High-Efficiency Control Method of Hybrid Energy Storage System for Power Grid Fluctuation Compensation based on Optimum Voltage Range

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Abstract: In order to reduce the fluctuation in the power grid generated by renewable energies, a grid connected hybrid energy storage system is used, combining lithium-ion batteries and ultracapacitors. In this paper, a new high-efficiency control method for the power division as well as for the stored energy balance is proposed. The battery bank, ultracapacitor bank and power converters are individually analyzed. The control method is based on the Optimum Voltage Range, which is a new method of determining the highest efficiency work-point of the energy storage systems. A 1 kW simulation is created in order to validate the performance of the control method, with detailed, experiment based energy storage and power converter models. The results demonstrate that the proposed method reduces the power overall power loss of the system, as well as compensating the power fluctuation on the grid and balancing the energy storage devices.

Keywords : renewable energy, energy storage, high efficiency, battery, ultracapacitor, storage control

1. Introduction

The increasingly rising usage of high powered renewable energy production has a natural issue. Due to the ever-changing climatological conditions, the power output of these installations varies significantly, which makes the grid power flow fluctuate (1)-(4). In order to compensate this fluctuation, energy storage systems such as batteries and ultracapacitors have been used to absorb or deliver the remaining energy. These solutions integrate a high powered energy storage component such as ultracapacitors, and a high energy storage component such as lead or lithium batteries, each with a power conversion phase for connecting them to the grid. Different power division methods have been used for defining the power delivery of both branches (battery and ultracapacitor), such as the frequency (FDAM) and amplitude (ADAM) division methods (5). However, none of these take the energy storage balancing into account, nor the internal behavior of the energy storage devices.

This paper proposes a high-efficiency energy storage balancing and power delivery control method, based on the optimum voltage range (OVP) of both the batteries and ultracapacitors (EDLCs). The proposed system combines Li-ion batteries in one branch, and EDLCs (electrolytic double layer capacitors) which can individually be controlled. The control method uses previously determined OVPs, which is the voltage range of the energy storage system where the efficiency is the maximum, in order to maintain the highest efficiency possible, as well as controlling the storage system´s energy balance. Using this method, three different modes are automatically selected, which decide the instantaneous power division. The power delivery of the battery and EDLC branch are separately determined taking into account the fundamental differences of the two technologies.

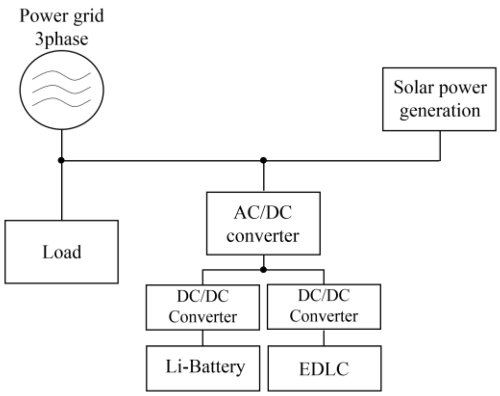

Fig. 1. Configuration of the grid connected system

The simulation results show that the proposed control method is able to compensate the power fluctuation of the grid, as well as keeping the energy storage system´s energy balance for working on longer periods of time that other control methods. Moreover, the efficiency of the whole system is shown to be higher, due to the use of the OVPs.

2. Principles of the stabilization power delivery

The system is composed by a grid connected AC/DC, where the DC side is divided in two branches. The first branch has a DC/DC converter and a battery bank, while the second branch has another DC/DC and an EDLC bank. These two branches are used separately, the battery bank is usually used for its high energy storage capabilities, whereas the EDLCs are used due to their high discharge currents and fast response. Fig. 1 shows this configuration.

In order to determine the power delivery for both branches, two main conventional methods have been used: FDAM (frequency division allotment), where the reference power is divided by the frequency of its components; and ADAM (amplitude division allotment) where the reference power is divided by the amplitude.

