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The impact of location and type on the performance of low-voltage network connected battery energy storage systems

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HIGHLIGHTS

- Placement of energy storage based on models of real LV distribution network.
- Energy storage for peak power reduction.
- Comparison of energy storage only versus energy storage with phase balancing.
- Additional benefit of voltage support and losses reduction.

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ABSTRACT

This paper assesses the impact of the location and configuration of Battery Energy Storage Systems (BESS) on Low-Voltage (LV) feeders. BESS are now being deployed on LV networks by Distribution Network Operators (DNOs) as an alternative to conventional reinforcement (e.g. upgrading cables and transformers) in response to increased electricity demand from new technologies such as electric vehicles. By storing energy during periods of low demand and then releasing that energy at times of high demand, the peak demand of a given LV substation on the grid can be reduced therefore mitigating or at least delaying the need for replacement and upgrade. However, existing research into this application of BESS tends to evaluate the aggregated impact of such systems at the substation level and does not systematically consider the impact of the location and configuration of BESS on the voltage profiles, losses and utilisation within a given feeder.

In this paper, four configurations of BESS are considered: single-phase, unlinked three-phase, linked three-phase without storage for phase-balancing only, and linked three-phase with storage. These four configurations are then assessed based on models of two real LV networks. In each case, the impact of the BESS is systematically evaluated at every node in the LV network using Matlab linked with OpenDSS. The location and configuration of a BESS is shown to be critical when seeking the best overall network impact or when considering specific impacts on voltage, losses, or utilisation separately. Furthermore, the paper also demonstrates that phase-balancing without energy storage can provide much of the gains on unbalanced networks compared to systems with energy storage.

1. Introduction

The transition to a low carbon economy is a major focus of energy policy in the UK and internationally as governments respond to challenging environmental targets [1,2]. In particular, the decarbonisation of the heat and transport sectors are areas of significant strategic focus and Low Carbon Technology (LCT) such as photovoltaic (PV) generation, electric vehicles (EV) and heat pumps (HP) are expected to make significant contributions to this transition [3,4].

As domestic consumers adopt these Low-Carbon Technologies (LCTs) in greater numbers and the penetration of such technologies within the network increases, the distribution networks will come under increased stress. Furthermore, the uptake is expected to not be evenly distributed with clusters forming in the early stages of adoption leading to certain LV networks exceeding their constraints even at low national adoption rates [5]. However, traditional planning approaches are not fit-for-purpose for this uptake of LCTs. For Low-Voltage (LV) networks, traditional

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planning commonly utilises established understanding of diversity where After Diversity Maximum Demand (ADMD) values are applied to voltage drop and loading calculations. Unchanged for many years, these methods are based on historical load analysis and incorporate standard load growth assumptions that are no longer valid. Furthermore, once installed, the networks are generally unmonitored.

DNOs are aware that changes are needed in the planning process and analysis of future network trends has predicted distribution network operators will become more active in operating via innovation in the use of existing and new technologies [6]. The Smart Grid which, although varying definitions exist, is often described in terms of a power system with increased use of innovative technology is considered essential in order to facilitate the low carbon transition [7–9], and so these changes and associated challenges cannot be avoided.

Traditional network reinforcement solutions involve adjustment of secondary transformer tap settings followed by asset upgrade (e.g. transformer upgrade and line re-conductoring) where the impact from changing the tap settings is insufficient. As a technical solution that avoids directly interfacing with customers to alter demand and generation profiles, Battery Energy Storage Systems (BESS) are receiving increased attention in academic studies and industrial trials. By locating BESS at strategic locations within the distribution network, power flows can be managed and benefits achieved in terms of voltage profile, cable loading (line utilisation) and losses. Appropriate charging and discharging can offset excessive voltage rise and reverse-power flow due to PV installations, excessive voltage drop and thermal overloads due to new LCT load, and in general improve losses through peak demand reduction. However, these benefits are often assessed in aggregation, and so don't consider the location of the BESS within the LV feeder, or are considered in isolation and assume that a location that is ideal for voltage, for example, is also ideal for peak power flow. This paper will demonstrate that this assumption is in most cases not valid and the in general location within the feeder is a critical consideration when trying to maximise the benefits from BESS.

