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Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: A case study in Sweden

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ABSTRACT

The optimal components design for grid-connected photovoltaic-battery systems should be determined with consideration of system operation. This study proposes a method to simultaneously optimize the battery capacity and rule-based operation strategy. The investigated photovoltaic-battery system is modeled using single diode photovoltaic model and Improved Shepherd battery model. Three rule-based operation strategies—including the conventional operation strategy, the dynamic price load shifting strategy, and the hybrid operation strategy—are designed and evaluated. The rule-based operation strategies introduce different operation parameters to run the system operation. multi-objective Genetic Algorithm is employed to optimize the decisional variables, including battery capacity and operation parameters, towards maximizing the system's Self Sufficiency Ratio and Net Present Value. The results indicate that employing battery with the conventional operation strategy is not profitable, although it increases Self Sufficiency Ratio. The dynamic price load shifting strategy has similar performance with the conventional operation strategy because the electricity price variation is not large enough. The proposed hybrid operation strategy outperforms other investigated strategies. When the battery capacity is lower than 72 kW h, Self Sufficiency Ratio and Net Present Value increase simultaneously with the battery capacity.

1. Introduction

The installed Photovoltaic (PV) capacity has increased rapidly in recent years. The installed capacity has reached 177 GW at the end of 2014 [1]. Supporting policies, including feed-in-tariff (Fit) and net-metering, are important incentives [2]. However, due to the intermittent nature of solar energy, the accumulated PV capacity in the grid brings in technical issues with power quality, frequency stability [3], and reliability. Batteries can not only smooth the PV output and alleviate the technical challenges [4], but also increase the economic benefits [5]. The interest in the grid-connected PV-battery system is increasing among researchers and owners [6].

Batteries can subject to different operation strategies and bring in different economic benefits. In the first place, batteries increase the self-consumed electricity through storing excess PV generation and discharging to supply consumption later [5]. The self-consumed electricity increases the economic benefits due to the higher economic value than exported electricity. A further battery management strategy is to charge it when the electricity price is low and discharge it during high price times (loading shifting) [7]. In this case, benefits can be achieved from the difference in electricity price. Furthermore, if the electricity user is partly charged based on the peak power, battery can be discharged during the peak demand (peak shaving) [8]. In this case, benefits are achieved through reducing the user's peak power.

During the planning stage of the grid-connected PV-battery system, PV and battery capacities need to be decided. Meanwhile, different operation strategies need to be taken into account to enhance the economic benefits. This is an optimization problem that simultaneously takes into account PV capacity, battery capacity, and operation strategy [9]. However, the literature survey indicates that component sizing and operation strategy are generally studied separately.

There are many researches addressing the component sizing issue, especially for the off-grid systems. For example, Yang et al. used Genetic Algorithm and obtained the PV, wind turbine and battery capacity for a stand-alone system [10]. Paliwal et al. intro-

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Nomenclature

Symbol

$C_{O\&M,y}$	operation and maintenance cost at year y
$C_{R,y}$	replacement cost at year y
CAP_i	capacity for component *i*
d_r	discount rate
$El_{r,t}$	retail electricity price at time t
$El_{w,t}$	wholesale electricity price at time t
$El_{r,H}$	high retail electricity price
$El_{r,L}$	low retail electricity price
Inv	investment cost
$P_{B,t}$	battery power at time t
$P_{G,t}$	grid power at time t
$P_{G,peak}$	grid peak power
$P_{Gim,t}$	imported grid power at time t
$P_{Gex,t}$	exported grid power at time t
$P_{L,t}$	load at time t
$P_{Mdisc,t}$	maximal discharge power at time t
$P_{Mchar,t}$	maximal charge power at time t
$P_{Net,t}$	net power at time t
$P_{PV,t}$	PV power production at time t
P_H	high power limit
P_L	low power limit
R_y	system revenue at year y
$R_{ER,y}$	electricity reduction revenue at year y
$R_{EX,y}$	export revenue at year y
$R_{PS,y}$	peak shaving revenue at year y
$r_{O\&M,i}$	O&M Ratio for component *i*
SOC_t	State of Charge at time *t*
t_s	conventional operation start time
t_e	conventional operation end time
t_{peak}	the appearance time of $P_{G,peak}$
UIC_i	unit investment cost for component *i*
η_{inv}	inverter efficiency