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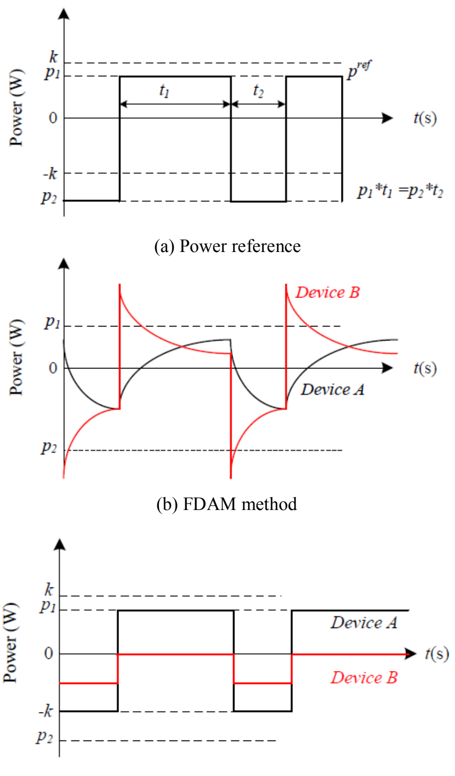


(a) Power reference

(b) FDAM method

(c) ADAM method

Fig. 2. Conventional methods of power division example

Fig. 2 shows the principles of the conventional methods. The power reference in Fig. 2 (b) demonstrate the FDAM method, where the power division is determined by a simple low pass filter. Fig. 2 (c) shows the ADAM method, where the power division is determined by a simple maximum limiter. These two methods have only one input, which is the reference power.

The proposed method takes into account the power reference, as well as both the battery and EDLC banks´ voltage. This allows for a more precise, technology specific control method.

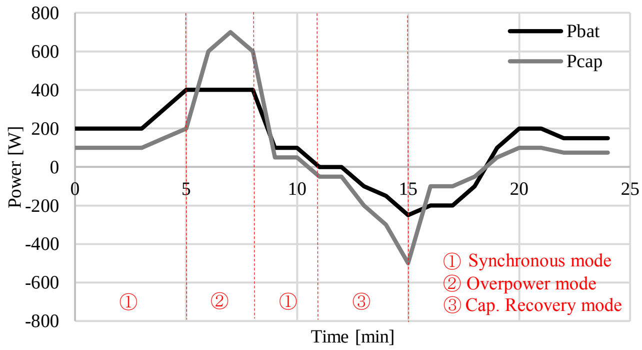
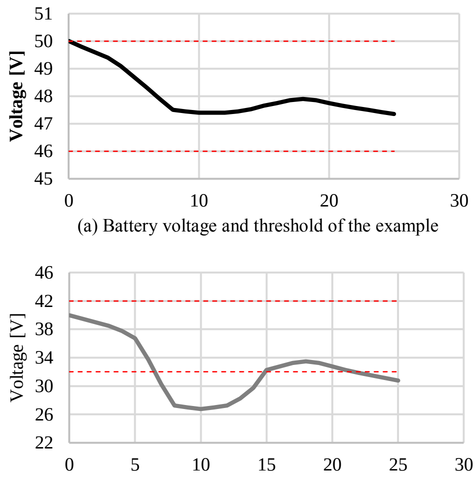


Fig. 3. Proposed method ATBM (Active Threshold Balancing Method) example power division example

Fig. 3. Shows the different modes that the proposed method (ATBM) works at. These modes are selected depending on the power reference and battery and EDLC voltages. The modes follow the voltage threshold laws displayed in Fig. 4.



(a) Battery voltage and threshold of the example

(b) EDLC voltage and threshold of the example

Fig. 4. Battery and EDLC pack voltage trends and thresholds

The voltage on the battery pack and the EDLC pack in the examples of Fig. 4 have a maximum of 50 V. Depending on the voltage they are at, the efficiency varies, thus there is a range where the efficiency of the energy storage is the maximum, which will be called Optimum Voltage Range (OVR). The theory of OVR is developed in chapter 4. The maximum and minimum thresholds are placed for each technology.

In the synchronous mode, 67% of the power is provided/absorbed by the battery, while the remaining 33% is provided/absorbed by the EDLC pack. This allows for a higher efficiency than using only one of the technologies at a time. Although the equivalent series resistance of the batteries is higher than the EDLC´s, as the battery packs are less costly, typical applications have a higher battery energy capacity than EDLC, therefore improving the energy stability of the system.

In the overpower mode, when the power reference exceeds the power limit of the battery, the battery is set to the power limit, while the EDLC pack provides/absorbs the rest. This is due to the high power rating of EDLCs, compared to the Lithium batteries.

