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Strategic allocation of community energy storage in a residential system with rooftop PV units

Junainah Sardi[a,b,*], N. Mithulananthan[a], Duong Quoc Hung[c]

[a] School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia
[b] Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[c] School of Engineering, Deakin University, Australia

HIGHLIGHTS

- A modified Center-of-Gravity formulation to site CES for energy loss minimization.
- An analytical framework to integrate CES in residential systems with rooftop PV.
- A simplified probabilistic model for existing PV units considering its uncertainty.
- A probabilistic CES sizing approach to achieving the desired load factor.
- Quantified financial benefits from the proposed allocation strategy.

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ABSTRACT

The electrical power sector has entered an era of decarbonizing energy generation by accommodating more Renewable Energy Sources (RES), especially solar energy in the power grid. However, high penetration of such a resource has negative impacts on the power network such as power fluctuations, reverse power flows and voltage rises. Energy Storage (ES) offers an effective solution to addressing those challenges while improving the load factor as well as the utilization of network infrastructures. This paper proposes a new framework to integrate Community Energy Storage (CES) units in an existing residential community system with rooftop solar Photovoltaic (PV) units. In this framework, three analytical approaches are respectively developed to handle three important parameters of the CES integration (i.e. locations, sizes and operational characteristics) to enhance network performances. Firstly, a simple approach is developed on the basis of a Center of Gravity (COG) theory to determine the location of CES for minimizing the annual energy loss. Secondly, a new analytical formulation based on a load following control method is presented to identify the proper rated capacity of CES and its hourly dispatch strategy for achieving a desired annual load factor. Lastly, a technique to estimate the optimal operational characteristic of CES is proposed for flattening the daily demand profile and improving the voltage profile. The proposed framework is tested on a 19-bus test system while considering the probability of PV generation along with load variations. The numerical results show that the developed framework can bring the system load factor to a maximum of 0.76, at which the penetration levels of CES and PV are at 22% and 5% respectively while reducing the energy loss by 24.21% and enhancing the voltage profile significantly. The results also indicate that 22% CES penetration can reduce the annual purchased energy cost from the grid by 11.1% and the annual energy loss cost by 36.88%, where the system accommodates respective PV penetration levels of 5% and 50%.

1. Introduction

Due to environmental benefits, governmental incentives and reductions in PV panel costs, there have been a significant increase in the integration of rooftop PV at the distribution system level around the world. Specifically, it has been reported that the total worldwide capacity of PV systems installed in the residential sector will rise to 1.8 TW by 2040 from 104 GW in 2014 [1]. In Australia, the number of PV systems installed on the rooftops of homes increased from 8 thousand to 1.4 million over the period of 2007–2014, and this figure is expected to

* Corresponding author at: School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia.
E-mail addresses: j.sardi@uq.edu.au (J. Sardi), mithulan@itee.uq.edu.au (N. Mithulananthan), hung.duong@deakin.edu.au (D.Q. Hung).

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Nomenclature

Indices

y	index of PV output states
t	index of time in hour
i, j, k, n	index of buses
s	index of combined generation-load states
h	index of CES penetration levels

