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Published in:
Proceedings of ELECTRIMACS 2017

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

OPTIMAL SCHEDULING OF A BATTERY-BASED ENERGY STORAGE SYSTEM FOR A MICROGRID WITH HIGH PENETRATION OF RENEWABLE SOURCES

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Abstract – A new scheduling method is proposed to manage efficiently the integration of renewable sources in microgrids (MGs) with energy storage systems (ESSs). The purpose of this work is to take into account the main stress factors influencing the ageing mechanisms of a battery energy storage system (BESS) in order to make an optimal dispatch of resources in the microgrid and enhance the storage system lifetime while minimizing the cost of electric consumption. The load demand and generation profiles are derived from the analysis of consumption and renewable production (solar photovoltaic sources and wind turbines) of the Western Denmark electric grid. Thus, the proposed microgrid is mainly fed by renewable sources and few electricity is coming from the main grid (which helps operating costs minimization). In this respect, a cost analysis is performed to find the optimal hourly power output of the BESS as well as the purchased electricity from the utility.

Keywords – Battery Management System (BMS), Energy Storage System (ESS), Microgrid (MG), Optimal scheduling, Wind and solar photovoltaic sources.

1. INTRODUCTION

In recent years, many efforts have been spent on tackling the challenge of climate change and sustainable access to energy. To this end, a new renewable decentralized energy production structure has emerged: the microgrid (MG) [1]. A MG is a small-scale system (e.g., aggregation of a few houses, a university, a military base, a commercial area, etc.) operating in a local area. The energy production mainly comes from renewable sources to meet the local energy needs and the remaining demand is fulfilled by the main grid. This system offers many advantages, such as energy transmission losses reduction, remote areas electrification, reliability improvement, easier integration of renewable sources and much more.

However, due to the intermittent nature of renewable sources and presence of uncertainties (e.g., renewable power generation, load demand, cost of electricity, cost of storage systems, etc.), the integration of energy storage systems (ESSs) in renewable MGs is a widespread practice. Batteries are often preferred to other ESSs in microgrid projects because of their relatively lower price, easy integration, good performances and level of maturity [2]-[3]. In order to deal with the uncertainties of the MG, stochastic programming is often used for modelling, planning and control [4]-[6]. Several stochastic optimization tools for microgrid planning are presented in [4]. In [5] a stochastic scheduling is performed on a IEEE 33-bus system (including electric vehicles, wind turbines, decentralized generators and storage systems). In addition, [6] proposes a robust and distributed energy scheduler with wind farms, storage systems and different loads (some of them are fully controllable and can be time-shifted).

Recent papers propose to optimize the operating conditions of batteries in MGs to enable longer lifetime and to minimize the cost of operation [7]-[10]. In this context, this paper aims at gathering some guidelines for improving the lifetime of batteries in order to reduce the cost of the battery energy storage system (BESS) on the long run. The presented methodology defines the optimal power level for the BESS and for the grid (purchased electricity) on an hourly basis, in a way to satisfy the load demand and to minimize the cost of electricity and the BESS cost (along its lifetime).

The renewable generation and load demand profiles of the MG are derived from the analysis of West Denmark electric market grid data [11].

The remainder of the paper is organized as follows: first, the formulation of the MG model (mainly focused on defining proper BESS operating conditions) and the mission profiles (load demand and renewable production) are presented. Then, the minimization problem is explained. Finally, the results of the proposed methodology are discussed.

NOMENCLATURE

Parameters

A, B, C	BESS parameters of the lifetime model
Cap_{nom}	Nominal capacity of the BESS
$C_{grid}(t)$	Cost of electricity from the main grid
$C_{1kWh}(t)$	Cost of 1kWh of BESS
$C_{rateCh}, C_{rateDis}$	BESS maximum current-rate at the charge and discharge
Δt	Time interval (1-hour)
η_{Ch} , η_{Dis}	Charge and discharge energy efficiency of the BESS
SOC_{ini}, SOC_{end}	Initial/Final daily state of charge (SOC)
SOC_{min}, SOC_{max}	Minimum/Maximum daily SOC
i	Interest rate of the project
$P_{Balance}(t)$	Power balance between production of renewables and consumption
$P_{gridMin}$, $P_{gridMax}$	Maximum power that can be sold/purchased from the utility

Variables

C_{Total}	Total cost (according to energy consumption and BESS costs)
C_{Elec}	Annual cost of electric consumption from the utility
C_{BESS}	Annual cost of the BESS
CRF	Capital recovery factor
ΔDOD	BESS delta depth of discharge – Cycle depth (per day)
$P_{grid}(t)$	Power exchanged with the utility
$P_{storage}(t)$	Output power of the BESS
SOC(t)	State of charge of the BESS
n	Lifetime of the BESS (years)

2. ENERGY MANAGEMENT FORMULATION

2.1. MICROGRID PRESENTATION

In this paper, the MG operator is responsible for the BESS management and scheduling of the energy exchanges with the utility in order to satisfy the stability of the MG and to minimize the overall costs. The examined MG architecture as well as the power flows are described in fig. 1.

