

Energy Management System for DC Microgrids Considering Battery Degradation

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Abstract—DC microgrids require sources that maintain dc microgrid voltages, with Battery Energy Storage Systems (BESSs) being a good option for this task, given their multiple control alternatives. However, BESS cycling is an issue, and thus, this paper proposes an Energy Management System (EMS) for dc microgrids that considers battery degradation. Therefore, an EMS model is proposed and discussed, demonstrating its application for a practical dc microgrid of a building in Xiamen University. The simulation results show that the proposed EMS, which accounts for BES degradation costs, is an effective tool that avoids frequent battery charging and discharging, while maintaining the required dc bus voltage.

Index Terms—Battery Energy Storage System (BESS), battery degradation, dc microgrid, Energy Management System (EMS).

I. INTRODUCTION

DC microgrids are being considered as an efficient structure for the integration of Renewable Energy Sources (RES), such as solar and wind power, providing more adequate and simpler system controllability than conventional ac microgrids [1]. Thus, dc microgrids do not need to deal with frequency issues, and, although voltage control is required, reactive power management is not necessary. In terms of Energy Management Systems (EMSs), dc microgrids are simpler than ac systems, since there is no need to deal with the reactive power nonlinearities. Furthermore, ac microgrids are three-phase power systems, leading to complex and computationally expensive EMS problems based on linear and nonlinear programming models [2], which is not necessary in dc microgrids, as these are simple two-wire systems.

EMSs are part of the top control levels from a hierarchical control perspective in dc microgrids [3], [4]. A typical dc microgrid and its control scheme is shown in Fig. 1, where the interactions of the generating sources are coordinated by a central controller (CC). Previous research works have focused on the primary and secondary control levels of dc microgrids, as for example in the case of droop controls [5]. On the other hand, various EMS papers have mainly focused on energy regulation at lower control levels. Thus, for example, in [6], dc

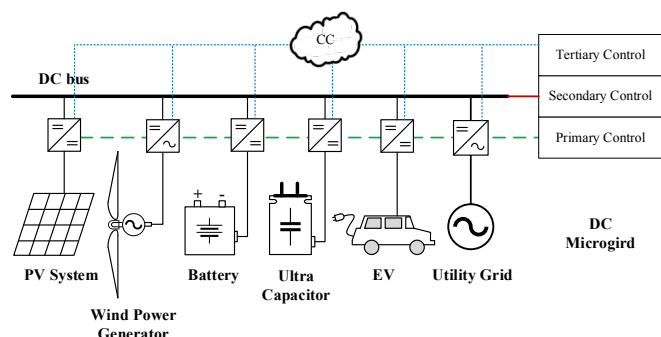


Fig. 1. Typical DC microgrid and its hierarchical control framework.

bus voltage levels are used to indicate the system state, so that energy storage can be regulated through the dc bus, focusing on system dynamic techniques as opposed to optimization approaches for optimal system operation. A rule-based EMS is proposed in [7] for dc microgrid operation, as opposed to applying optimization-based techniques for energy management. To the best of the authors' knowledge, there are not many papers on dc microgrid EMS based on optimization techniques similar to those that have been proposed for ac microgrids.

DC microgrids require a generating source to maintain the microgrid bus voltage. Usually, grid-connected bidirectional converters are used for these purposes, since the utility grid has sufficient power to adjust to the dynamic power changes of the microgrid. However, when the microgrid is operated in islanded mode, a local generating source must maintain the system dc bus voltage, using typically Battery Energy Storage Systems (BESSs) for these purposes, given their bidirectional power flow capability, and their ability to regulate voltage through interface converters. In fact, the need for a seamless switch for on-grid and off-grid operating modes can be avoided by using BESS to regulate bus voltages in dc microgrids directly [8]. However, BESSs have limited energy capacity and are affected by their Depth of Discharge (DoD), which determines the number of cycles that the battery can withstand before failure

