Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 1881 – 1887

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

# Energy analysis of a real grid connected lithium battery energy storage system

Danilo Antonio Sbordone[a*], Biagio Di Pietra[b], Enrico Bocci[c]

[a]*DIAEE - Electrical Engineering, University of Rome Sapienza, via Eudossiana 18, 00184 Rome, ITALY*
*ENEA, Italian National Agency for New Technologies,*
[b]*Energy and Sustainable Economic Development , Via Anguillarese 301 - 00123 Rome, ITALY*
[c]*Università degli Studi Guglielmo Marconi, Via Plinio 44, 00193 Roma, Italy*

**Abstract**

Today, in the grid there are more and more installation of renewable energy plants. The renewable sources are so discontinues and they may affect the stability and efficiency of the grid. Many distribution service operators are experimenting the battery energy storage systems (BESSs) to integrate them on the grid and resolve these problems. This paper analyses the energy performance under real conditions of a BESS prototype. The real BESS under focus has made by a lithium battery pack of 16 kWh, a DC/DC converter of 20 kW and an IGBT inverter of 30 kVA with a direct voltage bus of 600 V.

The energy analysis has been performed through an integrated data acquisition system that take data from on-board electronic diagnostic measurements and from smart metering data. This latter using remote devices. The tests have been carried out on the system to monitor the following characteristic parameters: current and voltage of the batteries, current and voltage of the grid and current and voltage of the auxiliaries. The system energy performances have been analyzed in dynamic and real conditions with particular reference to the following quantities: energy consumption for the auxiliary system and overall efficiency of the system in a distributed energy resources microgrid. The entire system has been analyzed until twenty-four hours.


Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Energy storage system, microgrid, lithium battery, energy performances, rlectrical fehicle, fast recharge

* Corresponding author. Tel.: +39-340-2818606;
*E-mail address:* danilo.sbordone@uniroma1.it


Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.171

## 1. Introduction

Renewable power and electricity have received considerable attention worldwide in recent years[1]. Further, battery energy storage systems (BESS) start to be used for multiple applications, such as wind and solar power smoothing, peak-shaving, frequency regulation, electric vehicle (EV) charging stations and others applications[2][3]. Further, the energy storage systems are needed to develop the microgrids and the future smart grid[4][5].

In this study an experimental activity has been performed on the prototype of BESS in order to test its energy performances into the integration in a grid available at the ENEA labs (Italian National Agency for New Technologies, Energy and Sustainable Economic Development)[6]. A microgrid has been made including a EV fast charging stations integrated with a emulated photovoltaic power plant production[7]. Many utilities, research centres and university are realizing different demonstrations of BESS to optimize its management and to check its real application[8]. As seen, many papers discuss the benefits and applications of energy storage technologies using simulation environment and systems[9][10][11]. In this paper are described some experimentations carried out to analyze the total efficiency of a real BESS including battery, converters and the auxiliary consume.

## 2. Main components of energy storage system analyzed

The prototype of analyzed BESS consists of a active front end (AFE), with a 30 kVA nominal power, connected to the grid and to a DC low voltage bus-bar at 600V through a DC link supplied by a 20 kW DC/DC buck booster and a Li-Polymer battery with 70 Ah and 16 kWh total capacity. The analysed energy storage system is based on scheme showed in Fig. 1.