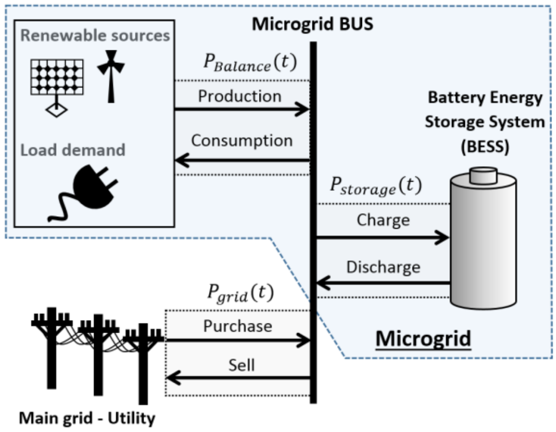

Fig. 1. Typical architecture of a MG.

In order to ensure the MG stability, the following equation must be satisfied at any time:

$$P_{Balance}(t) + P_{storage}(t) + P_{grid}(t) = 0 \qquad (1)$$

where $P_{Balance}(t)$ is the power balance between renewable production and load demand (2), $P_{storage}(t)$ is the power absorbed or delivered by the BESS (3) and $P_{grid}(t)$ is the power exchanged with the main utility grid. Any injected power to the bus is positive whereas the power taken out of the bus is treated as a negative value.

$$P_{Balance}(t) = P_{Prod}(t) - P_{Cons}(t) \qquad (2)$$

$$P_{storage}(t) = P_{Dis}(t) - P_{Ch}(t) \qquad (3)$$

$$P_{grid}(t) = P_{purchase}(t) - P_{sell}(t) \qquad (4)$$

where P_{Prod}, P_{Cons}, $P_{ch}(t)$, $P_{dis}(t)$, $P_{purchase}(t)$ and $P_{sell}(t)$ are the renewable production and consumption of the MG, the charging and discharging power of the BESS, the power purchased and sold to the utility, respectively. All these variables are positive.

2.2. STUDY CASE – DANISH ELECTRICITY PROFILE

In this study, the last three years of the Western Denmark electric grid data [11] have been used to define the load and renewable production profiles presented in fig. 2. Two different profiles of $P_{Balance}(t)$ (mean and median profiles of the data set) have been obtained by taking into account the whole generation of wind turbines and photovoltaic panels and half of the energy gross consumption of West Denmark (in order to get a daily profile that is producing more energy than consuming (mean profile), and conversely (median profile)).

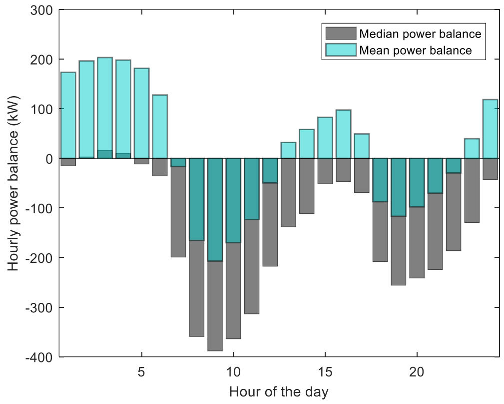

Fig. 2. Hourly median and mean $P_{Balance}(t)$ obtained from the considered West Denmark data.

In the same way, the hourly price of electricity evolution from the Nord Pool Elbas intraday market is presented in fig. 3. In this study, the mean value over the three last years (circle markers in fig. 3), $C_{grid}(t)$, has been chosen as the hourly price of electricity from the main grid.

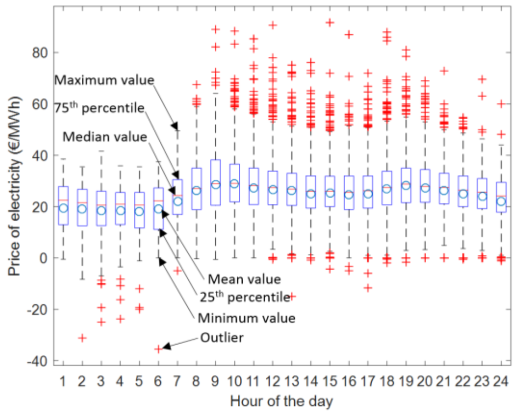

Fig. 3. West Danish hourly price of electricity [11].