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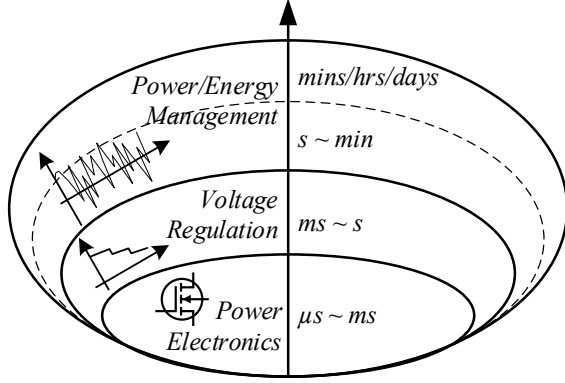


Fig. 2. Hierarchical control scheme of a dc microgrid.

[9]. Therefore, to increase a BESS lifespan, frequent charging and discharging needs to be avoided by maintaining the battery's State of Charge (SoC) at certain healthy levels, thus minimizing battery degradation.

There are several research works considering battery degradation costs in ac microgrid EMS. Thus, for example, a cooperative distributed energy scheduling algorithm is proposed in [9], studying the impact of DoD on battery lifespan. In [10], the authors present an EMS based on a stochastic dual dynamic programming model that considers battery degradation costs for optimal microgrids operation. The authors in [11], study battery degradation costs compared with utility electricity costs in ac microgrid operation. These and other papers focus on battery degradation in the context of ac microgrid EMS; however, the relevance of battery degradation in dc microgrid EMS has not yet been considered, to the authors' best knowledge.

Based on the aforementioned shortcomings in the existing technical literature, the current paper focuses on an EMS design for dc microgrids. The battery storage is used to maintain the dc bus voltage in the microgrid, and a battery degradation model is integrated into an EMS system model, proposing a degradation cost model for the EMS objective function. The proposed EMS model is simulated on a model of an existing grid-connected dc microgrid of a building in Xiamen University. Hence, the main contributions of this paper are the proposed function to represent battery degradation costs in dc microgrids, and an EMS model for optimal operation of BESS-based dc microgrids.

The rest of this paper is organized as follows: Section II reviews the basic control approach for dc microgrids, discussing the possible working modes of these microgrids. Section III describes the proposed EMS and battery degradation models, and a realistic case study and associated simulation results to demonstrate of the application of the proposed EMS are presented and explained in Section IV. Finally, relevant concluding remarks are provided in Section V.

II. BACKGROUNDS

A. EMS Overview of DC Microgrids

The hierarchical control scheme shown in Fig. 2 is normally applied in dc microgrids [3]. Primary controls deal with the

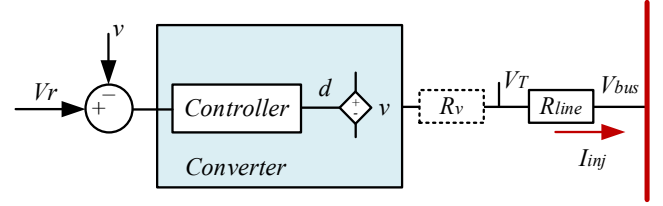


Fig. 3. An equivalent model of interface converter based renewable energy sources.

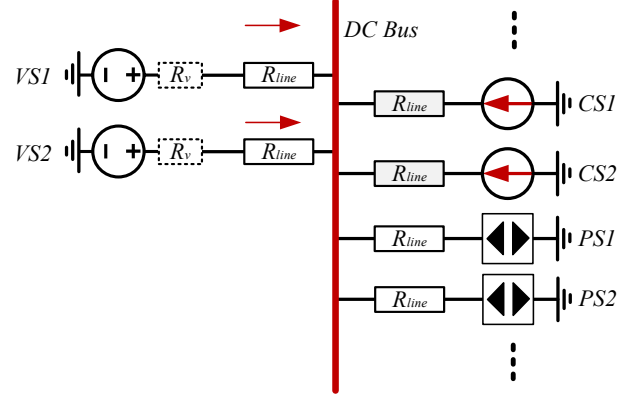


Fig. 4. Simplified model of renewable energy sources in a dc microgrid.

direct control of power electronic devices, and secondary controls are associated with dc bus voltage regulation, typically through droop controls. An EMS would be normally part of a tertiary control level, with either centralized or distributed control approaches, in a time scale of seconds to days. In this context, the EMS aims to schedule dispatchable microgrid generation in the most efficient manner to, for example, minimize running costs and power losses.