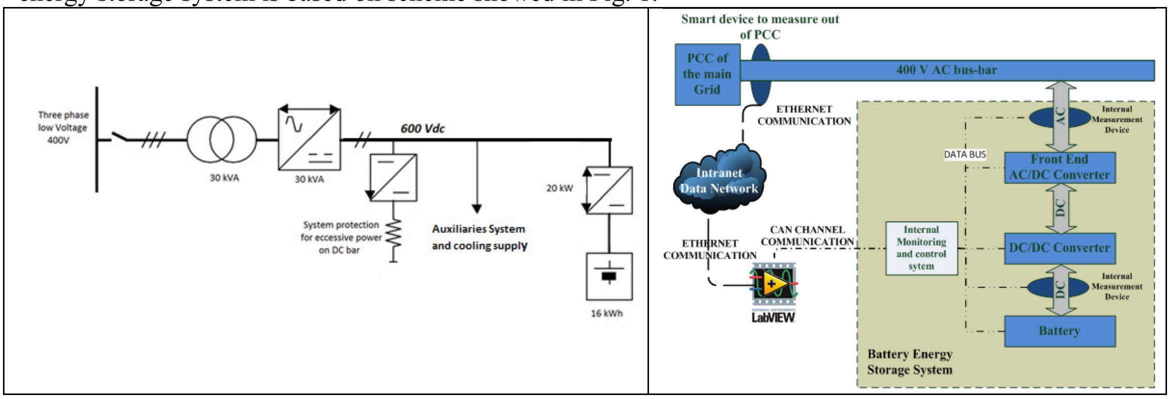



Fig. 1 – General Schema on the left and developed system on the right

An external monitoring and control system has been developed in Labview to perform experimental testes and analyze total efficiency of BESS. The system acquires the measurement data sent by BESS via CAN protocol with a bit rate fixed to 250 kbit/s. The following measurements have been acquired through this external system showed in Figure 1:

1) Active Power that the BESS exchanges with the grid;
2) Active power that the battery provides or absorbs by the DC/DC converter .

Measurement devices internal to ESS consists of a 12 bit converter A/D, and of a current transducer to measure buttery current and exchanged current with the grid (type LEM 100 P, measuring range 0 ±150 A, secondary nominal current 50 mA, accuracy 0,45%).

## 3. Energy analysis in stationary work conditions

### 3.1 Energy efficiency of battery pack

The first test has been performed in order to evaluated the performances of BESS in stationary working conditions. Battery efficiency was calculated as showed in (1)

$$\eta_b = \frac{E_{ch}}{E_{0,5}} * 100 \qquad (1)$$

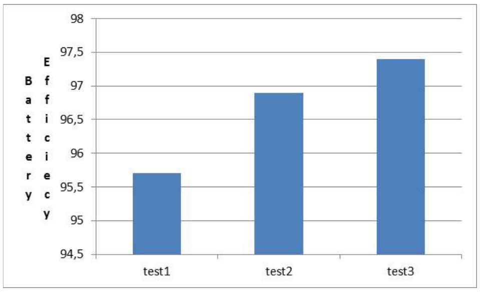
Where:

- $E_{ch}$: total energy discharged from battery from State Of Charge (SOC) 100% to SOC 20% at different battery current
- $E_{0,5}$: Total energy required to recharge the battery until original condition (SOC 100 %) from SOC 20% with a current equal to 50% of nominal current

Battery pack has been charge through Labview control system; the tests carried out start from SOC equal to 100% and 290 Volt battery voltage, discharging battery to SOC equal to 20%. Later the charging returning to original condition: SOC equal to 100% and voltage 290 V. The test results for different stationary conditions are showed in below in Table 1. The figure on the right shows how the efficiency battery is more and more efficient if the discharging power increase.

Table 1: Stationary working condition and energy efficiency of battery pack

| | battery current [A] | | battery current / nominal battery current | |
|---|---|---|---|---|
| | Dicharging | Charging | Discharging | Charging |
| test 1 | 70 | 35 | 1 | 0,5 |
| test 2 | 35 | 35 | 0,5 | 0,5 |
| test 3 | 20 | 35 | 0,30 | 0,5 |




### 3.2 Energy efficiency of power converters

The equations (2) and (3) have been used in order to evaluate power converter (inverter and buck booster) efficiency during charge ($\eta_{pc\_ch}$) and discharge phase ($\eta_{pc\_disch}$):

$$\eta_{pc\_ch} = \frac{E_{to\_batt}}{E_{f\_grid}} * 100 \qquad (2) \qquad\qquad \eta_{pc\_disch} = \frac{E_{to\_grid}}{E_{f\_batt}} * 100 \qquad (3)$$

Where: $E_{f\_grid}$ is the energy from grid and $E_{to\_batt}$ is the energy to the battery; $E_{f\_batt}$ is the energy from battery and $E_{to\_grid}$ is the energy to the grid. So the energy efficiency of power converters have been calculated for different powers during charge and discharge phases as shown in Table 2. The calculated energy from battery $E_{to\_batt}$ and energy from grid $E_{f\_batt}$ include the auxiliaries system loads reported in Table 3.

3.3 Energy consumption from battery to provide reactive power

Further, two tests have been performed in order to measure the battery energy consumption to provide only reactive power; the results of experimental tests are showed in Table 4 for one hour of working. The Table 4 shows also that when the BESS provides a positive reactive power, the thermal losses of converters and auxiliaries load are prvided by battery. So the battery energy consumption in test 1 is more than test 2.

