Applied Energy 195 (2017) 974–990

Contents lists available at ScienceDirect

Applied Energy

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

Network-aware approach for energy storage planning and control in the network with high penetration of renewables

Khashayar Mahani *, Farbod Farzan, Mohsen A. Jafari

Rutgers, The State University of New Jersey, USA

HIGHLIGHTS

- Approximate solution for energy storage (ES) sizing and operation planning.
- Approximate solution significantly reduces the complexity of problem.
- Approximate solution for complex network with multiple applications of ESs.
- A rule-based control scheme for the near real-time operation of complex ES network.
- The control schema has been developed by mining the I/O statistical relationship.

ARTICLE INFO

Article history:
Received 6 December 2016
Received in revised form 23 March 2017
Accepted 24 March 2017

Keywords:
Network-aware planning and control
Energy storage network
Data-driven control
Optimal planning
Community level micro-grid

ABSTRACT

In this paper, we consider multiple energy storage nodes distributed over a power distribution network, and are purposed for multiple applications. The research problems of interests are to optimally locate these nodes over the distribution network and to create day-ahead plans according to planned applications. The two problems are formulated as stochastic optimization problems, and hourly and time-aggregated approximate solutions are presented. The approximation identifies time periods where load and generation patterns demonstrate low variability, and marks the whole period as a single time zone, thus significantly reducing the number of decision variables and the overall problem size. We show that aggregate and hourly planning solutions are close. The planning problem can handle any number of storage nodes with general topology and load connections, and deterministic or stochastic capacities. In this paper, we focus on network of static energy storages with deterministic capacity. Finally, we build a novel rule based control scheme for the near real time operation of the storage network by mining the statistical relationship between input and optimal charge and discharge patterns.

1. Introduction

Energy storage (ES) has the potential to offer a new means of added flexibility on the electricity distribution systems. This flexibility can be used in a number of ways, including adding value towards asset management, power quality and reliability. An important factor in evaluating the feasibility of ES technology is the application(s) for which the storage is used for [1]. ES can provide local level services such as, peak shaving and renewable integration [2,3], and network level services, such as voltage and frequency control [4]. It can also be utilized for loss minimization and deferral of network infrastructure upgrades. With the use of energy storage in a distribution networks for multiple applications, however, comes the challenge of determining how best to control these storage units under load and system state uncertainties. For example, with increasing number of Electrical Vehicles (EVs) the uncertainty in the electricity demand rises due to EV charging demand [5–7]. But, on the other hand, Vehicle-to-Grid (V2G) technology, while mitigating some of this uncertainly, can add system dynamics complexities to the network [8–10].

Han et al. [11] and Wong et al. [12] provide control algorithms to maximize EV owner's profit, which comes from selling power to grid and participating in the frequency regulation market. They formulate the problem as a discrete-time Markov decision process and solve it by introducing an online learning algorithm which iterates every hours based on available information. Koutsopoulos et al. [13] study the optimal energy storage control problem by taking the point of view of a utility operator and focuses on arbitrage application of energy storage. The authors show that the model can be extended to account for a renewable source that feeds the storage device. The same problem was considered in [14], where the

---

* Corresponding author.
E-mail address: km723@scarletmail.rutgers.edu (K. Mahani).