B. DC Microgrids Operation

In dc microgrids, there must be at least one dc voltage source to regulate the bus voltage [8], with the configuration of a microgrid determining how power is dispatched. For instance, if grid interface converters are used to maintain the bus voltage, the grid would take care of any power shortage or surplus from the microgrid. However, when the system is operated in islanded mode, other converters must be assigned to maintain dc bus voltage. In most cases, BESSs are used for these purposes in isolated mode, given its bidirectional power flow capabilities. For grid-connected systems, if a BESS is tasked with constantly maintaining the microgrid dc bus voltage, a seamless switch is not required for proper system operation.

An equivalent control model of a generating source in a dc microgrid is illustrated in Fig. 3, where V_r is the controller reference voltage; V_T is the converter terminal voltage before considering the line resistance; V_{bus} is the bus voltage; I_{inj} is the current injected to the common dc bus from the distributed energy sources; R_v is the virtual resistance; and R_{line} is the line resistance. A simplified model of a dc microgrid is shown in Fig. 4, which illustrates various sources usually encountered in dc microgrids, i.e., voltage sources, current sources, and power sources. If the line resistances are not considered in this dc system, then current sources are equivalent to power sources in terms of energy calculations. For voltage sources, if there is

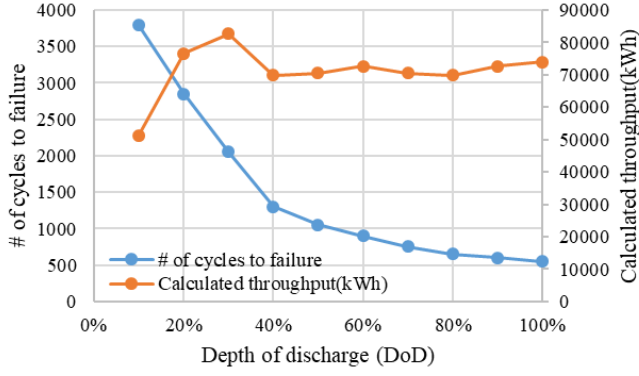


Fig. 5. Cycles to failure and total throughput for a lead-acid battery.

only one in the system, droop control is not required; however, if there is more than one, droop control is needed due to large circulating currents, because the output impedance at low frequencies tends to zero in tightly regulated dc-dc converters. On the other hand, if the line resistances are considered, the power injected from current and power sources is not the same, since for the power source, some of the power is consumed in the line resistance, increasing the terminal voltage. Without droop control for these sources, the system will lack controllability, since the line resistance is non-controllable, as opposed to the converter virtual resistance. For microgrid EMS, line resistances may be neglected, given the small impact that the grid has in a microgrid for dispatch purposes, due to the relatively short length and high amperage of wires, as demonstrated for ac microgrids in [2].

III. EMS MODELS

A. Battery Models

For BESS, the charging/discharging effect on SoC can be represented by the following constraint [12]:

$$SoC_{bat,t} = SoC_{bat,t-1} + \left(\eta_c P_{bat,t-1}^c - \frac{P_{bat,t-1}^{dc}}{\eta_d} \right) \Delta t \quad (1)$$

$$SoC_{bat,min} \leq SoC_{bat,t} \leq SoC_{bat,max} \quad (2)$$

where $SoC_{bat,t}$ is the battery SoC at time t ; η_c is the charging efficiency; η_d is the discharging efficiency; $P_{bat,t-1}^c$ is the charged power at time $t-1$; $P_{bat,t-1}^{dc}$ is the discharged power at time $t-1$; and Δt is the time step. The BESS minimum and maximum charging and discharging power constraints at time t can be written as:

$$P_{bat,min}^c \leq P_{bat,t}^c \leq P_{bat,max}^c \quad (3)$$

$$P_{bat,min}^{dc} \leq P_{bat,t}^{dc} \leq P_{bat,max}^{dc} \quad (4)$$

Based on the battery degradation model in [9], the degradation cost in \$/kWh can be represented as follows:

$$\varphi = \frac{C_{rp}}{E_{lc}} = \frac{C_{bu} \cdot E_b}{2 \cdot \mathcal{L}_b(DoD) \cdot E_b \cdot DoD} = \frac{C_{bu}}{2 \cdot \mathcal{L}_b(DoD) \cdot DoD} \quad (5)$$

where C_{rp} is the battery's total replacement (capital) cost (assumed here to be 200 \$/kWh [13]); E_{lc} is the total energy throughput in a lifecycle; E_b is installed battery power; $\mathcal{L}_b(DoD)$ is a mapping function of battery lifecycles to DoD ; and C_{bu} is the battery unit cost in \$/kWh.

The $\mathcal{L}_b(DoD)$ for a lead-acid battery in this paper is shown in Fig. 5. Note that large DoD s reduce the cycles to failure, which indicates that over-discharging will reduce the battery lifespan, even though the total throughput would not change. The total battery degradation cost can then be written as:

$$\begin{aligned} C_{dg} &= \sum_{\Delta t} \varphi \cdot (P_{bat,t}^{dc} + P_{bat,t}^c) \Delta t \\ &= \sum_{\Delta t} \frac{C_{bu}}{2 \cdot \mathcal{L}_b(DoD) \cdot DoD} (P_{bat,t}^{dc} + P_{bat,t}^c) \Delta t \end{aligned} \quad (6)$$

Observe that to reduce degradation costs, the BESS power usage, i.e., charging and discharging, should be reduced. This limits the BESS contributions to the grid.

B. Operational Constraints

The battery storage and grid interconnection are both bidirectional but cannot both charge and discharge at the same time. Thus, the following constraints reflect this constraint:

$$P_{g,t}^{dc} \cdot P_{g,t}^c = 0 \quad (7)$$

$$P_{bat,t}^{dc} \cdot P_{bat,t}^c = 0 \quad (8)$$

In dc microgrids, there is no reactive power, and the power injected to the grid should be balanced with the power demand. This power balance constraint can be written as:

$$P_{bat,t}^{dc} + P_{g,t}^{dc} + P_{PV,t} = P_{EV,t} + P_{AC,t} + P_{LED,t} + P_{bat,t}^c + P_{g,t}^c \quad (9)$$

where $P_{EV,t}$ is electrical vehicle power; $P_{LED,t}$ is LED light power.

C. Objective Function

For a grid-connect dc microgrid, the following multi-objective function can be defined:

$$C_t = \min \sum_{\Delta t} [\alpha \cdot \xi_{g,t}^{dc} P_{g,t}^{dc} + (1 - \alpha) \cdot \varphi (P_{bat,t}^{dc} + P_{bat,t}^c)] \Delta t \quad (10)$$

where $\xi_{g,t}^{dc}$ is the local electricity price; α represents a weighting factor, assuming that the battery degradation and grid electricity costs are complementary. This factor can be seen as a competition index of the power throughput between battery storage and utility grid, and thus can be manually adjusted to define the BESS contributions to the dc microgrid.

IV. CASE STUDY

A. Formulation of the DC System

The test dc microgrid used here is based on the dc building at Xiamen University [14], which can be represented as in Fig. 6. This system consists of a set of 150kW PV panels; a 200Ah, 336V lead-acid battery bank, with its parameters depicted in Table I; and a 160kW bidirectional ac-dc converter for grid

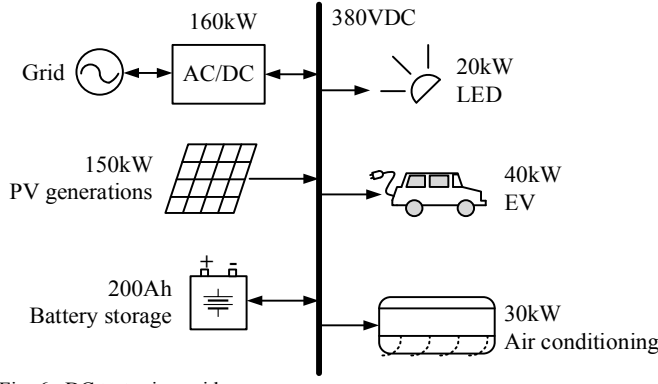


Fig. 6. DC test microgrid.