Table 2: Power converter efficiency measured for different working point

| | SOC [FROM - TO] | | Power converter [kW] | |
|---|---|---|---|---|
| | charging | discharging | charging | discharging |
| test 1 | 82-89 | 89-75 | -3 | 3 |
| test 2 | 76-81 | 83-49 | -5 | 5 |
| test 3 | 45-82 | 75-59 | -10 | 10 |
| test 4 | 35-80 | 43-74 | -20 | 20 |

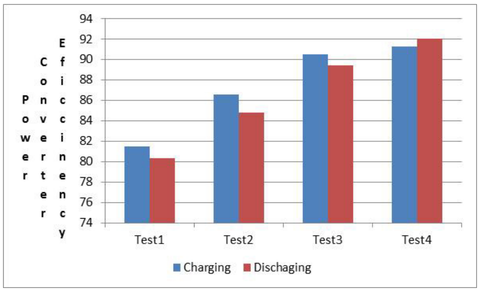



Table 3: Auxiliaries system loads for different working point

| Power to/from grid [kW] | Fan for inverter/booster cooling [W] | Fan for battery [W] | Electronic Board [W] |
|---|---|---|---|
| 5 | 192 | 105,6 | 80 |
| 10 | 192 | 177,6 | 80 |
| 20 | 192 | 182,4 | 80 |

Table 4: results of experimental tests to calculate energy consumption of ESS providing reactive power to the grid

| | Set point Reactive power for ESS | Energy from battery [kWh] | specific energy consumption [kWh/kVARh] |
|---|---|---|---|
| test 1 | 20 kVAR | 0,55 | 0,08 |
| test 2 | -20 kVAR | 0,49 | 0,03 |

## 4. Energy analysis in real work conditions

In order to calculate the total energy efficiency of ESS in real work conditions, the BESS have been tested using Labview and smart meter system in order to develop specific control system:
- Peak shaving service for electric station MV/LV
- Load shaving of a fast charging stations for Electric vehicles integrated with a photovoltaic power plant

4.1 Energy efficiency of EES for peak shaving service

In this first test the control system integrated with smart metering system has managed the BESS to apply a peak shaving service for a real MV/LV substation. This system has been shown in Fig. 1. The BESS provides the power that exceeds a fixed upper threshold (80 kW) and recharge the battery pack with 10 kW active power when the total load of MV/LV substation is less than the lower threshold (60 kW). In order to calculate battery efficiency has need to start and to finish the test at the same SOC. The data analysis of Table 5 show energy exchange between ESS and grid during peak shaving service in a day.

Table 5: Energy analisys of EES in discharge mode and charge mode working in peak schaving service I a day for MV/LV cabin.

| | | |
|---|---|---|
| Total energy discharged from battery | 21,82 | kWh |
| Total energy charged to battery | 22,08 | kWh |
| Total energy to grid | 12,62 | kWh |
| Total energy from grid | 26,44 | kWh |
| energy from battery in standby working (auxiliary suppling) | 8,74 | kWh |
| energy from grid in standby working (auxiliary suppling) | 0,43 | kWh |

The data analysis shows as the 40% of total energy delivered from battery is due to standby working to supply auxiliary only. This one causes a low power converter efficiency in discharge mode during peak shaving service as showed in Table 6.

Table 6 Efficiency analisys of ESS working in peak schaving service I a day for MV/LV cabin.

| | | |
|---|---|---|
| Battery efficiency | 98,84 | % |
| Power converter efficiency working in discharge mode | 57,82 | % |
| Power converter efficiency working in charge mode | 83,50 | % |

4.2 Energy efficiency of EES for load shaving of a fast charging stations for Electric vehicles

A wide experimental activity has been performed to test energy efficiency of BESS working in load shaving of EV fast recharge in the last year. A real implementation of EV fast charging station integrated with ESS is available at ENEA labs. The system implements the EV fast charger in reference to the International Standard IEC 61851-1 with an active power in output of 50 kW dc.

