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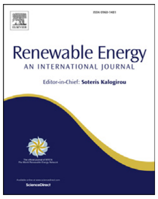

A linear programming approach for battery degradation analysis and optimization in offgrid power systems with solar energy integration

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ABSTRACT

Storage technologies and storage integration are currently key topics of research in energy systems, due to the resulting possibilities for reducing the costs of renewables integration. Off-grid power systems in particular have received wide attention around the world, as they allow electricity access in remote rural areas at lower costs than grid extension. They are usually integrated with storage units, especially batteries. A key issue in cost effectiveness of such systems is battery degradation as the battery is charged and discharged.

We present linear programming models for the optimal management of off-grid systems. The main contribution of this study is developing a methodology to include battery degradation processes inside the optimization models, through the definition of battery degradation costs. As there are very limited data that can be used to relate the battery usage with degradation issues, we propose sensitivity analyses to investigate how degradation costs and different operational patterns relate each others. The objective is to show the combinations of battery costs and performance that makes the system more economic.

1. Introduction

Storage technologies and storage integration are currently key issues in energy systems research, particularly due to the need to integrate high renewable energy capacities. Diagrams presented in Ref. [1] show the increasing penetration of renewable sources both in industrialized and developing countries between 1980 and 2010. The International Renewable Energy Agency IRENA discusses different technologies of battery storage for renewables in the report [2], where four main application areas are identified: islanded systems with off-grid rural electrification; households with solar photovoltaic; demand shifting; short-term electricity balancing in ancillary markets.

Off-grid power systems in particular have received wide attention around the world as further analyzed in Ref. [3]. They can bring electricity to remote rural areas at lower costs than grid extension. As described in Ref. [4] they are typically based on one or more renewable energy sources (e.g. solar photovoltaic or wind) together with a conventional power generator to provide backup when necessary.

Storage units, such as batteries, can be integrated in offgrid systems as they represent an alternative capacity source to the conventional generator which has high operational costs due to fuel consumption in addition to CO2 emissions [5]. Especially in offgrid applications like the one presented in Ref. [6], batteries perform several important tasks such as reducing intermittence of the renewable resources, extending the electrical service hours to night time periods, and allowing the system to run for extended periods without any power generation.

Optimization techniques and technical economic analyses has been widely used in literature in order to investigate smart operational management approaches both in distributed energy systems and islanded systems. Examples can be found in Ref. [7] where linear programming is used for distributed energy system operational optimization, and in Ref. [8] where comparisons between

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Nomenclature

Variables

x^t_{ij}	energy flow from the renewable source i to the storage unit j in time t
x^t_{iv}	energy flow from the renewable source i to the inverter v in time t
x^t_{jv}	energy flow from the storage unit j to the inverter v in time t
x^t_{vd}	energy flow from the inverter v to the final users d in time t
x^t_{rj}	energy flow from the rectifier r to the storage unit j in time t
x^t_{pd}	energy flow from the conventional generator p to the final users d in time t
x^t_{pr}	energy flow from the conventional generator p to the rectifier r in time t
Q^t_j	battery energy content in time t
$Q1^t$	available energy in the battery in time t
Qm^g	battery lowest state of charge in every day
Qp^g	battery highest state of charge in every day
Q^t_{end}	battery energy content at the end of a discharge sequence
Q^t_{start}	battery energy content at the beginning of a discharge sequence
θ^t	binary variable equal to 1 if the battery is charging
θ^t_{down}	binary variable equal to 1 if a charging sequence is starting
θ^t_{up}	binary variable equal to 1 if a charging sequence is interrupting
$\theta^t_{up,max}$	binary variable equal to 1 if a charging sequence is interrupting on a fully charged level
β^t	binary variable equal to 1 if the battery is discharging
β^t_{down}	binary variable equal to 1 if a discharging sequence is interrupting
β^t_{up}	binary variable equal to 1 if a discharging sequence is starting

Parameters

B	actual battery degradation cost ($/kWh)
c	battery capacity ratio (unitless)
C^{bank}_{rep}	battery bank purchase cost ($)
d^t	final users demand defined for period t (kWh)
E	square root of the roundtrip efficiency of the battery j (%)
I	battery maximum charge current (A)
K	cost of the energy produced by the conventional generator ($/kWh)
k	battery rate constant (1/h)
L	battery lifetime throughput (kWh)
N	number of batteries (n)
PC_p	conventional generator capacity (kW)
PP_p	conventional generator minimum production (kWh)
$Q^{bank}_{lifetime}$	battery bank lifetime throughput (kWh)
Q_{max}	battery capacity (kWh)
R	replacement cost of the battery ($)
Re^t	renewable energy forecast production in period t (kWh)
S_j	minimum state of charge of the battery j (%)
T	programming period
t	time step (h)
V	nominal voltage of the battery (V)
α	battery maximum charge rate (A/Ah)
λ_v	efficiency of the inverter v (%)
λ_r	efficiency of the rectifier r (%)

fuel-based systems and smart renewable-based systems are presented.

As outlined in Ref. [9], the economics of a hybrid energy system depend both on the size of the selected components and on the dispatch strategy. With regard to the latter, a key issue in cost effectiveness of such systems is battery degradation as the battery is charged and discharged [10]. Hence a question that arises is how storage operations might be carried out in a more economical way, taking into account the hidden costs related to the degradation issues involved in such technologies? And since these battery technologies have operation costs due to degradation issues, are they still cost effective for an off-grid system? These kind of questions can be well studied through using mathematical optimization techniques [11] to determine whether certain choices are cost effective or not and, if not, understanding under which conditions they can become cost effective and how to make better use of the available alternatives.

The present paper will discuss linear programming models that can be used to optimise management of off-grid systems. The key contribution of this work is the inclusion of battery degradation costs in the optimization models. As available data on relating degradation costs to the nature of charge/discharge cycles are limited, we concentrate on investigating the sensitivity of operational patterns to the degradation cost structure. The objective is to investigate the combination of battery costs and performance at which such systems become economic.

This paper is organized as follows. In Section 2 a brief literature review on battery control and optimization is presented, followed by an introduction to the main technical properties of battery in Section 3. The mathematical model developed for off-grid system optimal management including battery scheduling is described in Section 4 while the following Section 5 discusses mathematical formulations to take into account the main battery degradation issues. Computational testing of the model is presented in Section 6, and Section 7 draws conclusions and present possible future research directions.

2. Literature review

The available literature in the field of batteries can be classified into two main approaches, experimental studies and the mathematical analytical studies. The first focuses on chemical analyses and laboratory tests to increase knowledge of degradation processes. Examples of this approach can be found in Ref. [12] where authors discuss a method to diagnose electrode-specific degradation in commercial lithium ion (Li-ion) cells [13]; which presents a diagnostic technique which is capable of monitoring the state of the battery using voltage and temperature measurements in galvanostatic operating modes [14]; where authors describe life experiments performed on lithium polymer cells to investigate the cell life dependence on the depth of discharge; and [15] where a review on methods to mitigate battery degradation is presented.

On the other hand, the mathematical analytical approach is focused on computational simulations and optimization analyses.