Proceedings Paper:

Johnson, R.C., Mayfield, M. orcid.org/0000-0002-9174-1773 and Beck, S.B.M. orcid.org/0000-0003-2673-4179 (2018) Battery energy storage for management of LV network operational violations : a multi-feeder analysis. In: Cruden, A., Stone, D., Mayfield, M., Young, E., Inkson, B., Cumming, D., Boston, B., Jones, C. and Brown, S., (eds.) Energy Procedia. 3rd Annual Conference in Energy Storage and Its Applications, 11-12 Sep 2018, Sheffield, UK. Elsevier , pp. 31-36.

https://doi.org/10.1016/j.egypro.2018.09.023

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 151 (2018) 31–36

Energy Procedia

www.elsevier.com/locate/procedia

3rd Annual Conference in Energy Storage and Its Applications, 3rd CDT-ESA-AC,
11–12 September 2018, Sheffield, UK

Battery energy storage for management of LV network operational violations: a multi-feeder analysis

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Abstract

With increasing penetration of rooftop PV systems on UK LV networks, it is becoming more likely that specific LV networks will experience unacceptable line congestion and voltage rises. In this study, we use Mixed Integer Quadratically Constrained Program (MIQCP) formulations to examine the possibility of eliminating these violations via aggregation and control of behind-the-meter (BTM) battery energy storage systems (BESSs), therefore delaying traditional reinforcement. By applying the formulations to 29 UK LV feeders, we examine the trends between the violation control capability of each method and a set of feeder topology metrics, to determine whether the suitability of networks to violation management strategies may be predicted from easy to obtain metrics, rather than extensive power flow modelling. It is found that instances in which BESSs may be reliably used to manage violations exist but are infrequent,

Selection and peer-review under responsibility of the 3rd Annual Conference in Energy Storage and Its Applications, 3rd CDT-ESA-AC.

Keywords: "LV networks; PV; Aggregation; Optimization"

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1. Introduction

As consumer ownership of behind-the-meter battery energy storage systems (BESSs) increases, there is potential for control of such BESSs to be taken over by aggregators and operated in ways that prevent voltage and ampacity violations caused by increasing PV generation on LV networks, thus delaying the need for traditional reinforcement. MIQCP formulations used to determine the minimum number of customer BESS takeovers required to prevent PV-caused voltage and ampacity violations on LV networks were developed in our previous work [1]. The formulations allow consideration of varying PV penetrations, and non-optimal BESS availability and location, and are therefore better suited to simulating the non-ideal conditions that future network planners may have to tolerate if considering a BESS takeover and aggregation scheme. In this study, we apply these formulations to 29 different UK LV feeders, and analyse the extent of asset takeover required to sufficiently reduce violations on each network.

1. **Terminology**

The following terms are used as shorthand throughout,

- FIL – Feed-in-limiting control – BESSs charge when PV generation exceeds a threshold (details in [1]).
- Centralised – Centralised control – the set of BESSs are controlled as an ensemble, based on network voltages, line ampacities, present BESS SOCs and predicted BESS SOCs, with the aim of minimising total charging power (details in [2]).
- Solvable – Implies that a solution exists to the violation elimination problem (e.g. 'solvable placement configuration' means that the violations caused by this specific PV configuration are technically solvable by either takeover of BESS's or reconductoring, dependent on which technology we are considering).
- PV/BESS configuration – the specific location of each of the PV arrays/available BESSs .
- Storage availability % - percentage of PV array owners who also own BESS systems.
- PV fraction – percentage of residences who have a PV array installed on the rooftop of their property.

We define the following output metrics, which are used to assess success of violation control and the extent of required reinforcement.

- Specific feeder BESS control % (SFBC%) - The percentage of simulated PV placement configurations that are solvable using BESS takeover methods, at a given PV fraction and BESS availability %.
- Full Set BESS control % - The percentage of simulated feeders that achieve a SFBC% ≥ 95% at a given PV fraction and BESS availability %.

2. Methodology

Using the BESS optimal takeover formulations developed in [1], we determine the % of PV/ BESS placement configurations in which each network is solvable at PV penetrations of 0%, 20%, 40%, 60%, 80%, 100% and BESS availability %'s of 25%, 50%, 75%, and 100%. We assess 50 different PV placement configurations at each PV fraction. Within each PV placement configuration, 30 BESS placement configurations are tested, to account for the fact that in a customer owned storage situation, the pattern of available BESSs may change over time. PV generators are sized between 1 – 4 kWp, with array size probabilities based on UK ownership data [3], and BESS energy, power, and power factor capabilities are based on those of the Tesla Powerwall 2 [4].

The formulations are applied to 29 feeders across 7 UK LV networks located in the northwest of England, which were chosen for their range of different topological properties (fig. 1). Feeder models were obtained from the UoM dataset [5]. Power flow simulations are performed using openDSS, optimisation uses the MIQCP and MILP functionality of IBM CPLEX, and data communications and processing tasks are performed in MATLAB.

