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Economic optimal operation of Community Energy Storage systems in competitive energy markets

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HIGHLIGHTS

- The Community Energy Storage (CES) system control architecture is introduced.
- The market based optimization algorithm for energy storage scheduling is proposed.
- The proposed algorithm provides real time and day ahead optimal schedule for batteries.
- The multi-objective Gradient-based Heuristic Optimization method (GHO) is applied.
- Aggregated impact of all CES units on the distribution network is presented.

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ABSTRACT

Distributed, controllable energy storage devices offer several benefits to electric power system operation. Three such benefits include reducing peak load, providing standby power, and enhancing power quality. These benefits, however, are only realized during peak load or during an outage, events that are infrequent. This paper presents a means of realizing additional benefits by taking advantage of the fluctuating costs of energy in competitive energy markets. An algorithm for optimal charge/discharge scheduling of Community Energy Storage (CES) devices as well as an analysis of several of the key drivers of the optimization are discussed.

1. Introduction

Distributed energy storage devices may improve reliability by providing standby power when equipment outages would otherwise force customer interruptions. Additionally, energy storage devices can reduce equipment loading during peak hours, thereby decreasing pre-mature aging in network components [1]. They can also help with renewable energy resource integration into distribution networks. Volt–Var optimization, power quality, frequency regulation, reliability, efficiency, and demand response can all benefit from distributed energy systems [2–5]. These benefits are so great that they sometimes outweigh the high cost of installing the energy storage devices and the communication infrastructure to support them [6].

This paper presents a means of realizing additional benefits from energy storage devices by taking advantage of the fluctuating costs of electricity in competitive energy markets. By combining electricity market information with real-time control of energy storage devices, utilities may enjoy year-round economic benefits from the storage devices, in addition to the occasional benefits mentioned above.

The increasing adoption of intermittent Distributed Energy Resources (DER) into the power grid and technological merit for batteries in recent years brings more attention to Energy Storage Systems (ESS) as viable solutions. Energy storage system integration with renewable sources are discussed in many publications [7–9]. In [7], the authors used a clustering optimization approach to maximize the renewable energy utilization integrated with a pumped storage unit. Authors in [8] explored a large scale battery application for ancillary services in an electricity market. Ref. [10] provides a load leveling algorithm with solar power generation and energy storage under a Time of Use (TOU) price scheme. However,

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Nomenclatures

Symbols

a_t, b_t, c_t	interpolation coefficients
$Ch/Dch\ Pairprofit_t$	CES charging and discharging pairs at time t
C_{max}	maximum CES capacity (kW h)
C_{min}	minimum CES capacity (kW h)
$C_{Rsv\ t}$	CES reserve capacity at hour t (kW h)
C_t	CES capacity in time t (kW h)
H_R	outage support duration (h)
K_{config}	battery cell configuration coefficient
L	transformer loading
LMP_t	Locational Marginal Price in hour t
NT	number of time points
P_{max}^{Ch}	maximum charge rate (kW)
P_{max}^{DCh}	maximum discharge rate (kW)
P_{MaxPri}	maximum CES power for primary issues (kW)
$P_{max}^{Trans\_j}$	kVA rating of the transformer j
P_{MinPri}	minimum CES power for primary issues (kW)
$P_t^{CESLoss}$	CES loss function (kW)
P_t^{CESout}	output power of the CES in hour t (kW)
$P_t^{FeedLossRed}$	reduction in feeder losses in hour t (kW)
P_t^{Load}	load in hour t (kW)
R_{cell}	battery cell internal resistance
R_t^{Ch}	charging revenue (cost) in hour t
R_t^{Dch}	discharging revenue (cost) in hour t
Sch_{profit}	CES scheduling profit (\$)
Sch_{profit}^{opt}	CES optimal scheduling profit (\$)
SS_{Max}	maximum iteration step size (kW)
ΔC_t	change in stored energy in hour t (kW h)
$\Delta C_t^{(i)}$	change in ΔC_t decided upon in iteration i

Acronyms

AMI	Advanced Measurement Infrastructure
CCU	CES Control Unit
CES	Community Energy Storage system
DCC	Distribution Network Control Center
DER	Distributed Energy Resources
DESS	Distributed Energy Storage Systems
DEW	Distributed Engineering Workstation
DMS	Distribution Management System
DR	Demand Response
ESS	Energy Storage Systems
GCU	Group CES Control Unit
GHO	Gradient-based Heuristic Optimization method
ISM	Integrated System Model
LMP	Locational Marginal Price
PEV	Plug-in Electric Vehicle
PBR	Performance Based Rates
TOU	Time of Use

the real-time electricity market and the effect of time varying loads were not considered in the demand control algorithm.

Much literature has focused on utility scale energy storage applications (battery capacities more than 1 MW) [11], but few have attempted to realize system wide operational benefits of distributed energy storage systems with battery units with 50 kW and or less capacity. Distributed Energy Storage Systems (DESS) can provide different services for distribution network operators ranging from demand response to power quality issues to peak shaving and renewable resource firming. Moreover, the emergence of microgrids as a special case of network architecture increases the need for DESS [12]. The authors of [13–15] looked at the DESS from the perspective of controlling customer-owned storage devices that integrate with other generation sources. Authors in [16] focused on the DESS application for voltage regulation in the presence of high penetration photovoltaic panels. The customer side of DESS provided voltage regulation in exchange for subsidies from utilities to cover battery costs.

Ref. [17] presented a load management approach with substation level energy storage systems for a large load aggregator to determine the electricity price for participation in the day ahead market. A lumped load was considered while distribution grid topology and operational constraints were not considered. In [18] a DESS is used to minimize the forecasting errors associated with DER generation. In [19], the authors integrated DESS into the Distribution Management System (DMS) controller. However, the DESS is a centralized battery unit to serve the whole substation territory. Refs. [18,19] and most of the literature related to DMS and distribution network control have proposed a top-down strategy for feeder control starting from the substation. These centralized control approaches need accurate network models and detailed operational constraints for network components to achieve optimal control functionality which is a difficult task [12]. Moreover, energy storage units in those studies are mostly located at the substation.

In distribution networks with DER and DESS sources, the boundaries and operational conditions for each distributed source and the network constraints related to each source need to be included in the control framework. This leads to a distributed control strategy starting from DER and DESS up to the substation. In recent literature, the distributed control approach for DERs is addressed. Refs. [20,21] present a distributed control system for DESS in distribution networks. However, the DESS control objective is only the feeder loss reduction. The authors in [22] proposed a load management system for residential customers with combined DER and DESS. However, the proposed approach is a single objective optimization to minimize the electricity cost without considering the system's day ahead behavior.

The other school of thought in distributed control strategies for distribution networks is based on Demand Response (DR) programs [23,24]. DR can play a crucial role in peak shedding and reliability, but there are embedded uncertainties due to DR dependency on customer participation, customer life style, and implementation of Advanced Measurement Infrastructure (AMI) [25].

This paper focuses on the utility owned DESS units installed on residential distribution networks and referred to as a Community Energy Storage (CES) system [26]. The CES term is also addressed in the Department of Energy Smart Grid Recovery Act [27]. The authors of this paper were involved in the CES demonstration project for the State of Michigan, funded by the U.S. Department of Energy [28]. The study presented here is based on the actual CES control system design and implementation. The CES unit in this paper is a 25 kW Lithium-Ion battery. This paper is not focused on the detailed model of the chemical reactions inside the battery. However, the operational limitations of each CES unit are considered.

From the mathematical point of view, the distributed control approaches have some difficulties with system wide optimal DER operation [29]. This paper proposes a hierarchical control approach