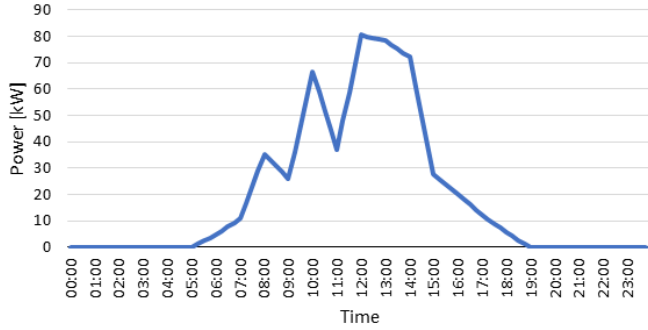


Fig. 7. PV solar generation profile (summer).

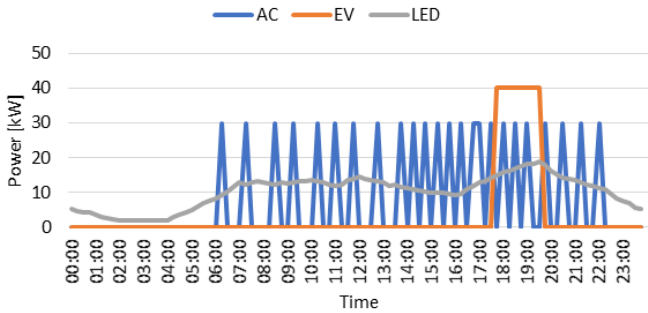


Fig. 8. Daily load profiles.

TABLE I.
BESS PARAMETERS

Parameter	Value
$SoC_{initial}$	80%
DoD	60%
$SoC_{bat,min}$	$1 - DoD$
$SoC_{bat,max}$	95%
$P_{bat,max}^{dc}$	67.2kW
$P_{bat,min}^{dc}$	0
$P_{bat,max}^c$	67.2kW
$P_{bat,min}^c$	0
η_c	95%
η_d	90%

connection. On the load side, there are 20kW of LED lights, a 40kW Electrical Vehicle (EV) charging station, and a 30kW Air Conditioning (AC) system. In this system, the battery storage is used to maintain the bus voltage, and line resistances are neglected given the small-scale dc grid, as previously argued.

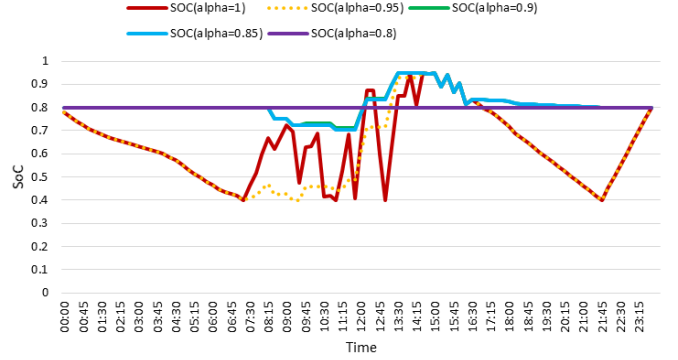


Fig. 9. SoC for different values of α .

