Applied Energy 179 (2016) 590–600

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Operating conditions of lead-acid batteries in the optimization of hybrid energy systems and microgrids

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HIGHLIGHTS

- Analyzing the behavior of electrochemical storage devices is a hot research topic.
- Lead-acid batteries may work under stress conditions, negatively influencing lifetime.
- GA method combined with weighted Ah ageing model is improved in this paper.
- A hybrid energy system to be installed in Zaragoza, Spain, is analyzed as case study.
- Near-optimal design in a reduced computational time is obtained.

ARTICLE INFO

Article history:
Received 29 May 2016
Received in revised form 3 July 2016
Accepted 6 July 2016

Keywords:
Energy systems
Lead-acid battery
Wind energy
Genetic algorithm
Weighted Ah ageing model

ABSTRACT

The promotion and deployment of storage technologies in autonomous and grid-connected systems plays a relevant part in the massive integration of renewable power sources required for the worldwide development of a sustainable society. In this regard, analyzing the behavior of electrochemical storage devices such as lead-acid batteries installed on hybrid energy systems and microgrids in terms of their lifetime and economic profitability is an important research topic. Since renewable generation is characterized by its random nature, lead-acid batteries typically work under stress conditions, which directly influence their lifetime in a negative way by increasing the net present cost. Due to the fast growing of renewable sources as a consequence of governmental policies and incentives, the number of manufacturers to be considered worldwide is becoming really high, so that optimization techniques such as genetic algorithms (GAs) are frequently used in order to consider the performance of a high number of manufacturers of wind turbines, photovoltaic panels and lead-acid batteries subject to the environmental conditions of the location under analysis to determine a cost-effective design. In this paper, GA method combined with weighted Ah ageing model is improved by including expert experiences by means of stress factors and the categorization of operating conditions, as a new contribution to earlier studies. The effectiveness of the proposed method is illustrated by analyzing a hybrid energy system to be installed in Zaragoza, Spain, resulting in a near-optimal design in a reduced computational time compared to the enumerative optimization method.

1. Introduction

Within energy system categories, Hybrid Energy Systems (HESs) and Microgrids (MGs) have gained attention due to their high integration of renewable resources, which, from an environmental viewpoint, is crucial for the development of a sustainable society. HESs typically operate in isolated regions with abundant natural resources [1], while MGs are provided with modern capabilities to integrate Battery Storage Systems (BSSs), distributed generation, and demand response programs, which increase the efficiency of the system, allowing for the active participation of the consumers [2]. In a general sense, these systems are mainly

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http://dx.doi.org/10.1016/j.apenergy.2016.07.018
0306-2619/

