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Technico-economic assessment of a lead-acid battery bank for standalone photovoltaic power plant

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ABSTRACT

In this work, we will present and discuss the results of a long-term monitoring of a lead-acid battery bank, which is a part of a modular 7.2 kW_p standalone photovoltaic power plant. Indeed, technical parameters such as the state of charge (SOC), battery voltage/temperature, and charging/discharging currents were monitored together with power flow into and out of the battery inverter. The incremental charge/discharge efficiency between two SOCs, the duration of charge (T_c) and discharge (T_d) cycles, Coulomb efficiency and the internal resistance of the battery bank, were evaluated from the measured data. Furthermore, a statistical analysis of the SOC was performed in order to specify the delivered energy from the battery bank. This allowed the assessment and a detailed understanding of the system operating performance from a technical and economical point of view.

The average minimum and maximum SOC of the battery were found to be respectively, 34.0% and 87.45%, for the monitored period. The incremental cycle efficiency (Y_{cd}) was found to vary between 68 and 90%. A low efficiency is usually observed when either the charge or the discharge durations are small (or the corresponding currents are high). The Coulomb efficiency is marked by a quasi-constant degradation rate of 1.8% per year, and the internal resistance of the battery bank increased from 0.07 to 0.27 Ohms during the 4 year monitoring period. From the monitoring of these parameters, and by using real costs, the levelized cost of storage (LCOS) was determined for various discount and capacity degradation rates as well as battery bank replacement periods. The calculated LCOS was affected by the discount rate and the replacement period of the battery bank. Additionally, the LCOS analysis revealed that for PV standalone systems lead-acid battery is more cost effective than li-ion on the short term. The latter storage technology is expected to be cost effective for medium and long term.

1. Introduction

Renewable energy systems (RES) are good alternatives that can supply green electricity, and therefore mitigate the greenhouse gas emissions and the resulting global warming caused by the use of conventional energy sources such as natural gas, oil, and coal. In some rural areas where the extension of the utility grid is unfeasible or more expensive, it is economically and environmentally preferred to use RES based on solar, wind, or hydro sources [1]. In order to reduce the impact of the intermittence of a single renewable energy source on the reliability of the supply, it is necessary to combine two or more sources with an energy storage system such as batteries for more reliability of the supply [2].

In the last years, the solar PV and electrical energy storage (EES) technologies have undergone a considerable evolution in terms of technical and economical maturity. This evolution prompted the deployment of these technologies in standalone and grid-connected power plants. In this regards, both technical and economic analysis of hybrid systems combining PV and EES are well motivated.

In the case of standalone PV power plants, the battery bank is designed to meet the load demand in the absence of sufficient sunlight, or at night, and therefore to increase the reliability of the system. Lead-acid batteries have been widely used in RES due to their affordability and availability on the market [3]. The batteries are the only dynamic element in the entire PV system due to their ability to be recharged and discharged depending on the operating conditions, such as the meteorological conditions, and the load demand. The batteries are typically designed to operate as much as possible in high states of charge (SOC) in order to increase the battery lifetime. Such constraints need to be taken into consideration during the sizing phase of the battery bank designed to operate in a standalone PV power plant.

Several research works were dedicated to the evaluation of some

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performance parameters of standalone PV plants, such as the reference, the array, and the final yields, in the intent to assess their performance ratios [4]. Some works were carried out on lead-acid batteries regarding issues, such as the estimation of the SOC, which is an important indicator usually used in the energy management of standalone power plants [5]. This estimation has been done using different methods, such as the Coulomb counting [6], and the adaptive extended Kalman filter [7]. Other works were performed in the intent to estimate the state of health (SOH), which is an indicator of the battery lifetime [8]. Other authors focused on the technical, economic, and environmental assessment of lead-acid batteries. McKenna et al examined the addition of batteries to grid-connected domestic PV systems and the ability to be used under current feed-in tariff arrangements [9]. In this case, the results indicate that it is not economically and environmentally feasible to use lead-acid batteries. Oliveira et al studied the coupling of lead-acid batteries with photovoltaic for increased electricic self-sufficiency in households under different scenarios in Belgium [10]. Unlike in reference [9], the authors found that the most economical option for self-sufficiency values over 40%, is to couple PV with batteries, which are especially effective for small capacities, although always at a higher cost, than the use of electricity from the grid.

However, the evolution of the storage element performance and the economic assessment in standalone PV plants under specific conditions of a given site, has not received considerable attention despite being one of the critical elements in such systems. This requires a long-term onsite monitoring of battery-bank parameters under the actual operating conditions. Ma et al analyzed only one year of collected data in order to assess the energy performance of an entire PV system, including PV array, inverters, and a valve regulated lead-acid (VRLA) battery bank. The performance was evaluated in terms of daily energy balance, normalized performance parameters, and overall system energy utilization ratios. The battery bank evaluation concerns only the battery SOC hourly variations, the monthly battery SOC profile for one year, and the frequency distribution of the battery bank's SOC [11].