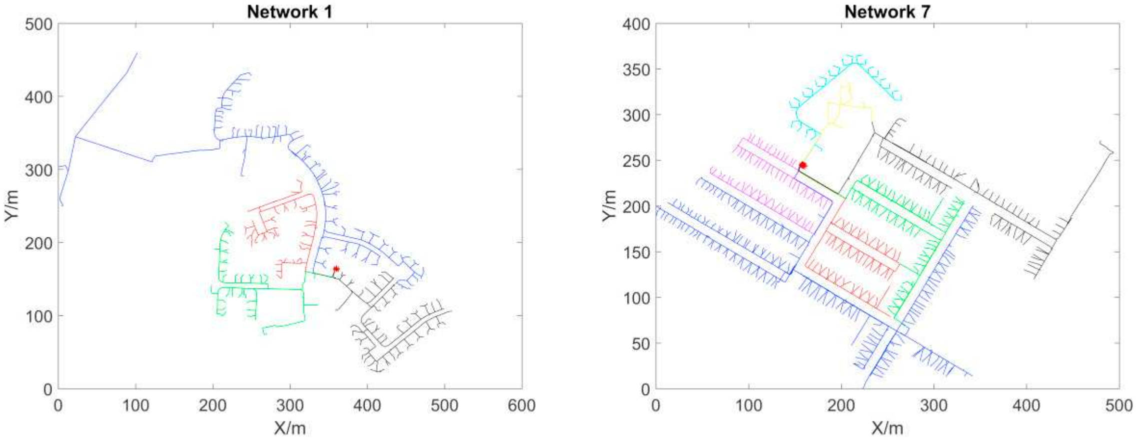

Fig. 1 – Topology of networks 1 & 7 (feeders 1-7 shown in colour order black, green, red blue, magenta, yellow, cyan). Network 1 (left) represents a residential portion of a typical suburban area, whereas network 7 (right) is typical of a densely populated urban area.

We also examine the correlation between the output metric SFBC% and the set of topological metrics (Table 1), to determine whether the technical feasibility of BESS or reconductoring based violation management may be adequately approximated without the need for detailed simulation.

Table 1. Definition of topological metrics

Topological Metric	Definition
Load count	The total number of residences on the feeder
Convex area	Total area of the feeders' convex hull (km^2)
Convex load density	Ratio of load count to convex area
Feeder head loading	The ratio of number of loads to the feeder head capacity (in kVA).
Mean path resistance	Average resistance between residence and the SSS.
Total resistance	Sum of resistances of the entire feeder (i.e. laterals and service cables included).
Main path resistance	Resistance of the main length of the feeder (i.e. laterals excluded)
Mean path length	Average cable length between residence and the SSS.
Total length	Total length of the entire feeder (i.e. laterals and service cables included).
Main path length	Length of the main feeder path (i.e. laterals and service cables excluded)

In the centralized control context, BESS control is feasible for 80% of networks at PV fractions ≤ 0.4. However, at BESS availability = 50%, control % is only slightly higher than the no reinforcement case, and at BESS availability = 25%, control % is nearly equal to the no reinforcement case. No BESS availability < 75% results in a significant control % improvement at PV fractions ≥ 0.8 (fig. 2). FIL control results are almost identical to the centralized case at BESS availability ≤ 0.5. However, technical feasibility falls at all PV penetrations when BESS availability = 0.75. When BESS availability < 100% and PV fractions ≥ 0.8, no control % improvement is seen over the base case at BESS availability = 1.0, 0.5 and 0.25 (fig. 2).

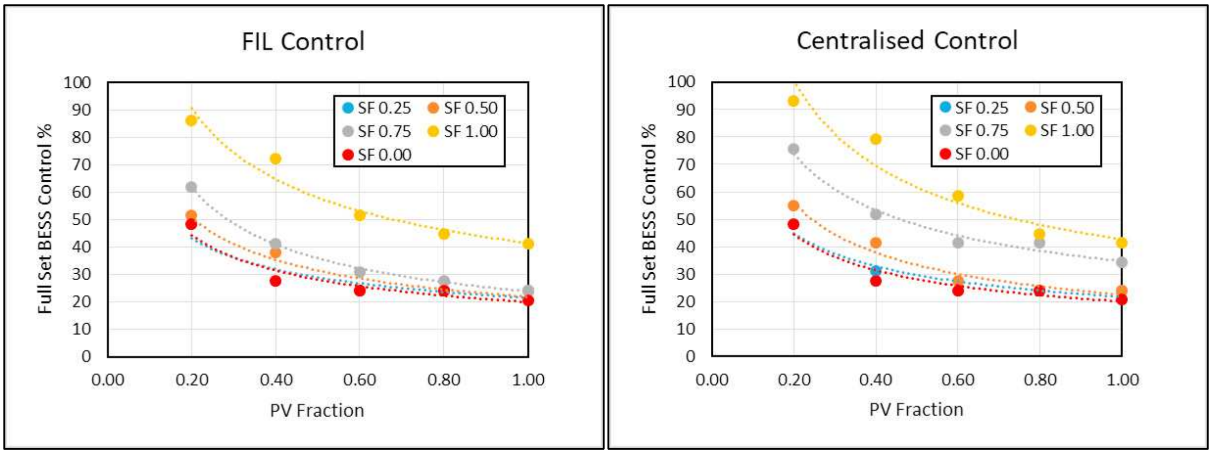

Fig. 2 – (left) shows Full Set BESS Control % at every tested BESS availability % and PV fraction in the FIL control case (right) the same for the centralised control case.