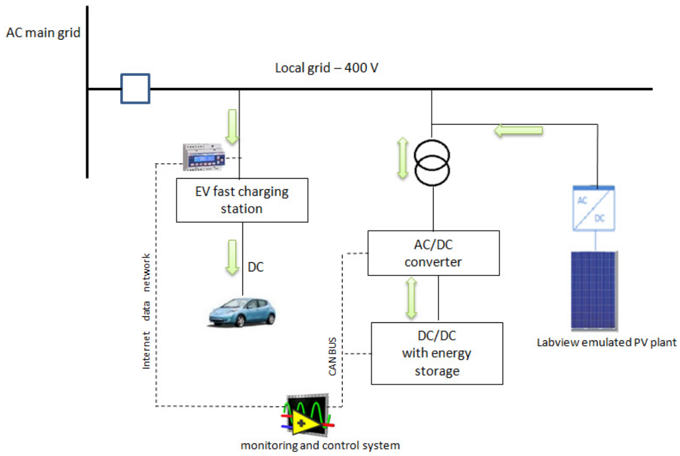



Fig. 2: Scheme for the integration of the ESS with the EV charger station and control system

The control system implemented in LabView has been used[12] to have a full integration with the EV charging station. Further the system includes a 30 kWp PV plant emulation. The photovoltaic generation has been simulated providing a real production profile and absorbing this power from the grid. The scheme for the integration of the ESS with the EV charger station system is based on Fig. 2. The system has worked for 24 hours. The energy accumulated by BESS has been used to recharge an electric vehicle (Nissan leaf) of 24 kWh. So the total efficiency of the system has been calculated. The tests carried out starting from SOC equal to 100%, discharging battery system during load shaving service to SOC equal to 20%. Further, the next charging has been provided by a real profile of a 30 kWp PV plant to reach start condition: SOC equal to 100%. The results of the tests are reported below in Table 7 and Table 8. The total efficiency in this case is 70%.

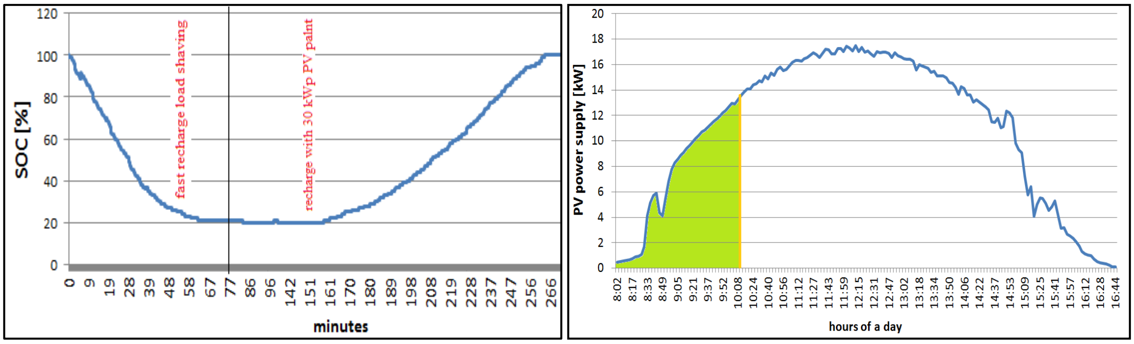



Fig. 3: on the left: Evolution of SOC of ESS during load shaving service and next recharge; on the right: energy provided by emulated PV plant in AC mode used to recharge ESS (green area)

Table 7 The energy analysis of ESS working in load shaving service and next recharge by 30 kWp PV plant

| | | |
|---|---|---|
| EV fast charger station load | 17,29 | kWh |
| Total energy to grid | 11,73 | kWh |
| Total energy discharged from battery | 13,79 | kWh |

| | | |
|---|---|---|
| PV energy production in a day | 95,55 | kWh |
| Total energy provided from PV plant to ESS | 16,55 | kWh |
| Total energy charged to battery | 14,59 | kWh |

Table 8: EES efficiency in the experimental tests: load-shaving and next recharge by 30 kWp PV plant

| Power converter efficiency working in discharge mode (including auxiliary loads) | Power converter efficiency working in charge mode (including auxiliary loads) | Battery efficiency |
|---|---|---|
| 0,85 | 0,88 | 0,94 |

## Conclusion

The results of the experimental tests show the ESS energy performance in the implementation peak shaving function for a real MV/LV substation and in the EV fast recharge station applications. The ESS is connected to the grid in peak shaving service and it works in standby mode for most of the time. The experimental test shows a low efficiency of ESS because the battery's energy supplies the auxiliary system. So about 40% of total energy discharged from battery in a day. This could be avoided disconnecting the BESS from the grid when it doesn't work. The second experimental test calculates the efficiency for a load shifting application. Indeed, the BESS is charged by the PV system in the first hours of the day. Successively, the BESS's energy is used to charge an EV vehicle. This shows a total efficiency of 70%. In this case it occurs choose a right size of PV plant.

