Journal of Energy Storage 17 (2018) 272–286

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Optimal placement, sizing, and dispatch of multiple BES systems on UK low voltage residential networks

R.C. Johnson[a,*], M. Mayfield[a], S.B.M. Beck[b]

[a] Department of Civil and Structural Engineering, University of Sheffield, UK
[b] Department of Mechanical Engineering, University of Sheffield, UK

ARTICLE INFO

Article history:
Received 27 November 2017
Received in revised form 14 March 2018
Accepted 15 March 2018
Available online xxx

Keywords[1]:
Energy storage
LV networks
OPF
Sizing

ABSTRACT

As the penetration of renewable technologies on UK low voltage networks increases, the likelihood of line utilization and voltage violation rises. Whilst previous studies have examined the use of centrally controlled energy storage to manage violations, the economic feasibility of such methods are generally not considered. In this paper, a novel approach to the placement and dispatch of behind-the-meter battery energy storage for voltage and utilization control is presented. The placement strategy is formulated as a multi-period mixed integer linear programming (MILP) that allows for both variable and fixed size storage systems. The real time dispatch strategy is presented as a 2-stage convex linear programming (LP) heuristic that involves management of both real and reactive power, and incorporates ARIMA based generation forecasting methods to aid prediction of future generation, which is used to optimise for end user self-consumption, line loss reduction, storage efficiency loss reductions, and storage degradation minimisation. We apply both models to an unbalanced 3-phase openDSS model of a particularly sensitive LV feeder in the northwest of England, compare placements costs to the costs of reconductoring (which are calculated using a further novel MILP formulation), and use the real time dispatch strategy to identify self-consumption potential that cannot be determined from a placement calculation. We show that even with near ideal placement, costing, and control conditions, storage for voltage and utilization control at the 230 V level cannot compete economically with traditional means of reinforcement in the UK for our particular case study.

1. Introduction

Since the impact of traditional fossil fuel generation on the environment and on the security and sustainability of supply has become a concern, the penetration of renewable and low carbon technologies in the UK energy mix has continuously increased. Current estimates suggest a total installed capacity of 12.7 GW solar photovoltaic (PV) [1] and 17.9 GW wind [2], CHP systems make up 560 MW of electrical power capacity and 2.3 GW heat capacity [3], and interest in poly-generation and microgrid systems and their operation is growing in literature [4,5].

The rate of rooftop PV uptake in the UK has somewhat slowed since a significant reduction in feed in tariff [6], though sources still predict a potential for increase in penetration between 18%–25% by 2035 [7]. Reductions in system costs may further influence uptake; IRENA show that the costs of PV modules have fallen by 80% over the last 8 years due to efficiency improvements and general economy of scale [8], and it is predicted that system costs could fall by a further 59%, which is in some part due to projected improvements in affordability of state of-the-art technologies such as concentrated silicon solar cells [9] and multi-junction solar cells, which have been shown to achieve efficiencies of 27.5% and 42% respectively [10]. Though individual array sizes are unlikely to increase above 4 kWp (as generation and export tariffs fall for systems that exceed this size [6]), the increase in number of systems could stress some low voltage (LV) network topologies to the point of violation.

With an increasing penetration of distributed PV generation on UK networks, it becomes increasingly likely that LV (230 V 1Ø, 400 V 3Ø) networks will experience utilization and voltage conditions that violate network capacity constraints and statutory regulations [11]. It is therefore important to consider the methods that may be used to limit LV network violations to within acceptable levels. Previous work often concerns the installation and control of on-load tap changers (OLTCs) at secondary

* Correspondence to: 44 Lavender Way, Wincobank, Sheffield, S5 6DH, UK.
E-mail address: RCJohnson2@sheffield.ac.uk (R.C. Johnson).