A number of BESS were installed and trialled in the UK distribution networks. Above the LV level, the main purpose of BESS is to provide support for primary substations and mitigate operational constraints [10,11] or provide balancing services and reduce curtailment of renewable generation [12]. In these cases, the anticipated impact of BESS is known, as the distribution networks at medium voltage are closely monitored. On the LV network, BESS have been installed within the customer premises aiming to increase self-consumption of domestic PV generations and making use of time-of-use tariffs [13]. Community energy storage has been trialled to support the LV feeder through peak shaving and reactive power injection/absorption [14]. BESS have also been deployed on LV feeders at the street-level, owned and controlled by the DNO, in order to reduce peak demand on a given feeder as well as to address voltage constraints and harmonics [15].

In all the cases described above, forecasting at least day-ahead power and energy demand is essential in order to optimise management of the BESS. Set-point based control methods, that operate a battery rather like a thermostat regulates temperature and charge or discharge based on one or more thresholds, are able to demonstrate a net positive impact but achieve far from optimal performance and so often require bigger batteries for the same gain compared to forecast-based methods. By incorporating an expectation of future demand, albeit with a level of uncertainty that must be taken into account, control methods that include forecasts are able to outperform set-point based methods by reserving headroom for the periods of lowest demand and capacity for the periods of highest demand in the day [16,17].

In practical situations, the feasible installation locations and configurations of storage units may be limited. Field trial deployments have used engineering judgement and product availability to configure and locate BESS in distribution networks to evaluate benefits [18,14]. Further evaluation indicates that practical BESS deployments can support voltage and power flow events but should not be expected to provide a solution to all events at all times. Establishing the business case requires maximising the benefits against multiple objectives and realising the full potential of the technology. Paying attention to the impact of the location of the BESS within a feeder is one key part maximising these benefits.

The work presented in this paper is motivated by the LCNF New Thames Valley Vision Project (NTVV) where BESS have been installed on the LV network at the street level and are operated by the DNO [19]. Assuming access to retrospective smart meter data but limited real-time network monitoring, the existing control strategy for these BESS is to forecast individual end-point (e.g. household) load profiles, aggregate them at the substation level, and then determine the charge and discharge schedule for the BESS on a per phase basis that minimises the overall daily peak demand seen at the substation. However, although the result of this peak reduction is improved voltage profile, cable loading and losses upstream of the BESS, LV feeder conditions are not explicitly included in the control strategy and the potential benefits to the LV network are not considered. This paper builds on the existing scheduling algorithm work and addresses this issue of how best to locate and operate such BESS units in LV networks for maximum overall benefit within the LV network itself. The paper develops an analytical method for the positioning of known configurations of BESS, operating in the peak reduction mode described above, on LV feeders for maximum benefit to the LV network conditions.

2. Methodology

The impact of various BESS peak configurations and associated control algorithm, on real LV networks under worst case loading conditions, is assessed in order to establish the key considerations and trade-off's between a range of network performance metrics and BESS location. The LV networks selected, described in detail in Section 2.1, are real urban LV feeders with common characteristics such as multiple branches and single phase spurs. Furthermore, existing demand is pushing the operational conditions of these networks outside the statutory limits. Examining real networks instead of a theoretical, simple radial feeder helps to highlight the complexities of real networks. However, as discussed further in Section 2.1.1, real smart meter data for individual customers from a separate study is used to drive the models in this paper. Nevertheless, network constraints on the two networks are also breached in the results presented later in the paper suggesting that the reason for these violations is partially due to the existing network structure.

The configurations and algorithms, explained in detail in Section 3, illustrate a range of operational examples and highlight key issues, but are not necessarily intended as optimal or best-in-class exemplars. The selected configurations and algorithms do highlight the separate role of power electronics and energy storage in terms of both phase-balancing and peak reduction, which is not commonly considered in the literature. The algorithms used in this paper seek to reduce the peak power demand during day and do not take into account voltage, losses or utilisation. However, the