In the capacitor recovery mode, if the EDLC exceeded the maximum voltage threshold, as soon as the power reference changes to negative (towards the grid) the EDLC pack provides the 67% of the power, while the 33% is provided by the battery pack. The low energy EDLC pack is therefore pulled back inside the OVR.

3. Optimum Voltage Range

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), 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, plus the converter losses. In this chapter, all of this losses are experimentally quantified, in order to create a simulation model of the system, and determine the OVR of both the battery side and the EDLC side.

3.1 Battery losses

As previously said, the battery losses are related to the ESR (6)-(7).

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

In order to calculate the power loss, first the ESR needs to be estimated. The ESR depends mostly on the instantaneous current, SOC and temperature of the battery (8).

The battery pack used for the ESR experiment is a 12 series of 31 Ah 3.6 V Li-ion, which combined have a maximum 50 V.

Fig. 5. Single 3.6 V Li-ion cell used in the battery pack

A thermostatic chamber is used to control the battery´s temperature, and a series of experiments are carried out at 0.01 C to 0.36 C and at 90% to 10% SOC. The battery is discharged at different current rates, and the voltage drop of the battery is measured at every 10% SOC discharge (9).

The resulting voltage drop is divided by the instantaneous current and the ESR for each case is obtained. This data is arranged using Matlab, in a four dimensional graph. The data points are interpolated in order to have more accuracy:

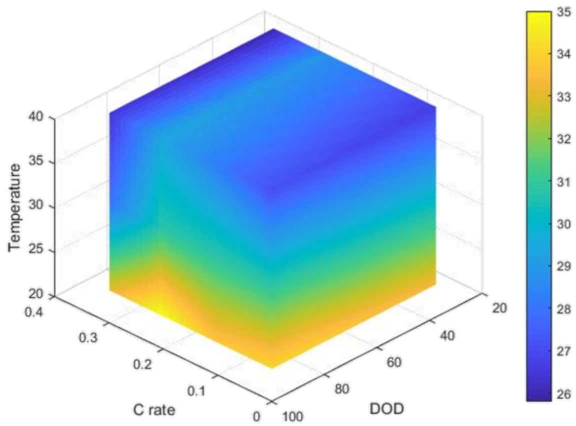


Fig. 6. Battery ESR relation with temperature, C rate and DOD

The ESR does not suffer a noticeable change either with the C rate or the DOD. However, the ESR decreases with the temperature, due to the easier flow of the chemicals though the electrolyte (10). The ESR value has a maximum of 35 mΩ at the lowest temperature, while the lowest ESR is achieved at the highest temperature, 26 mΩ at 40 ℃. This data is used for the battery model in the simulation which will later be explained.

3.2 EDLC losses

The power losses of the EDLC´s depend on the ESR and also on the self-discharge of the cell (11)-(12). First, the same experimental tests as with the battery pack were carried out. In this case, the EDLC pack is formed by 63 2400 F 2.5 V EDLCs, arranged in 21S3P, which combined have 2.5 Ah and a maximum of 52.5 V. The tests were carried out at 20 ℃ to 40 ℃, 100% to 20% SOC and 0.1 C to 10 C.

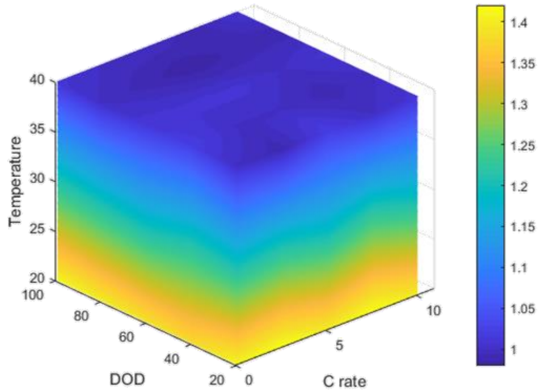


Fig. 7. EDLC ESR relation with temperature, C rate and DOD

The ESR does not seem to change with SOC or current, just a 2%, which is inside the margin of error. However, there is a clear decrease in ESR as the temperature increases. The ESR ranges from 1 mΩ to 1.4 mΩ, which is about 30 times lower than in the case of the battery pack.

Besides the ESR, the self-discharge also contributes to the power loss of the device, due to the imperfections in the EDLC layers, which create a parallel resistance (13)-(14). In order to quantify this power loss, the EDLC pack was charged to 100% of its capacity at 2 C, and its voltage was measured for 4 hours.