[1] BES – Battery Energy Storage, BESS – Battery Energy Storage System, SSS – Secondary Substation.

https://doi.org/10.1016/j.est.2018.03.005
2352-152X/

Nomenclature

$\otimes$	Tensor product
$\circ$	Elementwise multiplication of vectors
$\boldsymbol{J}_{i,k}$	$i \times k$ vector of 1's
$0_{i,k}$	$i \times k$ vector of 0's
$A_{ch,i,t}$	Import cost for BESS i (£)
$\boldsymbol{A}_{ch,t}$	$n_l \times 1$ vector of $A_{ch,i,t}$ values
$\boldsymbol{A}_{deg,t}$	$n_l \times 1$ vector of $A_{deg,i,t}$ values
$A_{GenDem,i,t}$	Cost penalty for import/export of real power by BESS i at time t
$\boldsymbol{A}_{GenDem,t}$	$n_l \times 1$ vector of $A_{GenDem,i,t}$ values
$\boldsymbol{A}_{LL,P,t}$, $\boldsymbol{A}_{LL,Q,t}$	$n_\varnothing n_c \times 1$ vectors of line loss costs for all major line segments on all phases (£) caused by real and reactive power transfer respectively
$\boldsymbol{A}_{m,t}$	$n_l \times 1$ vector of max trajectory penalties for each BESS (£)
$\boldsymbol{A}_{PF,t}$	$n_\varnothing \times 1$ total excessive reactive power cost penalty for each phase at the feeder head (£)
$\boldsymbol{A}_{Q,t}$	$n_l \times 1$ penalty for reactive demand/export from BESS inverters at each residential site at time t (£)
$\boldsymbol{A}_{SL,t}$	$n_l \times 1$ vector of BESS i η losses at time t (£)
$\boldsymbol{B}_{VP}$, $\boldsymbol{B}_{VQ}$	Sensitivity matrices that describe the change in voltage at each monitor point with change in real and reactive power inject/demand at each residence.
$\boldsymbol{B}_{Recon}$	Sensitivity matrix that describes the change in voltage at each monitor point with reconductoring of each major line segment
$c_{deg,i,t}$	Predicted cost of BESS i capacity loss per change in power setting (£/ΔkW)
c_E	Cost per unit of BESS energy capacity (£/kWh)
$c_{kWh,d,i,t}$	Per kWh energy import costs for customer i at time t (£/kWh)
$\boldsymbol{c}_{kWh,d,t}$	$n_l \times 1$ vector of $C_{kWh,d,i,t}$ values
$\boldsymbol{c}_{kWh,ex}$	$n_l \times 1$ vector of per kWh penalty for export of power (£/kWh) – all elements equal
$c_{LL,P}$	Per kWh penalty for line losses related to real power transfer (£/kWh)
$c_{LL,Q}$	Per kWh penalty for line losses related to reactive power transfer (£/kWh)
c_m	Per kWh penalty for breach of the maximum SOC trajectory (£/kWh)
c_{PF}	Per kvar penalty for excessive reactive power consumption (£/kvar)
c_S	Cost per unit inverter power capacity (£/kW)
$\boldsymbol{c}_{Recon}$	$n_c \times 1$ vector of conductor segment reinforcement costs
$c_{sys,i}$	Cost of BESS i (£)
c_X	Cost of installation per BESS (£/installation)
$DNS_{total,i}$	Predicted demand that will not be served by either PV generation or the BESS at residence i
ΔD_i	Change in daily capacity loss with increase in SOC by 1 kWh
E_i^s	Energy capacity of BESS i (kWh)
$\boldsymbol{E}^s$	$n_l \times 1$ vector of BESS energy capacities (kWh)
$\boldsymbol{I}^{Head}$	$n_\Phi \times 1$ per phase feeder head ampacities (A)
$\boldsymbol{I}_{\max}^{Head}$	$n_\Phi \times 1$ per phase feeder head maximum acceptable ampacities (A)
n_c	Total number of line segments
n_l	Total number of residences
η_{eff}	BESS charging/discharging efficiency
n_E	Number of voltage monitoring points
PF	Power factor