Nomenclature

List of symbols

t	index for time ($t = 1, \ldots, T$) with $T = 8760$ h
m	index for each interval of discharging-current histogram ($m = 1, \ldots, M$)
s	index of each individual of the population ($s = 1, \ldots, S$)
v	index for the generation of GA under analysis ($v = 1, \ldots, V$)
l	index for SOC operating ranges ($l = A, B, C, D, E$)
Δt	time step (Typically 1 h)
$U_{(t)}$	battery voltage per cell at time t (A)
U_0	open-circuit voltage of a single cell (V)
$U^c_{(t)}$	corrosion voltage per cell at time t (V)
U^c_0	corrosion voltage under open-circuit and fully-charged conditions (V)
U^G_0	voltage of gassing process (V)
U_r	reference voltage for the reduction of acid stratification (V)
$I_{(t)}$	battery current per cell at time t (A) (charge: $I_{(t)} > 0$; discharge: $I_{(t)} \leqslant 0$)
$I^G_{(t)}$	gassing current at time t (A)
I^G_0	normalized value of gassing current at U^G_0 and T^G_0 (A)
$I^G_{0(t)}$	normalized value of gassing current at time t (A)
ΔI^G_0	increment rate of gassing current (A)
$I^d_{(t)}$	discharging current at time t
$I^{\max}_{1\%}$	stress factor for the highest discharge rate ($\times I_{10}$)
I_r	reference current (A)
$I^{1th}_{(t)}$	discharging current at the beginning of the partial cycling operation (A)
I_{10}	discharging current after 10 h (A)
w	intermediate variable
g	coefficient of variation of open-circuit voltage with SOC
C_{10}	rated capacity of the battery after 10 h (Ah)
M_c/M_d	resistance of charge-transfer process
$C_c/C^d_{(t)}$	normalized capacity of a single cell
C_U	voltage parameter of gassing process (1/V)
C_T	temperature parameter of gassing process (1/K)
$T^a_{(t)}$	ambient temperature at time t (K)
T^G_0	temperature of gassing process (K)
$R^c_{(t)}$	internal resistance during charging process (Ω Ah)
$R^d_{(t)}$	internal resistance during discharging process (Ω Ah)
$\Delta R_{(t)}$	resistance of corrosion layer (Ω Ah)
$\Delta R_{\max}$	limit value of resistance of corrosion layer (Ω Ah)
$\Delta W_{(t)}$	corrosion layer thickness
$\Delta W_{\max}$	limit value of corrosion layer thickness
$DOD_{(t)}$	depth of discharge at time t
$SOC_{(t)}$	state of charge at time t
$SOC^{low}_{\lim}$	limit value for operation at low SOC
$SOC^{\max}_{\lim}$	limit value between full charging and partial cycling operation
$k^{sp}_{\max}$	limit value of corrosion speed parameter
k_{sp}	corrosion speed parameter
n	number of poor charge cycles
Δn	weighting factor for the number of poor charge cycles
C_P	coefficient of the increment of acid stratification
C_M	coefficient of the reduction of acid stratification
C_Z	parameter for the capacity loss due to degradation
C_F	counter for number of full charge events
T_F	stress factor for time between full charge (days)
T_S	stress factor for time at low SOC (%)
D	diffusion constant (m^2/s)
L	amount of intervals required to fulfill 1% of Q_{thr}
K	population of GA
CF	charge stress factor
FL	rated battery lifetime under float operation (year)
PC	stress factor for partial cycling operation
$A - E$	SOC operating ranges
$H(\cdot)$	Heaviside function
Z_I	operating cycles of the battery under standard conditions
Z_D	typical value for battery height (cm)
c^{soc}_0	coefficient of SOC impact factor (function slope)
$c^{soc}_{\min}$	coefficient of SOC impact factor (minimum SOC)
$\Delta C^c_{\max}$	limit value of capacity loss due to corrosion process
$\Delta C^c_{(t)}$	loss of capacity due to corrosion process
$\Delta C^d_{(t)}$	capacity loss due to degradation process
$\Delta C^d_{\max}$	limit value of capacity loss due to degradation process
$\Delta t^{soc}_{(t)}$	time since the last full charge (h)
$\Delta f^+_{(t)}$	factor for the increment of acid stratification
$\Delta f^-_{(t)}$	factor for the reduction of acid stratification
$\Delta f^-_{G(t)}$	factor for the reduction of acid stratification due to gassing
$\Delta f^-_{D(t)}$	factor for the reduction of acid stratification due to reduction
$f^{soc}_{(t)}$	SOC impact factor
$f^I_{(t)}$	current factor
$f^{ST}_{(t)}$	factor for degree of acid stratification
$f^A_{(t)}$	factor for total impact of acid stratification
Q_{thr}	normalized total Ah discharged per year ($\times C_{10}$)
$l_{(m)}$	interval m of discharging-current histogram
$f_{(m)}$	frequency of interval m of discharging-current histogram
$P_{(l)}$	partial cycling factor of range l
$P^{\min}_{(l)}$	inferior limit of range l
$P^{\max}_{(l)}$	superior limit of range l
$F_{f(s)}$	value of fitness function for individual s
$\vec{k}_{(s)}$	individual s on the population
$k^1_{(s)} - k^4_{(s)}$	chromosomes of individual s of GA
$k^1_{\min} - k^4_{\min}$	inferior limit for each chromosome
$k^1_{\max} - k^4_{\max}$	superior limit for each chromosome

powered by renewable sources such as wind and solar energies, a conventional generating unit that operates during a short period of time or is dispatched producing a reduced amount of energy. A BSS is typically based on lead-acid technology [3] that provides flexibility to the system by storing the excess energy to be consumed later during those periods of low renewable energy [4]. On the one hand, BSS is the weakest element of the system, as its lifetime is difficult to understand and predict. On the other hand, the variability of renewable resources and the operating philosophy imposes stress conditions on the storing system, reducing its lifetime and increasing its Net Present Cost (NPC).

This problem has been widely studied for a long time, resulting in quantitative and qualitative approaches. Quantitative approaches could be classified in three different categories: physico-chemical ageing models, weighted Ah ageing models, and event-oriented ageing models. Physico-chemical ageing models are based on detailed knowledge of the relationship between the state variables and their corresponding effects on the ageing mechanisms, specifically, the degradation of the active mass and the loss of grid conductivity as a consequence of the corrosion process. This relationship is based on the mathematical equations of chemical reactions; hence, the operating conditions can be