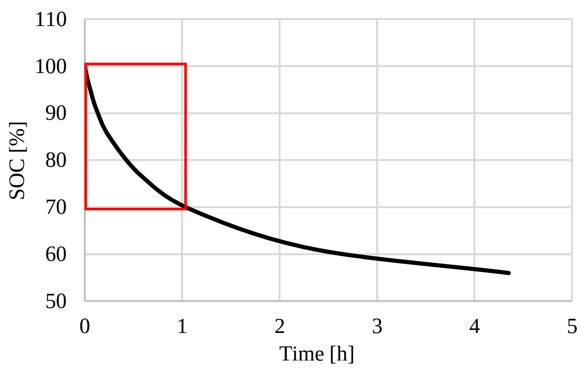


Fig. 8. EDLC self-discharge trend in a 4-hour period from 100% SOC

Fig. 7 shows the decline in stored energy due to the self-discharge. The EDLC pack tested loses the 30% of its charge in just an hour (highlighted with the red square), which means that even if the EDLC pack is not being used, there are power losses. The power loss decreases as the SOC of the device decreases, suggesting that using the device at a lower SOC will increase its efficiency.

The both the data of the ESR, as well as the self-discharge data are used for creating the EDLC pack model in simulation.

3.2 Converter losses

The converter losses can easily be calculated by using equations, but in order to the data to be as close to reality as possible, an experimental setup was built.

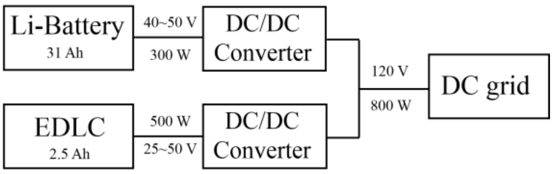
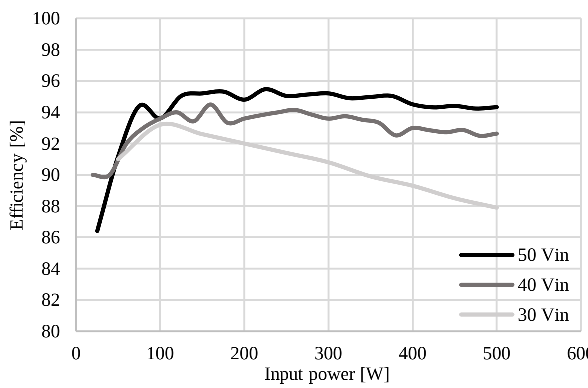


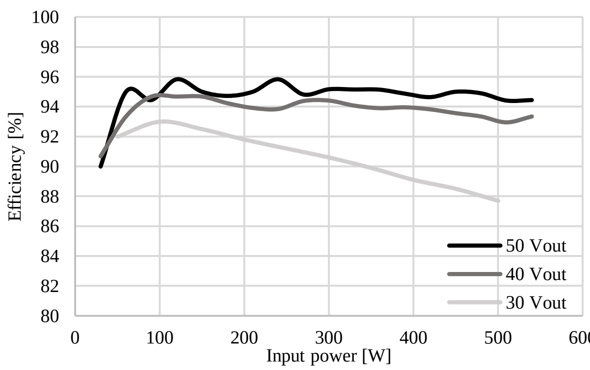
Fig. 9. Fluctuation balancing system schematic

As already mentioned, the battery pack and the EDLC pack have a maximum voltage of 50 V, 300 W maximum power for the battery and 500 W for the EDLC. The grid is a DC supply/load, as the DC/AC converter´s efficiency does not change depending on the control strategy, the power reference in it will always be the same regardless of the control method. This grid is at a constant 120 V. Due to this, the converters need to work as step-down when the energy flows into the energy storage, and as step-up when energy has to be provided to the grid.

With this information, two buck-boost converters were built, with a maximum power output of 300 W and 500 W respectively. In order to quantify the efficiency of the converters, tests from 50 W to 800 W were carried out, the power difference at the input and the output of the converter measured and the efficiency was obtained.



(a) Boost mode efficiency at 30, 40 and 50 Vin, 120 V output



(a) Buck mode efficiency at 30, 40 and 50 Vout, 120 V input

Fig. 10. Double buck-boost converters efficiency trend with input power

The experiment shows that the converters are more efficient at higher voltages, there is a clear increase in power loss when the battery of EDLC side voltage decreases. This data is used in order to create the converter model in the simulation for the OVR calculation, as well as for the control method simulation.