2.3. Energy storage system model

Worldwide, several technologies of ESSs are available, such as pumped hydroelectric storage, fuel cells, flywheels, compressed air energy storage [3]. In our context, electrochemical storage (more precisely lithium batteries) is the most appropriate way to store energy. The following section describes how to model a BESS based on [5], [12]-[15]. First, the definition of the state of charge (SOC) is given in (5). As explained in a previous work [12], a round trip energy efficiency of 92% is considered for lithium batteries ($\eta_{Ch} = 0.92$ and $\eta_{Dis} = 1$). The BESS SOC have to be limited as described in (6) and (7). It has been shown in [15] that a mid-range SOC level and a low cycle depth are guaranteeing the highest lifetime of lithium batteries (so it has been chosen to use the following values $SOC_{ini} = 50\%$, $SOC_{min} = 35\%$, $SOC_{max} = 65\%$).

$$SOC(t) = SOC(t-1) + \eta_{Ch}\frac{P_{Ch}(t)\cdot\Delta t}{Cap_{nom}} - \frac{P_{Dis}(t)\cdot\Delta t}{\eta_{Dis}\cdot Cap_{nom}} \quad (5)$$

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (6)$$

$$SOC_{ini} = SOC_{end} \quad (7)$$

As advised by manufacturers, the charge and discharge current-rates (expressed in [h^{-1}]) have to be limited for lifetime and energy efficiency reasons. Moreover, the most efficient BESS charging method is a constant current charge followed by a constant voltage charge (often referred “CC-CV charge”). It implies a power capability limitation of the BESS when a high SOC level is reached (typically around 80% for lithium batteries). (8) and (9) ensure the power capability limitations of the BESS during charge and discharge.

$$0 \le P_{dis}(t) \le C_{rateDis}\ Cap_{nom} \quad (8)$$

$$\begin{cases} 0 \le P_{ch}(t) \le C_{rateCh}\ Cap_{nom} \\ 0 \le P_{ch}(t) \le C_{rateCh}\ Cap_{nom}\ \Delta t\ D_1\ e^{(D_2\,SOC)} \end{cases} \quad (9)$$

Indeed, when the BESS reaches SOC_{CV} the power that can be absorbed is limited by a decreasing exponential law [8], [13], as described in fig. 4 (D_1 and D_2 are obtained by curve fitting of data from manufacturers).

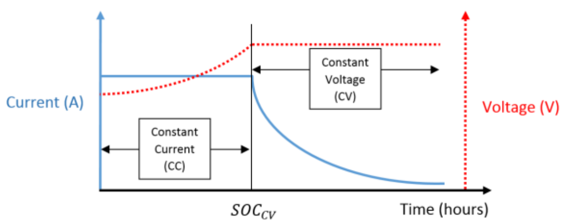

Fig. 4. CC-CV charging method of the BESS.

The lifetime of the BESS is quantified by a capacity and power capability fade. It is commonly accepted that a battery is considered at its end of life when its nominal capacity reaches 80% of its initial capacity. The lifetime of a BESS relies on two mechanisms, calendar and cycle ageing [13]-[15]. According to [14] and [15], cycle lifetime is always lower than calendar lifetime (shelf life). Considering that the temperature of the BESS room will be regulated, the cycle depth and the SOC-level are the two main stress factors influencing the cycling lifetime.

Performing low cycle depths will enhance the BESS number of cycles [13]-[15], as depicted in fig. 5.

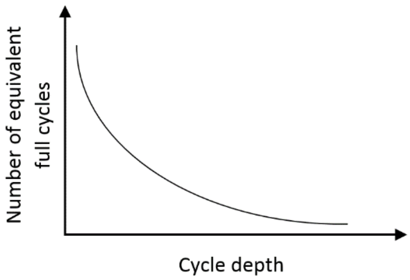

Fig. 5. Number of equivalent full cycles vs. cycle depth of the BESS.

The degradation of the battery can be sensed with the rainflow counting method by following the SOC level and counting the number of cycles with their respective cycle depth, as described in [16]. In order to limit the number of equations while keeping a good level of accuracy, it has been chosen to model the lifetime of the battery with the Ah-throughput method described in [17].

In this study, the cycle depth (difference between the maximum and minimum SOC performed in a cycle) has been fixed to 30% as in [12]. The maximum energy that the BESS can exchange is:

$$E_{ExchMax} = A\, e^{-100.B.\Delta DOD + C} \times Cap_{nom} \times \Delta DOD \qquad (10)$$

where A, B and C are constants obtained by curve fitting of experimental lifetime data from [15] (A=1.057e4, B=0.05459, C=455 with R^2=0.9729 and RMSE=689.1).