Parameters and variables

C_{CES}	CES capacity needed to achieve a desired annual LF
C_{CESR}	rated capacity of CES in kWh
C_{CESopt}	optimal C_{CES}
$C_{PV}(y)$	normalized output power of PV corresponding state y
$E_{CES,k,t}$	CES energy variation
$E_{D,annual}$	annual demand energy
$E_{DISs,t,w}$	CES discharging energy of state s at hour t in winter
$E_{DISs,t,sp}$	CES discharging energy of state s at hour t in spring
$E_{DISs,t,su}$	CES discharging energy of state s at hour t in summer
$E_{DISs,t,au}$	CES discharging energy of state s at hour t in autumn
$E_{L,i}$	annual energy required by a load at bus i
E_{Ltot}	total annual energy consumed by all the loads in a system
$E_{PV,i}$	annual energy produced by a PV unit at bus i
E_{PVtot}	total annual energy generated by all the PV units in a system
EL	annual energy loss without CES
$EL_{CES,h}$	annual energy loss when the system is subjected to the h level of CES penetration
ELR_{avg}	average value of the annual energy loss reduction that considers different CES penetration levels
$f_b(g)$	beta probabilistic distribution function of a solar PV output
g	random variable of a solar PV output (p.u)
H	total CES penetration level
K_{Qji}	scalar value related to ΔV_j and Q_i
LF	annual load factor
LF_{CES}	annual load factor for a system with CES
M	total number of combined generation-load states for every time-segment
N	total number of buses in a system
N_{CES}	minimum CES penetration in %
N_{PV}	PV penetration level in %
$P_{CESk,t}$	active power dispatched by CES
P_{ch}	charging threshold
$P_{D,CESmax}$	maximum demand power of all combined generation-load states for a system with CES
$P_{DA,CESmax}$	maximum value of the daily average demand over a year for a system with CES
P_{dis}	discharging threshold
P_{Dmax}	maximum substation demand power throughout a year
$P_{Ds,t,w}$	substation demand power of state s at hour t in winter
$P_{Ds,t,sp}$	substation demand power of state s at hour t in spring
$P_{Ds,t,su}$	substation demand power of state s at hour t in summer
$P_{Ds,t,a}$	substation demand powers of state s at hour t in autumn
P_{Dt}	total active power demand of a substation at hour t
P_G	generated active power
P_L	active power of load demand
$P_{PVo}(y)$	expected output power from a PV module at state y
$P_{PV,rated}$	capacity of a PV module or the maximum PV output throughout a given time period
$P_{PV}(t)$	total expected output power of a PV module across any period t
P_{PVR}	capacity of PV generation
$Q_{CESk,t}$	reactive power dispatched by CES
Q_G	generated reactive power
Q_i	reactive power injection at bus i
Q_L	reactive power of load demand
V_{low}	lower limit of operating voltages
$V_{n,t}$	operating voltage of bus n during t hour
V_{up}	upper limit of operating voltages
X_{COG}	x-axis coordinate based on the COG method
X_i	x-axis coordinate of bus i
Y_{COG}	y-axis coordinate based on the COG method
Y_i	y-axis coordinate of bus i
Y	line admittance
$P\{R_y\}$	probability of a PV output for state y
δ	voltage phase angle
θ	line admittance phase angle
$\rho\{C_{s,t,w}\}$	probability of the related state, s in winter
$\rho\{C_{s,t,sp}\}$	probability of the related state, s in spring
$\rho\{C_{s,t,su}\}$	probability of the related state, s in summer
$\rho\{C_{s,t,a}\}$	probability of the related state, s in autumn
η	round-trip efficiency of CES
γ	maximum depth of discharge for CES
κ	self-discharge rate of CES
ΔV_j	voltage magnitude change at bus j
Δt	time duration of period t

significantly grow in the coming years [2]. The efficient usage of solar PV can bring multiple technical and economic benefits to utilities, PV owners and customers. However, due to its inherent intermittency and variability, the high penetration of this PV source along with demand variations has caused several negative effects on distribution systems such as power fluctuations [3]. The reverse power flows along with voltage rises also occur as the PV generation exceeds the local demand. Meanwhile, it has been forecasted that the worldwide capacity of Energy Storage (ES) will increase over 40 GW by 2022 from 0.34 GW in 2012 [4]. ES can be used to effectively alleviate the above technical network problems caused by the high penetration of Renewable Energy Sources (RES) including solar PV energy. It can also be employed as an efficient solution to managing energy and facilitating more RES in distribution systems while maintaining grid reliability [5–9]. This paper develops three approaches to handle three important aspects of CES systems, namely its locations, sizes and operational characteristics to address those challenges while enabling higher PV penetration.

The planning of ES in power distribution systems integrated with RES has been reported in a number of recent research efforts considering various applications and approaches. Specifically, ES units were allocated and sized using heuristic algorithms for demand management, energy price arbitrage and wind curtailment reductions in a distribution system with RES [10–12]. A genetic algorithm-based method was developed to determine the optimal allocation of ES units in a distribution network with PV units [13]. In this study, the electric rates, power losses and voltage deviations were evaluated. A strategy to integrate ES units and capacitors in a distribution grid with wind and PV units was also reported in [14], where the voltage improvement, network upgrade deferral and VAr regulation were investigated. The optimal size of ES systems for PV energy time-shift was calculated on their performance, durability and economic benefits [15]. A probabilistic analytical approach was proposed to size and schedule ES units for the integration of Plug-in Hybrid Electric Vehicle (PHEV) and PV systems in residential distribution systems [16]. In this study, ES units were utilized to increase the time coincidence between PHEV charging and PV generation. The authors also suggested that each secondary

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