4. Simulation configuration

4.1 OVR simulation

The first thing for building the control method is determining the OVR of both the battery side and the EDLC side. Using the data from the experiments, models for the battery pack, EDLC pack and converters are created in Matlab and PSIM. This models can be simulated in order to know the OVR.

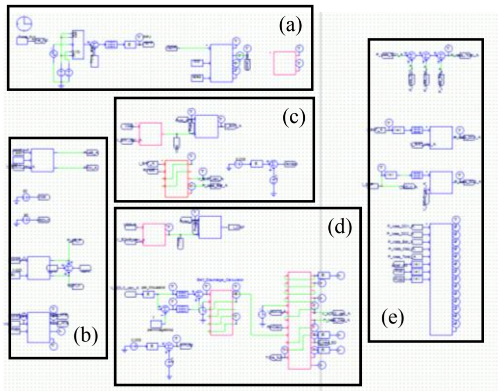
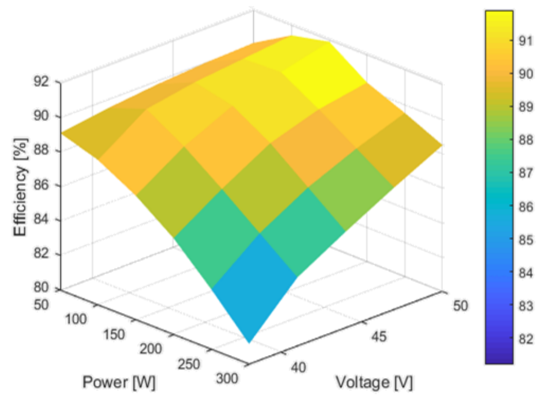
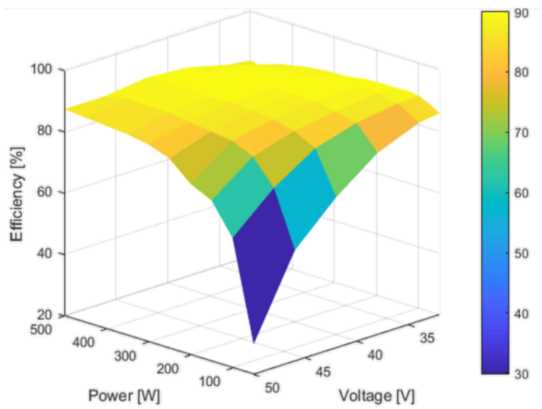


Fig. 11. PSIM complete system simulation: (a) PV generation module, (b) control method module, (c) battery pack model, (d) EDLC pack model, (e) converter model and total efficiency calculation

The PSIM simulation inputs real PV generation data and different control methods can be tested for the fluctuation balancing. This simulation works with the Matlab models previously shown. The simulation can be used to determine the OVR, setting the battery and EDLC packs to a range of SOCs, the total efficiency of the energy storage, combined with the converter´s efficiency is obtained.



(a) Battery pack and battery side converter combined efficiency at 38 V to 50 V (10% SOC to 95% SOC)



(a) EDLC pack and EDLC side converter combined efficiency at 33 V to 50 V (39% SOC to 95% SOC)

Fig. 12. Combined efficiency of battery side and EDLC side depending on the device voltage

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. Fig. 8 shows that the self-discharge is stronger at higher voltages. 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. Both of the OVR was previously shown in Fig. 4, where the thresholds are located at the maximum and minimum values of the OVR.

4.2 ABTM simulation

Knowing the OVR of the battery pack and the EDLC pack, the Active Balancing Threshold Method´s working modes shown in Fig. 3 can be decided.

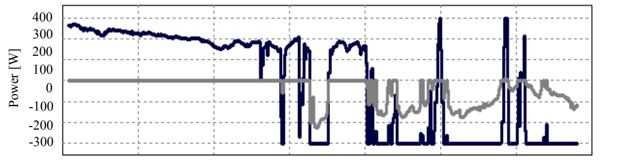
In synchronous mode the EDLC will start working only above 50 W load, due to the low performance at that power level shown in Fig. 12. The control method draws the energy storages to their respective OVR, while having the fulfilment of the grid power reference as a priority.

The simulation for comparing the performance of the ATBM with ADAM is composed of the same elements as in the individual experiments.