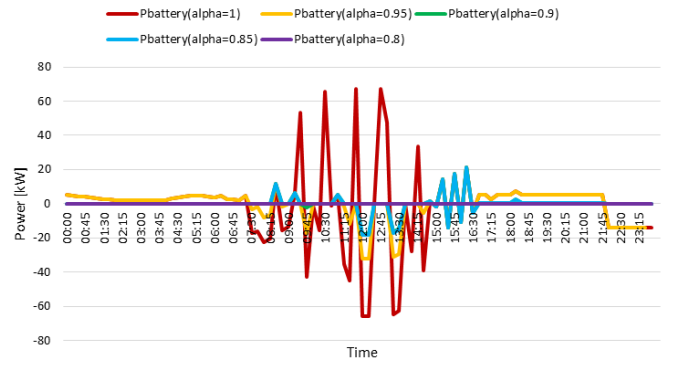


Fig. 10. BESS power for different values of α .

The PV generation profile is shown in Fig. 7 [15], and the load profile is illustrated in Fig. 8. The load profiles are depicted in Fig. 8, where the LED load was extracted from [16], the EV charging is assumed to take place during off-work hours, and the air conditioning is an intermittent load operating mostly during work hours. The local daytime electricity price is 0.077\$/kWh from 8am to 10pm, while for the remaining time is 0.044\$/kWh. The dispatch time interval is assumed to be 15 minutes.

B. Simulation Results

Applying the optimization model described in Section III, the resulting BESS SoC and power consumption are depicted in Fig. 9 and Fig. 10 for different values of α . Observe that when the degradation cost component increases as α decreases, the BESS SoC flattens out, while the charging and discharging power tends to be zero, as expected.

Two representative optimal dispatch solutions are shown in Fig. 11 and Fig. 12. In Fig. 11, note that some of the excess PV power is used to charge the BESS. However, when α decreases, i.e., as the battery degradation cost share increases, this is not the case, resulting in a reduced use of the battery in the dc microgrid, and thus a longer lifespan.

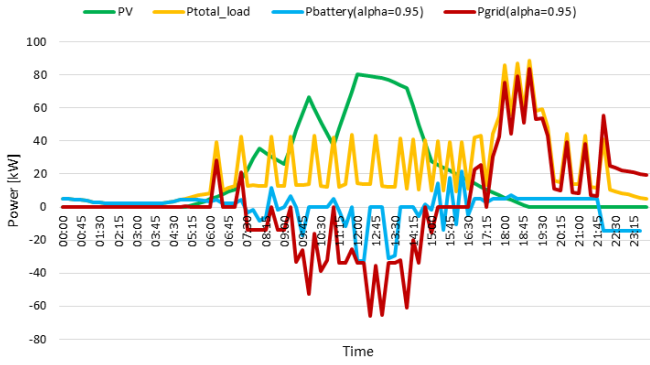


Fig. 11. Optimal model dispatch for $\alpha = 0.95$.

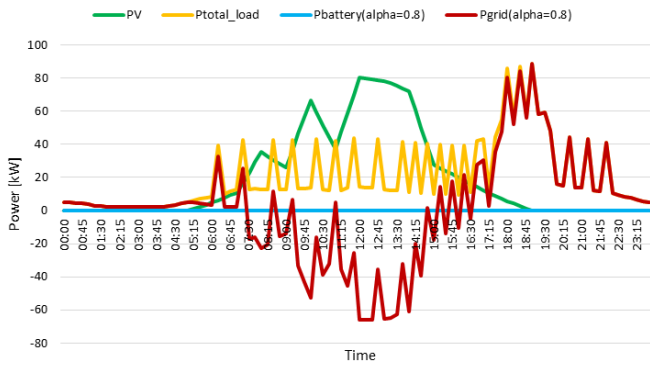


Fig. 12. Optimal model dispatch for $\alpha = 0.8$.

V. CONCLUSIONS

An EMS model for dc microgrids was proposed in this paper, considering basic control strategies in these types of systems, as well as battery degradation, which reduces the battery storage participation in dc microgrids to increase its the lifespan. The effectiveness of the proposed EMS was demonstrated through simulation results on a practical dc building in Xiamen University, where battery storage maintenance is an issue. The air conditioning and EV loads were modeled as non-dispatchable; however, in future EMS model enhancements, these should be considered as controllable loads.

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