## 5. Copyright



## References


[1] Hao Qian, Jianhui Zhang, Jih-Sheng Lai, e Wensong Yu, «A high-efficiency grid-tie battery energy storage system», *Power Electron. IEEE Trans. On*, vol. 26, n. 3, pagg. 886–896, mar. 2011.

[2] Xiangjun Li, Dong Hui, Ming Xu, Liye Wang, Guangchao Guo, e Liang Zhang, «Integration and energy management of large-scale lithium-ion battery energy storage station», *Electr. Mach. Syst. ICEMS 2012 15th Int. Conf. On*, pagg. 1–6, ott. 2012.

[3] A. Tani, M. Camara, e D. Brayima, «Energy management in the Decentralized Generation Systems based on Renewable Energy -Ultracapacitors and Battery to compensate the wind/load power fluctuations», *Ind. Appl. IEEE Trans. On*, vol. PP, n. 99, pagg. 1–1, 2014.

[4] D. E. Olivares, A. Mehrizi-Sani, A. Etemadi, C. . Canizares, R. Iravani, M. Kazerani, A. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. . Jimenez-Estevez, e N. D. Hatziargyriou, «Trends in Microgrid Control», *Smart Grid IEEE Trans. On*, vol. 5, n. 4, pagg. 1905–1919, lug. 2014.

[5] M. C. Falvo, L. Martirano, e D. Sbordone, «Sustainable Energy Microsystems for a Smart Grid», in *Neural Nets and Surroundings*, Springer, 2013, pagg. 259–269.

[6] M. C. Falvo, L. Martirano, D. Sbordone, I. Bertini, B. Di Pietra, e F. Vellucci, «A flexible Customer Power Device for energy management in a real Smart Micro-Grid», *Ind. Electron. Soc. IECON 2013 - 39th Annu. Conf. IEEE*, pagg. 7586–7591, nov. 2013.

[7] M. C. Falvo, D. Sbordone, I. S. Bayram, e M. Devetsikiotis, «EV charging stations and modes: International standards», *Power Electron. Electr. Drives Autom. Motion SPEEDAM 2014 Int. Symp. On*, pagg. 1134–1139, giu. 2014.

[8] T. H. Mehr, M. A. S. Masoum, e N. Jabalameli, «Grid-connected Lithium-ion battery energy storage system for load leveling and peak shaving», *Power Eng. Conf. AUPEC 2013 Australas. Univ.*, pagg. 1–6, set. 2013.

[9] S. V. Giannoutsos e S. N. Manias, «A cascade control scheme for a grid connected Battery Energy Storage System (BESS)», *Energy Conf. Exhib. ENERGYCON 2012 IEEE Int.*, pagg. 469–474, set. 2012.

[10] M. T. Lawder, B. Suthar, P. W. C. Northrop, S. De, C. M. Hoff, O. Leitermann, M. L. Crow, S. Santhanagopalan, e V. R. Subramanian, «Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications», *Proc. IEEE*, vol. 102, n. 6, pagg. 1014–1030, giu. 2014.

[11] Seung Tae Cha, Haoran Zhao, Qiuwei Wu, A. Saleem, e J. Ostergaard, «Coordinated control scheme of battery energy storage system (BESS) and distributed generations (DGs) for electric distribution grid operation», *IECON 2012 - 38th Annu. Conf. IEEE Ind. Electron. Soc.*, pagg. 4758–4764, ott. 2012.

[12] D. Sbordone, I. Bertini, B. Di Pietra, M. C. Falvo, A. Genovese, e L. Martirano, «EV fast charging stations and energy storage technologies: A real implementation in the smart micro grid paradigm», *Electr. Power Syst. Res.*, 2014.


**Danilo A. Sbordone** has received the Master Degrees in telecommunication engineering at University of Rome, Sapienza, in 2006. He is a Ph.D. student in electrical engineer now. He is collaborating with Enea (Italian Energy Agency) and he has been at North Carolina State University as visiting researcher to develop smart grids.