$\boldsymbol{P}_t^{Head}$	$n_\Phi \times 1$ vector of real power flows across each phase of the feeder head (kW)
$\boldsymbol{P}_{i,t-1}^d$	$n_l \times 1$ vector of real power demand on network by load i at time $t-1$ (kW)
$\boldsymbol{P}_t^d$	$n_l \times 1$ vector of predicted load demand values at each residence in prediction model
$\boldsymbol{P}_{i,t-1}^g$	$n_l \times 1$ vector of real power inject by generator i at time $t-1$ (kW)
$\boldsymbol{P}_t^g$	$n_l \times 1$ vector of predicted generation values at each residence in prediction model
$P_{i,t-1}^s$	Real power discharged onto network by BESS i at time $t-1$ (negative charging) (kW)
$\boldsymbol{P}_{t-1}^s$	$n_l \times 1$ vector of $P_{i,t-1}^s$ values
$P_{i,t}^s$	Real power discharged onto network by BESS i at time t (negative charging) (kW)
$\boldsymbol{P}_t^s$	$n_l \times 1$ vector of $P_{i,t}^s$ values
$\Delta P_{i,t}^s$	Change in real power discharged onto network by BESS i at time t (negative towards charging) (kW)
$\Delta\boldsymbol{P}_t^s$	$n_l \times 1$ vector of $\Delta P_{i,t}^s$ values
$\boldsymbol{Q}_t^{Head}$	$n_\phi \times 1$ vector of reactive power flow across each phase of the feeder head (kvar)
$\boldsymbol{Q}_{t-1}^s$	$n_l \times 1$ vector of leading reactive powers injected onto network by each BESS at time $t-1$ (negative lagging) (kvar)
$Q_{i,t}^s$	Leading reactive power injected onto network by BESS i at time t (negative lagging) (kvar)
$\boldsymbol{Q}_t^s$	$n_l \times 1$ vector of $Q_{i,t}^s$ values
$\Delta\boldsymbol{Q}_t^s$	$n_l \times 1$ vector of changes in leading reactive powers injected onto network by each BESS at time t (negative towards lagging) (kvar)
S_i^{inv}	Total apparent power capacity of BESS inverter i (kVA)
$\boldsymbol{S}^{inv}$	$n_l \times 1$ vector of S_i^{inv} values
$SOC_{DA,i}$	Maximum allowed SOC at the beginning of the next day for BESS i
$\boldsymbol{V}_t^{End}$	$n_\Phi n_E \times 1$ vector of voltages on each phase of each end monitoring point at time t
$\boldsymbol{V}_{\min}$	$n_E \times 1$ vector of the minimum allowable steady state voltage – 216 V ESQCR, 207 V EN 50160 (V)
$\boldsymbol{V}_{\max}$	$n_E \times 1$ vector of the maximum allowable steady state voltage – 253 V (V)
$\boldsymbol{X}^{Recon}$	$n_l \times 1$ vector of binary variables for the existence of reinforcement on conductor segments
$\boldsymbol{X}^s$	$n_l \times 1$ vector of binary variables for the existence of each BESS

substations (SSSs) [12], reactive power compensation using PV inverters [13], traditional reconductoring [14], Curtailment of generation [15], and control of distributed battery energy storage systems (BESSs) [13]. Availability of affordable residential BESS systems with large enough capacities to handle feed in limiting tasks across multiple hours, such as the Tesla Powerwall 2 (13.2 kWh, 5 kW max continuous) [16] and the Mercedes-Benz Energiespeicher (2.3–18 kWh, 1.25–4.6 kW max continuous) [17], have made violation control via BESS charging a potential solution. Furthermore, modern BESS inverters often have the capability to operate at non-unity power factors [16,18], and research and development of inverters able to make operational decisions based on remote grid signals is ongoing; for example, Ippolito et al. [19] developed an inverter capable of determining the appropriate