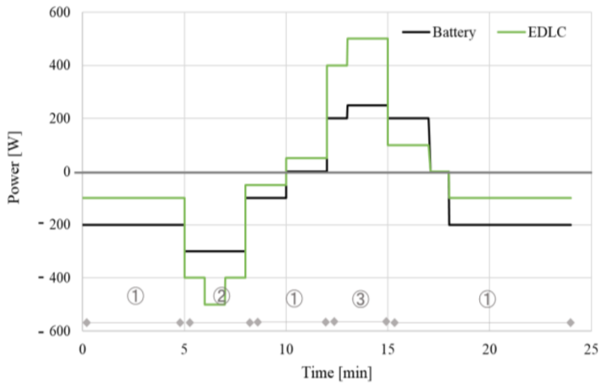

Fig. 12: ATBM example battery power reference and EDLC power reference

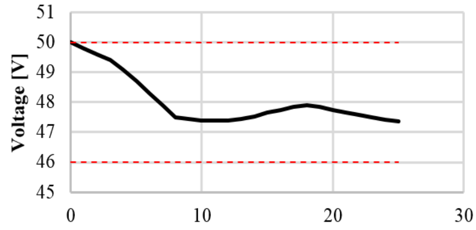

Fig. 13: ATBM example battery voltage trend

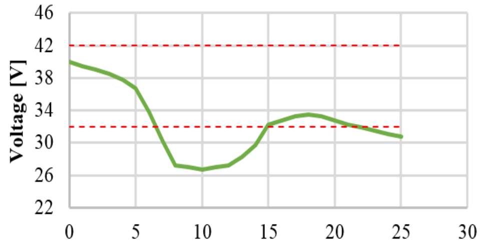

Fig. 14: ATBM example EDLC voltage trend

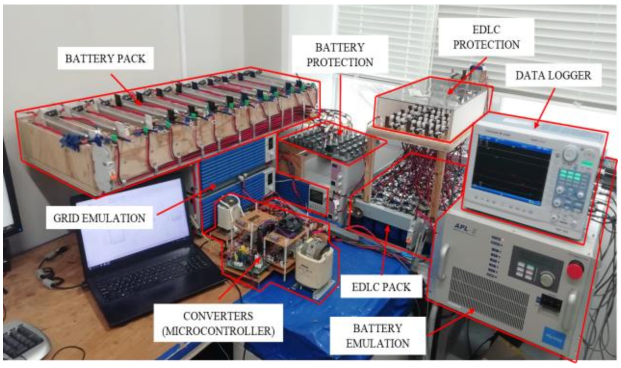

Fig. 15: Experimental setup front view

1:4 ratio, 1:3 ratio and 1:2 ratio. The ratio meaning how much of the power is supplied/absorbed by the EDLC in synchronous mode and the charging speed in capacitor recovery mode. The experiments were run for 2.5 hours (9000 seconds) with the input being the PV power generation data. From that data, using a ROC limiter, the excess power is inputted as the grid power reference to attenuate.

Comparing the three experiment results (Fig. 17, Fig. 18 and Fig. 19), it can be seen that the higher the power ratio, the more the EDLC is used. Both the 1:4 and 1:3 ratios are able to supply and absorb all the power in the 9000s experiment.

However, the 1:2 ratio´s battery and EDLC power waveforms end at about 7200 seconds into the experiment. This is caused by the EDLC not having enough energy in order to keep supplying the power grid. This is clearly caused by the ratio being too high for the EDLC to battery capacity configuration of the experiment.

Besides the 2.5 hours uninterrupted operation, the main objective of this work is to analyze the change in efficiency of the whole system. For this, the following equation were used for the efficiency calculation:

- For charging operation:

$$\eta_{DCDC} = \frac{\int I_L V_L}{\int I_H V_H} \quad \text{(2)}$$

$$\eta_{BAT} = \frac{\int I_{L\_BAT} V_{BAT} - \int P_{loss}}{\int I_{L\_BAT} V_{BAT}} \quad \text{(3)}$$

$$\eta_{EDLC} = \frac{\frac{1}{2}c\left(\left(\frac{V_2}{21}\right)^2 - \left(\frac{V_1}{21}\right)^2\right)63}{\int I_{L\_EDLC} V_{L\_EDLC}} \quad \text{(4)}$$

- For discharging operation:

$$\eta_{DCDC} = \frac{\int I_H V_H}{\int I_L V_L} \quad \text{(5)}$$

$$\eta_{BAT} = \frac{\int I_{L\_BAT} V_{L\_BAT}}{\int I_{L\_BAT} V_{L\_BAT} + \int P_{loss}} \quad \text{(6)}$$

$$\eta_{EDLC} = \frac{\int I_{L\_EDLC} V_{L\_EDLC}}{\frac{1}{2}c\left(\left(\frac{V_2}{21}\right)^2 - \left(\frac{V_1}{21}\right)^2\right)63} \quad \text{(7)}$$

where I_l is the current of the low side of the DC converter, V_l is the low side voltage, I_h and V_h are the high side current and voltage, C is the capacitance of an individual EDLC cell, I_c and V_c are the EDLC pack´s current and voltage, p is the number of EDLC cells in parallel, s the number of series cells, and V_1 and V_2 the voltage of the EDLC pack at the beginning and the end of the charging or discharging period.