One of the main objectives of this work is to go even further in monitoring the operation and technically assessing the performance parameters of a flooded lead-acid battery bank, as well as their evolution with time under real conditions. Indeed, the monitoring was performed for a period of 4 years, which is close to the expected end of life of the battery bank. Other performance parameters, such as, the incremental efficiency, the Coulomb efficiency, the efficiency near top of charge and the internal resistance were closely monitored for this period under the real conditions of the site instead of accelerated test conditions that are usually reported in the literature.

In addition, since the sizing of a battery bank depends strongly on the actual and operation conditions, a statistical analysis of the SOC is required to determine its maximum and minimum values and consequently choose the suitable period of the year for a given site to be considered for an eventual resizing of the storage system. Moreover, this statistical analysis will be used to calculate the levelized cost of storage (LCOS) based on realistic capital, operation and maintenance costs, and measured amount of stored energy.

2. Location of the PV power plant

A standalone PV plant was installed to supply the Elkaria village in Essaouira (Morocco) with electricity in the framework of HYRESS project (Hybrid Renewable Energy Systems in Rural Settlements of Mediterranean Partner Countries).

As described in details in a previous work [4], the PV plant is installed in a coastal area in the middle of Morocco between the cities of Safi and Essaouira. This region is well-known for its interesting irradiance levels and an average annual wind speed between 7 and 8 m/s [12].

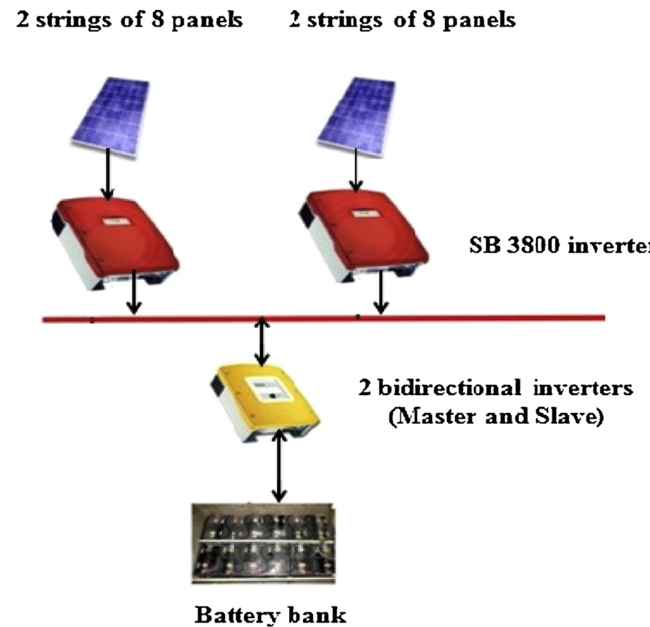

Fig. 1. Block diagram of the PV-power plant (arrows indicate the direction of energy flow).

3. The power plant configuration

The power plant configuration was described in details in a previous work [4]. Briefly, it consists of 32 (Sunpower SPR-225-WHT) panels with a nominal power of 225 W_p and an efficiency of 18.1% in standard test conditions (STC). The array was subdivided into 4 strings of 8 panels each mounted in series: each two strings are connected to a PV-inverter (Sunny Boy 3800, SMA, Germany) with a rated power of 3.8 kW. The two inverters feed the electricity to the local isolated grid than run through the village (about 2.5 km long). The grid-forming unit consists of two Sunny Island SI5040 bidirectional inverters (SMA, Germany) and a lead-acid battery bank. The rated input DC voltage of the SI5040 is 48 V while its rated power is 5 kW. The battery bank consists of a series combination of 24 batteries (Hawker Pb TYS7/2 A T 1101 Ah, 2 V) with a C100 capacity of 1100 Ah (Fig. 1). The grid control is performed by the Sunny Island battery inverter (BI) using the Droop Mode control [13,14] which also records all the operating parameters on a SD card.

A Sunny Boy control plus data logger (SMA, Germany) was used to record the metrological data, such as irradiance, wind speed, ambient and panel temperature, acquired using the Sunny Sensor box (SMA, Germany). Other relevant parameters are also recorded to provide information about the power levels, AC/DC currents and voltages, battery SOC, and the charge/discharge duration. These parameters are necessary to evaluate the efficiency of the battery bank. The data is recorded and saved on a daily basis. An inside view of the power plant is shown in Fig. 2.

4. Results and discussion

4.1. Load curve

Fig. 3 shows an average of the measured daily load profile of the village. As it can be seen in this figure, in addition to some fluctuations in the consumed power, the energy is mainly consumed at night between 18 h and 22 h. The maximum power demand is about 4 kW on the average. The silent features of the load curve are almost the same for all other days. It should be noted that the appliances of the households that are supplied by this plant include mainly light bulbs, TV with digital receivers, and in some cases refrigerators.