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Determination of optimal battery utilization to minimize operating costs for a grid-connected building with renewable energy sources

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ABSTRACT

This paper proposes strategies to optimize the daily charge and discharge schedule of a battery bank, in order to minimize the operating cost of a building that uses renewable energy sources. The schedule was optimized using a range of battery charge and discharge rates over a 24 h period. These rates were controlled using a genetic algorithm (GA) and a particle swarm optimization algorithm (PSO), which utilized day-ahead prediction data for electricity consumption and electricity price, as well as electricity output from a photovoltaic system and a wind turbine. The results showed that the building operating costs decreased as the number of available charge and discharge rates was increased. The average daily operating cost was reduced by up to 31% using the GA and by up to 28% using the PSO, compared to the scenario where no battery was used. Furthermore, the reduction in average daily operating costs began to plateau as the number of charge and discharge rates reached 12. It was also shown that the scaling of irradiance, wind speed and electricity price inputs impacted the optimized daily operating cost of the building. A sensitivity analysis was conducted to investigate how this scaling of inputs affected the overall performance of the GA. It was found that the optimized daily operating costs were almost unchanged after numerous scaling percentages were applied to the electricity price, with additional cost reductions of up to 3% compared to the scenario where no scaling percentages were applied. In contrast, scaling percentages applied to weather data were found to have a more significant impact on the optimized operating costs, with additional cost reductions of up to 17% compared to the scenario where no scaling percentages were applied. Moreover, a non-linear relationship was observed between the weather data scaling percentage and optimized daily cost.

1. Introduction

In recent years, renewable energy sources such as photovoltaic systems (PVS) and wind turbines (WT) have been increasingly used in conjunction with energy storage systems for buildings. The amount of electricity generated from these renewable energy sources varies greatly according to weather conditions such as irradiance and wind. This electricity may be supplied to a desired system, exported to the national power grid (NPG) or stored in batteries. A building's electricity demand can be met by a combination of the NPG, renewable sources and battery storage [1,2]. The objective of minimizing cost for a building with integrated renewable energy sources, a NPG connection and a connected battery bank (BB) is an area of significant research interest. Examples in the literature include a building integrated PVS and WT system in Bahrain [3], a PV, battery and diesel system in rural India [4], and a grid-connected building using battery storage in France [5]. The present work focuses on renewable energy sources in buildings in Ireland, where research on PVS and WT in buildings has previously been carried out [6].

Much of the research interest in this area has focused on minimizing operating costs by either controlling the operation of a BB [7] or scheduling the building's load (also referred to as load shifting) [8,9]. In load shifting the load operating schedule is altered based on predicted variations in electricity price and weather conditions [10,11]. A linear programing model was used to reschedule the operation of household appliances in order to reduce the total electricity costs of a building in [12]. In [13], the authors proposed strategies for reducing building operating costs through the use of a GA, by matching load consumption with PVS and WT generation. The results from previous studies show that controlling load consumption in this way can achieve substantial electricity and cost savings [14,15].

A disadvantage of load shifting techniques is that that the optimized schedule can represent significant inconvenience for users [16]. An alternative technique of minimizing operational cost, which doesn't

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Nomenclature

P_{mpp}	PV cell power at maximum power point (W)
V_{mpp}	PV cell voltage at maximum power point (V)
I_{mpp}	PV cell current at maximum power point (A)
V_{oc}	PV cell open-circuit voltage (V)
I_{sc}	PV cell short-circuit current (A)
V_T	thermal voltage (V)
FF_s	fill factor
R_s	series resistance (Ω)
$V_{oc,std}$	PV cell open-circuit voltage at the standard conditions (V)
$I_{sc,std}$	PV cell short-circuit current at the standard conditions (A)
G	irradiance (W/m^2)
T	temperature (K)
G_{std}	standard irradiance = 1000 (W/m^2)
T_{std}	standard temperature = 25 °C (298 K)
K_V	temperature coefficients of V_{oc}
K_I	temperature coefficients of I_{sc}
P	wind turbine output power (kW)
ws	wind speed (m/s)
V_c	battery charge voltage (V)
V_D	battery discharge voltage (V)
SOC	state of charge (%)
SOC_o	initial SOC (%)
SOC_i	state of charge at the i^{th} interval (%)
I_c	battery charge current (A)
I_o	initial value of charging current (A)
I_D	battery discharge current (A)
C	battery cell capacity (Ah)
t	charge time (hour)
μ_c	charge efficiency
μ_D	discharge efficiency
I_{10}	battery current at rate C/10 (A)
RTP_i	electricity price at the i^{th} interval (€/kWh)
SMP_i	system marginal price at the i^{th} interval (€/kWh)
AC_i	additional costs at the i^{th} interval (€/kWh)
$Ecoe_i$	amount of electricity consumed by the building during the i^{th} interval (kWh)
GS_i	amount of electricity used during the i^{th} interval for general services (kWh)
L_i	amount of electricity used during the i^{th} interval for lighting (kWh)
H_i	amount of electricity used during the i^{th} interval for heating (kWh)
E_{Li}	amount of electricity consumed at the i^{th} interval by the building (kWh)
E_{Pi}	amount of electricity generated at the i^{th} interval by the PV system (kWh)
E_{Wi}	amount of electricity generated at the i^{th} interval by the wind turbine (kWh)
E_{Bi}	amount of electricity stored in or extracted at the i^{th} interval from the Battery Bank (kWh)
E_{Gi}	amount of electricity purchased from or sold to the NPG at the i^{th} interval (kWh)
Tcost	operating cost for one day (€)
S_{Pi}	operating cost at i^{th} interval (€)
$SELL_i$	selling price at the i^{th} interval to the NPG (€/kWh)
st_i	state of purchasing/selling electricity from/to the NPG (1 when purchasing, 0 when selling)
pst	current particle
x	velocity of current particle
lcl	local best particle