http://dx.doi.org/10.1016/j.apenergy.2017.03.118
0306-2619/

Nomenclature

t	time index
s	static storage node index
j	demand node index
k	renewable node index
i	temporal zone index
d	day index
y	year index
Sc	scenario (cluster) index
b	tree index in tree-bagging method
CL	number of clusters
γ	annual inflation rate (%/year)
α	annual discount rate (%/year)
$En_{s,max}$	storage unit s energy capacity (kWh)
$P_{s,max}$	energy storage s rated capacity (kW)
Inv_s^{Cap}	investment unit cost on storage capacity ($/kWh)
Inv_s^{PR}	investment unit cost on power rating ($/kW)
$L_{Sc}(j,i)$	total electricity demand during zone i at demand node j for cluster Sc (kWh)
$R_{Sc}(k,i)$	total renewable generation during zone i at renewable node k for cluster Sc (kWh)
$L_{d,y}(.)$	demand matrix for day "d" in year "y"
$R_{d,y}(.)$	renewable generation matrix for day "d" in year "y"
$Pr_{d,y}(.)$	electricity price matrix for day "d" in year "y"
$L_{Sc}(.)$	representative demand matrix for cluster Sc
$R_{Sc}(.)$	representative renewable generation matrix for cluster Sc
$\mathrm{Pr}_{Sc}(.)$	representative electricity price matrix for cluster Sc
$e_{s,i,Sc}^{ch,g}$	total energy charged from grid during zone i in storage unit s for cluster Sc (kWh)
$e_{s,k,i,Sc}^{ch,r}$	total energy charged from renewable node k during zone i in storage unit s for cluster Sc (kWh)
$e_{s,j,i,Sc}^{d}$	total energy discharged during zone i from storage s to demand node j for cluster Sc (kWh)
$e_{j,i,Sc}^{dem,g}$	total energy from grid during zone i to demand node j for cluster Sc (kWh)
$e_{j,k,i,Sc}^{dem,r}$	total energy from renewable k during zone i to demand node j for cluster Sc (kWh)
$c_{i,j}$	configuration number between nodes i and j
$Eff_{ch,s}$	energy storage "s" charging efficiency
$Eff_{dis,s}$	energy storage "s" discharging efficiency
$Pr_{Sc}^{w}(i)$	average electricity whole sale price during the hours of zone i for cluster Sc ($/kWh)
Pn_{sub}	penalty for damage to substation due to reverse flow of power ($/kWh)
Dem	demand charge for peak demand ($/kW)
$SOC_{s,i}$	storage s energy level at the end of zone i (kWh)
dr_i	duration of temporal zone i
En^{max}	maximum energy reservoir capacity
P^{max}	maximum power rating
SF_s	safety reserve capacity for storage unit s
ESL	Storage - Demand Eligibility Matrix
ERS	Renewable - Storage Eligibility Matrix
ERL	Renewable - Demand Eligibility Matrix
ST_t	network state vector at time t
π^s	control policy for storage s
a_t^s	control action of storage s at time t
$rw_t^s\ (ST,\ a_t^s)$	reward function for storage s when action a_t^s is taken in state ST
V^{π^s}	value storage s under control policy π^s
Y	classification response vector (Control action vector)
LR	level of on-site renewable generation
LD	level of demands
EP	electricity price
X	classification feature matrix
B	number of bags
τ	memory window in control module
d_n	nth digit in control action code

cost of energy is minimized subject to both user demands and prices using a Markov Decision Process. Dufo-Lopez et al. [15] consider the energy storage in private facility to reduce the electricity bill. They conclude that electricity price variation has a great effect on the profitability of storage system. Renewable resource integration is an important application of energy storage, and charge-discharge control policy of energy storage to serve this application is presented by Wang et al. [16]. Renewable energy sources are considered by Teleke et al. [17] too, where an open-loop optimal control scheme was developed which incorporates the operating constraints of battery energy storage. They use the battery energy storage in a smoothing application where a wind farm is dispatched on an hourly basis based on the forecasted wind conditions.

Earlier works on component sizing or optimal operation employ different approaches, which are differentiated by decisional variables. Studies that take into account both sizing and scheduling problems are generally scarce. Ru et al. in [18] determine the optimal size of a grid-connected PV-battery system which is used in an arbitrage application. Their objective is to minimize the net power purchase cost plus battery capacity loss, without considering any initial capital investment. Khalilpour et al. [19] introduce a decision support tool for sizing and operation of PV-battery system in a single facility, with the objective of maximizing the net present value generated by bill reduction. Zhang et al. [20] introduce a rule based charge and discharge strategy which simultaneously optimizes the battery sizing and operation in a bill management application. The introduced rule-based approach works well for a single PV-battery system with in the facility, however the interaction between multiple battery units in more complex distribution network has not been investigated. The similar problem was considered by Brekken et al. [21], where sizing and control methodologies for a battery-based energy storage system is presented for wind farm applications. The sizing problem of distributed generator and energy storage system (single application – electricity cost reduction) for demand response applications in smart households has been studied in [22,23]. Andreotti et al. [24] consider a network of renewable generation units and formulate a single-objective optimization problem whose objective function is power loss minimization while satisfying constraints on active and reactive power at the interconnection bus. Nick et al. [25] studied the optimal allocation of storage systems in an active distribution network by defining a multi-objective optimization problem. The application of renewable generation integration is also considered in [26–29]. Van de ven et al. [30] present a battery control policy, which minimizes the total discounted costs, taking into account arbitrage application of energy storage. Jayawarna et al. [31] studied the energy storage power reliability application and present the concept of using central energy storage system as the main fault current source in micro-grid islanded mode.

To the best of our knowledge, there is a major gap in understanding how multiple storage units programmed for multiple applications should operate in a distribution network. This paper intends to fill this gap by developing simple but verifiable control