As many of the networks experience voltage violations before ampacity violations, it was seen as necessary to consider the effect of reducing the tap position at SSSs to either 1.025 p.u. or 1.0 p.u where possible. Of the 29 feeders examined, only 9 could host any reduction in tap position; most violated the lower voltage limit during high demand periods in this instance, or were served by the same transformer as another feeder that could not tolerate a tap position reduction. FSBC% was improved in all decreased tap scenarios, though the presence of BESSs at an availability level <50% resulted in no rise of FSBC% above the base case (fig. 3).

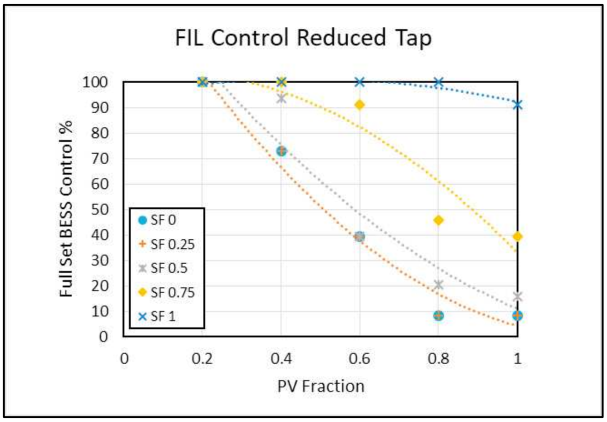

Fig. 3 – FSBC % vs PV fraction for the 9 feeders that can operate at lower tap positions, in their lower tap positions.

Unfortunately, no correlation strong enough to be represented by regression could be found between SFBC% and any of the metrics listed in table 1 (e.g. fig. 4). This phenomena can be explained by the binary nature of SFBC%; BESS control has a tendency to be able to solve either almost all placement configurations of a given network, PV fraction and BESS availability, or almost none (in fact only 16% of points on fig. 5 fall between 5% - 95% success).

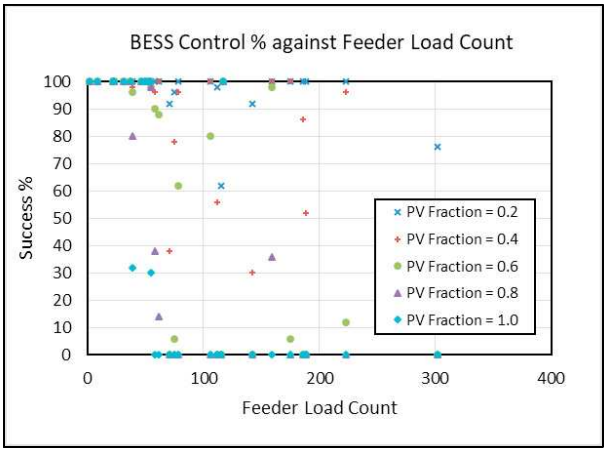

Fig. 4. SFBC% for specific feeders vs load count - whilst there is a general reduction in control with increase in all metrics (except load density), we do not observe an obvious linear trend.

However, it was clear from the FSBC% results that the same analysis could be performed across different bands of topology metrics to give different distributions (e.g. 0-100m mean path, 101-200m mean path). Though we could not analyse this trend with only 29 feeders, it may be worth further investigation.

3. Discussion

The FSBC% analysis provides an insight into the fraction of LV networks that could benefit from the use of BESS's to defer traditional reinforcement, as a function of PV penetration and availability of behind-the-meter BESS systems. However, due to the extensive resources required to run the simulations we have only been able to analyse a small number of feeders. We therefore endeavour to perform a wider scale analysis to confirm the reproducibility and generality of the observed trends.

Results suggest that instances in which FIL based BESS takeover can provide a solution to violations with BESS availability ≤ 50% are rare, even at low PV fractions. Furthermore, even at higher BESS availability %'s, slight changes in PV and BESS placement configurations were seen to alter the technical feasibility of BESS control on many feeders, and so it may be irresponsible to rely on BESSs for long term control due to the high likelihood of such changes occurring.

In the centralized case, FSBC% is consistently higher than in the FIL case, though little improvement is observed when availability % < 75%. This suggests that unless customer BESS ownership is extremely commonplace in future, FSBC% will be near independent of control strategy complexity.

4. Conclusion

We have analysed the technical feasibility of BESS based violation control across 29 feeders. The results suggest that the technical feasibility of such schemes are often not guaranteed, and at BESS availability % < 75% feeders cannot usually be solved consistently. We therefore believe that whist FIL based BESS control may be useful on certain networks for short term deferral of reconductoring, BESSs should not be relied on to provide long term deferral.

Acknowledgements

The authors would like to acknowledge the support of the Engineering and Physical Sciences Research Council (EPSRC) Centre for Doctoral Training in "Energy Storage and Its Applications" (EP/L016818/1).

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