inconvenience the user involves the storage and release of electricity from a battery. Controlling the amount of electricity stored in or released from a battery can satisfy the load demand of a building while lessening inconvenience for users. Previous research in this area has primarily focused on optimizing the charge and discharge schedule for a BB [17,18]. The amount of electricity stored in or released from the BB may be controlled using a battery operating schedule based on simulated electricity generation, consumption, and electricity price. Dynamic programming methods were used in [19,20] to optimize a battery operating schedule for a building with a grid-connected PVS, with the goal of minimizing building operating costs. In both studies, the amount of electricity stored in or released from the batteries was controlled through the state of charge (SOC) values of the BB. An alternative approach aimed to optimize the dispatch schedule of the BB for a grid-connected PVS-battery system in order to minimize the cost of the system. A linear programing strategy used in [21] managed the charging schedule of the battery through a targeted peak load reduction, and leveraged PVS power output and load forecasts to determine how best to release stored electricity from the battery in order to minimize costs. In [22], the optimized schedule using metaheuristic optimization methods ensured that the BB stored electricity when the PVS and WT generated more than the building required, or released electricity to supply the building during periods in which electricity price was anticipated to be high.

Batteries have non-linear characteristics for both the storage and release of electricity. The amount of electricity stored in or released from the battery depends on properties including charge and discharge rates, charge and discharge methods, charge and discharge times, and SOC [23]. Previous research has primarily focused on controlling the amount of electricity stored in or released from batteries [22] or the SOC of batteries [19]. However, little research has been conducted in which charge and discharge rates and methods have also been taken into account. More specifically, previous studies have focused primarily on the amount of electricity stored in or released from the batteries rather than the method by which it is stored and released. Therefore, in this paper charge and discharge rates and methods were considered. Regarding the SOC of batteries, in [24] the amount of electricity stored in or released from the batteries was controlled via SOC values. The work in this paper differs from these due to the fact that a variety of charge and discharge rates are used to develop the schedule for the BB. These multiple rates allow the SOC values for each interval to alternate between small values (light rates) and large values (deep rates). Hence, the quantity of electricity stored in or released from the battery at each interval is flexible. This method differs from [19,20], in which the changes in SOC values at each interval were fixed. The battery models used in [19,20] were assumed to be perfect models or linear models, with the amount of electricity stored in and released from the battery considered to be either a constant or a linear value. The work addressed in this paper differs from these as a model validated using real empirical data is used for battery simulations.

The problem of optimizing the charge and discharge schedule of a BB in order to minimize a systems operating cost was presented in the author's previous publications. The performance of a PSO algorithm was assessed when applied to the problem of minimizing operating costs for a system consisting of a PVS, BB and NPG [25]. The PSO produced an optimized schedule of charge and discharge rates for the BB. Subsequently, a WT was added to the system and a GA was applied to optimize the battery charge and discharge schedule [26]. Unlike the work presented in this paper, the operating schedule for the BB in [25,26] used a small number of charge and discharge rates to meet the demand of the system. Due to the limited number of charge and discharge rates used, the amount of electricity which could be stored in and released from the battery at each interval was not sufficient to meet the building's overall electricity demand. In addition, the PVS, WT and