The exchanged energy per day is calculated as follows:

$$E_{ExchDay} = \sum_t \left(P_{Dis}(t) + P_{Ch}(t)\right) \times \Delta t \qquad (11)$$

Finally, BESS lifetime (in years) is given by:

$$n = \frac{E_{ExchMax}}{365.25\, E_{ExchDay}} \qquad (12)$$

2.4. Optimization problem

In this study, the objective function (13) is a trade-off between the need to use intensively the BESS to decrease the annual cost of the electricity (14) and the need to improve the BESS lifetime (i.e. to reduce its annual cost) (15).

$$\text{Min}\ \{C_{Total} = C_{Elec} + C_{BESS}\} \qquad (13)$$

$$C_{Elec} = 365.25 \sum C_{grid}(t) \times P_{purchase}(t) \times \Delta t \qquad (14)$$

$$C_{BESS} = C_{1kWh} \times Cap_{nom} \times \text{CRF} \qquad (15)$$

A cost of 350€/kWh has been considered for lithium batteries [18]. The capital recovery factor, CRF, converts the initial investment into annual equally separate payments over a given period:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (16)$$

where i is the interest rate (7.7% for this type of project [12]) and n is the BESS lifetime in years.

A last constraint concerning the main grid utilization should be considered as follows:

$$P_{gridMin} \leq P_{grid}(t) \leq P_{gridMax} \qquad (17)$$

3. Results

The proposed non-linear optimization problem based on equations (1)-(17) has been solved with the General Algebraic Modeling System (GAMS) software. For this simulation, a 1.5MWh BESS has been used and the maximum power that can be exchanged with the utility has been fixed to 200 kW.

The results of the scheduling method are presented in fig. 6. Due to the power exchanges limitations with the main grid that have been set, the BESS enables to reduce peak demand from 8:00 to 12:00 and from 19:00 to 22:00 for the median profile (fig 6-A). It can be also noticed that due to the price of electricity (fig. 3), the BESS is charging most of all when the tariffs are relatively low. As expected, the BESS satisfies the constraints of SOC, cycle depth and C-rate. Regarding the profile described in fig 6-B, the minimization of the BESS annual cost implies to minimize the energy exchanges between the MG and the BESS.

For both profiles, the annual cost of electricity is by far lower than the annual cost of the BESS. This is mainly due to the capacity and the cycle depth chosen in this example, based on a previous work on optimal sizing of a lithium battery pack [12]. Obviously, when the capacity of the BESS and the maximum daily cycle depth are changing, the optimal charge/discharge profile will be modified. This highlights the necessity to analyze together the sizing and scheduling problems in order to get the best from the BESS. Indeed, in this case, it seems that the actual sizing does not lead to the best scheduling that can be achieved.

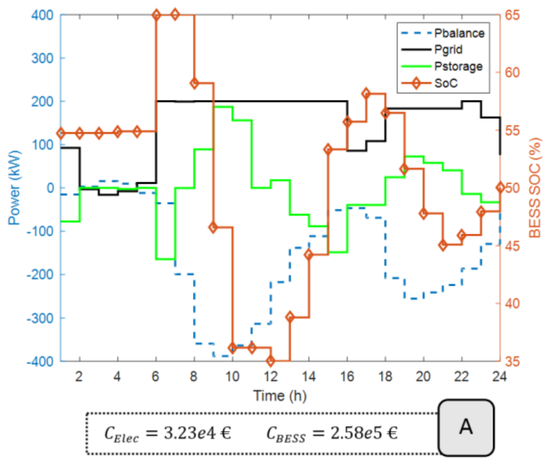

Fig. 6. MG scheduling for a 1.5 MWh BESS A) Median profile, B) Mean profile.

4. Conclusion

A methodology for optimal scheduling of a microgrid (MG) supplemented by a battery energy storage system (BESS) was described. The BESS behaviour and lifetime models have been discussed and implemented in order to minimize the annual cost of electricity and the annual cost of the BESS considering operating limitations (e.g. cycle depth, SOC level, C-rate, etc.).

However, it has been seen that the annual cost of the BESS is far more expensive than the annual cost of electricity. This is mainly due to the fact that the sizing of the BESS can be improved by changing the nominal capacity and maximum daily cycle depth. Further research will be conducted in this field order to reduce the cost of stored electricity. Furthermore, the BESS is a valuable resource that enables, among other things, the flattening of peak demand which may help to reduce significant costs in infrastructures, environmental impact and risks of outages.

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