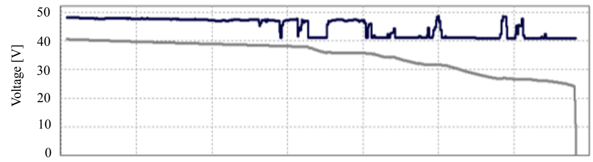
Table 1. Simulation components specifications

Component	Voltage	Power	Capacity
Battery Pack	38 V to 50 V	300 W	31 Ah
EDLC pack	33 V to 50 V	500 W	2.5 Ah
Battery converter	33 V to 50 Vin 120 Vout	300 W	
EDLC converter	33 V to 50 Vin 120 Vout	500 W	
Grid	120 V	800 W	

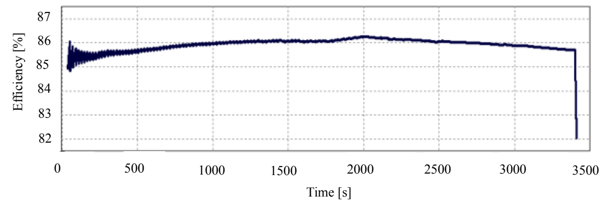
The same PV generation data and starting parameters (SOC of the battery pack and EDLC pack) are used with both control methods. The aim of the simulation is to validate the energy managing capabilities of the ATBM and to compare its efficiency with the ADAM.



(a) ADAM simulation power delivery

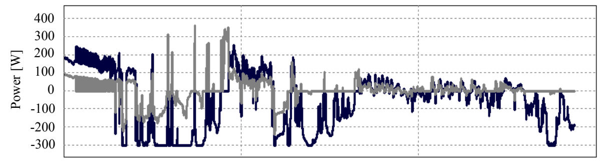


(b) ADAM simulation voltage

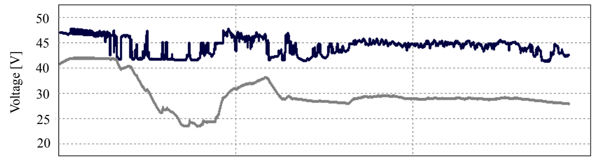


(c) ADAM simulation efficiency

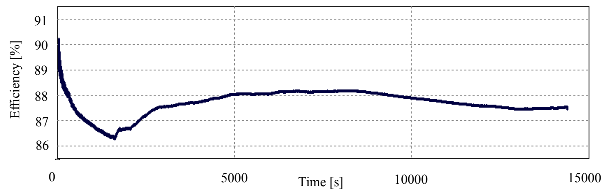
Fig. 13. ADAM power delivery, storage voltage and efficiency simulation results



(a) FDAM simulation power delivery



(b) Voltage



(c) Efficiency

Fig. 14. ABTM power delivery, storage voltage and efficiency simulation results

Fig. 13 and Fig. 14 show the ADAM and the ATBM performance respectively. On the one hand, the ADAM, the control system is not able to control the energy storage, which results in an over discharge of the EDLC pack, stopping the system completely in less than one hour. The decline of the EDLC voltage can be seen as well as the efficiency of the system. This efficiency is not the instantaneous one, but the cumulative power loss divided by the cumulative power delivery:

$$\eta = \frac{\sum_{i=1}^{j} P_{loss}}{\sum_{i=1}^{j} |P_{ref}|} \quad (2)$$

Where j is the actual step, P_{loss} is the total power loss of the system, and $P_{in/out}$ the total power supplied to or absorbed from the grid. This means that the latest point is the efficiency of whole simulation during that time, not the instantaneous one. ADAM is able to achieve 85.7% of efficiency before failing.

On the other hand, the ABTM method successfully control the energy storage, being able to control it for four hours, and could continue working for longer. The system recharges the EDLC pack when the lower threshold is surpassed in the EDLC recovery mode, and shares some of the power load with the battery pack, while drawing the devices to their respective OVR, achieving a higher efficiency than the ADAM control method.

5. Conclusions

The paper proposes a high-efficiency control method for a grid fluctuation stabilization hybrid energy storage system. The efficiency of the proposed method is proven to be 2% higher than that of the conventional method. It is also proven that, unlike the conventional method, the proposed method is able to control the energy storage devices, and does not fail to maintain the energy balance of the system and secure its uninterrupted operation.

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