Abbreviations

DOD	Depth of Discharge
Elspot	Electricity Spot
EMS	Energy Management System
GA	Genetic Algorithm
LOC	Level of Confidence
NPV	Net Present Value
SOC	State of Charge
SSR	Self Sufficiency Ratio
TOU	Time-of-Use

duced particle swarm optimization method to determine the system configuration [11]. Xu et al. studied the possible combinations of various PV, wind turbine and battery capacities, and obtained the system design under either grid-connected or stand-alone condition [12]. Mulder et al. studied the relationship between battery capacity and exported electricity to the grid in a grid-connected PV-battery system. The relationship is further used to dimension the battery size [13]. Bortolini et al. carried out a techno-economic analysis and determined the PV and battery capacity to minimize the levelized cost of electricity in grid-connected PV-battery system [14]. Zhou et al. addressed the battery sizing issue with consideration of demand response under Time-of-Use (TOU) tariff [15]. Mokhtari et al. determined the component size through the optimization towards different objectives (i.e. maximizing power export) [16]. The above studies cover the component sizing issue. However, the issue of maximizing economic benefits with different operation strategies is not well addressed.

The optimal operation of a given system, which is achieved by Energy Management System (EMS), also attracts lots of research attention [17]. A short-term power scheduling model for a grid-connected PV-battery system was proposed by Lu et al. using a Lagrangian relaxation-based optimization algorithm [18]. Riffonneau et al. used dynamic programming and obtained the 24-h ahead power scheduling based on the accurate prediction of weather and load [19]. Li et al. used dynamic programming to get predictive charge control strategies for different objectives (i.e. maximizing battery life, maximizing self-sufficiency) [20]. Marzband et al. proposed a power scheduling method based on mixed-integer nonlinear programming and verified it with test bench [21]. An EMS that was based on multi-layer ant colony optimization was reported to decrease the energy cost by 20% compared with the conventional EMS [22]. Gravitational Search Algorithm was demonstrated as an effective tool for peak consumption reduction and electricity generation cost minimization [23]. Imperialist competition algorithm was used in EMS to provide multiple optimum solutions [24]. When considering demand response of customers in the microgrid, further decrease of energy cost (30%) was achieved [25]. The above studies obtained short-term power scheduling based on forecasted weather and load data. The optimal operation issue is well addressed. However, the components in the studied systems have pre-assumed and fixed sizes.

The literature survey indicates that studies on component sizing or optimal operation employ different approaches, which are differentiated by decisional variables (component sizes/power scheduling), input data (historical and representative data/forecasted data) and simulation time frame (year/day).

Studies that take into account both sizing and scheduling problems are generally scarce. Ru et al. determined the battery capacity in grid-connected PV-battery system with consideration of load shifting and peak shaving under TOU tariff [26]. However, the optimal battery capacity is determined based on the simulation of one typical day, indication that the seasonal variation of solar irradiation and load is not considered. Gitizadeh et al. [27] extended the research by Ru et al. Instead of one typical day, multiple typical operation scenarios, which are obtained from Fuzzy Clustering Method, are used in solving the optimization problem. Khalilpour and Vassallo proposed a decision support tool to decide system size concurrently with finding the optimal operation schedule [28]. The support tool offers users to choose among different PV and battery modules. The above studies merged component sizing and optimal scheduling. They carried out long period simulation (several days or one year) using the historical data as input, and determined the decisional variables including component sizes and power scheduling. However, because of the extremely large amount of decisional variables (i.e. 18, 659, 330 in Khalilpour and Vassallo [28]), the complex non-linear system was reduced to linear system to facilitate the problem solving. Moreover, the studies assumed that correct weather and load forecasting can be ensured during the real-time operation.

In this study, a new approach of determining the battery capacity and operation strategy is proposed. Instead of determining the power scheduling, the new approach is based on rule-based operation strategy. The approach largely decreases the numbers of decisional variables and enables carrying out optimization with non-linear system. Specially, batteries are complex electrochemical devices. Their efficiency, power constraints and lifetime are all influenced by the operation condition. The approach enables to employ a more detailed model.