The efficiency analysis shows that the higher the ratio, the higher the total efficiency of the system. This is logical as the EDLC has very low conduction losses and thus the efficiency increases at high EDLC usage. The efficiency is as shown in Table 2. The system benefits about 3.6% from the 1:3 ratio compared to the 1:4 ratio, and when using the 1:2 ratio it is already at diminishing returns.

In conclusion, with the current experimental setup, the most suitable ratio is the 1:3, as it is the highest efficiency ratio which can supply continuous power for 2.5 hours.

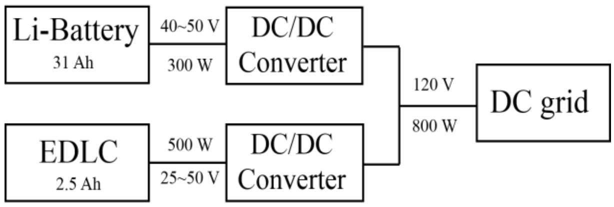

Fig. 16: Experimental system configuration schematic

Table 1: Experiment component specification

Component	Voltage	Power	Capacity
Battery Pack	38 V to 50 V	300 W	31 Ah
EDLC pack	25 V to 50 V	500 W	2.5 Ah
Battery converter	38 V to 50 Vin 120 Vout	300 W	
EDLC converter	25 V to 50 Vin 120 Vout	500 W	
Grid	120 V, DC	1000 W	

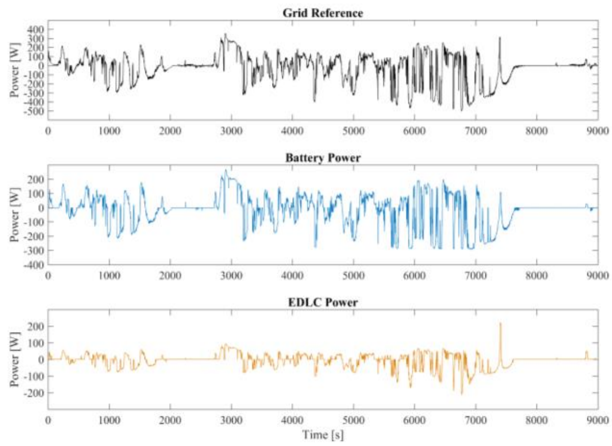

Fig. 17: 1:4 power ratio experiment. Grid power reference, battery power reference and EDLC power reference

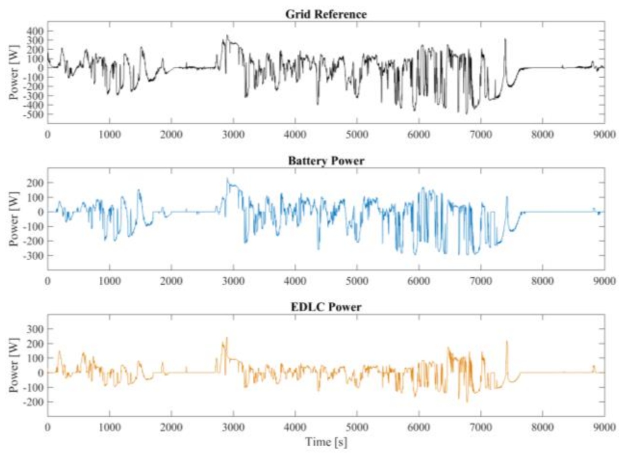

Fig. 18: 1:3 power ratio experiment. Grid power reference, battery power reference and EDLC power reference

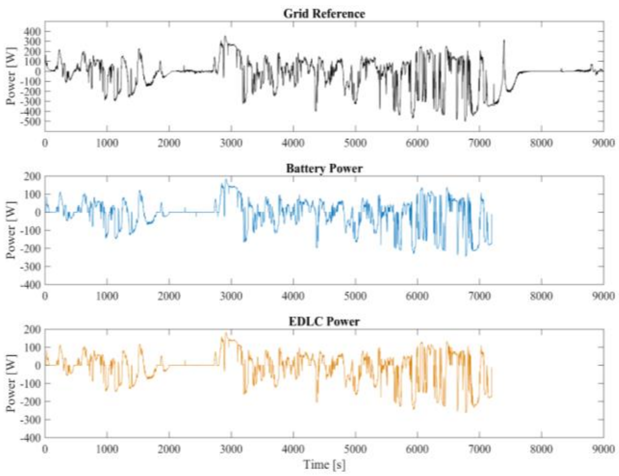

Fig. 19: 1:4 power ratio experiment. Grid power reference, battery power reference and EDLC power reference

Table 2: ATBM 1:4, 1:3 and 1:2 ratio experiment results

Ratio	**1:4**	**1:3**	**1:2**
Total Efficiency [%]	82.6	86.2	86.6
Working time test	Passed	Passed	Failed

5. Conclusions

The control method being analyzed is the ATBM, which was developed in a previous work. A 1kW experimental setup is used in order to assess the impact of the power ratio (how much power the EDLC pack supplies relative to the total power reference) in a hybrid storage grid fluctuation compensation system. The experimental results (from 1:4 ratio to 1:2 ratio) show that the higher the ratio the higher the efficiency. However, as the EDLC pack is lower energy dense than the battery pack, at high ratios the EDLC´s energy can go down to zero and thus the system cannot continue operation.

Thus, the best performing ratio is the 1:3, with the highest efficiency which can operate for the full experiment length. The relationship between the installed capacity, desired operation time and power ratio needs to be further analyzed theoretically, in order to automatize the selection of the ratio via equations.

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