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# Comparative analysis of domestic and feeder connected batteries for low voltage networks with high photovoltaic penetration

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ABSTRACT

Excessive voltage and power flow issues associated with domestic solar power are threatening UK distribution system operation and the use of energy storage is one method proposed to mitigate these issues. In this study a data orientated approach was taken in order to simulate the effect of the location of the energy storage on the low voltage network. A number of small (<15 kWh) domestic batteries were compared to a single larger (>50 kWh) feeder connected battery in terms of their ability to shave load demand peaks, fill load demand valleys and counter voltage violations on a typical radial feeder system. To achieve this MatLab was used to create dispatch strategies for each battery and introduce them into an aggregated load, and OpenDSS was then used to model this scenario on a typical UK radial feeder based on the IEEE European Low Voltage Test Case.

It was found that the feeder connected battery was more successful at mitigating the thermal overload effects of distributed generation at the low voltage level. Domestic batteries offer ease of installation and consumer support, likely to make their utilisation increasingly inevitable. However, their exposure to domestic energy flows and focus on minimising grid import to the home led to a reduced network level impact. This work shows that a feeder connected battery can respond to the power flows of the aggregated load and thus provides a far more capable tool for reducing network peak loads and preventing feeder system export.



## 1. Introduction

The UK has a requirement to reduce its carbon dioxide emissions by 80% by 2050 when compared to 1990 levels [1]. In order to achieve this ambitious target increasing numbers of renewable energy installations are being integrated into the national grid [2]. Renewable energy sources are, by their nature, intermittent and as such, a mechanism must be adopted to reduce mismatch between the demand and supply of electrical energy. Energy storage has been proposed as one method of achieving this where energy is stored when supply peaks and released when demand outstrips supply.

A recent concern within the UK has been electric network issues caused by domestic solar power, creating a demand for energy storage in two areas. Firstly, a homeowner with installed photovoltaic (PV) panels may want to reduce their reliance on supply from the grid and become self-sufficient. In this way the price paid for electricity can be minimised as well as reducing the homeowner's environmental impact. An energy store must be employed to enable this since domestic electrical demand does not match well with solar irradiance [3]. Secondly, clustering of PV installations through community organisational effects and passive peer influence [4] leads to a high level of pressure on the grid infrastructure. This, without intervention, can lead to power flows and voltages straying from regulated limits [5]. As such, increased utilisation of energy storage in the distribution system can prevent or defer costly network upgrades needed due to these effects.

There was a large growth in solar PV installations in the UK during 2014, with overall PV capacity at the end of 2014 at 5095 MW following a 79% annual increase [6]. This huge growth provided a significant stress to the ageing distribution system and caused a large change in the demands placed on the distribution infrastructure. This became an issue since the distribution network

*Abbreviations:* VUF, voltage unbalance factor; ADMD, after diversity maximum demand; MA, moving average; MSTD, moving standard deviation.

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was not designed to enable distributed generation, where the component capacities for power flow are too low to be effective at high penetration levels, increasing the risk of circuit overload and voltage violation causing damage to components both within the distribution system and at the consumer end [7]. This continues to be a rapidly growing issue due to the prolific uptake of distributed generation and unlike most previous network issues it is not localised, rather it is affecting the entire system and a system wide approach must be adopted in order to mitigate it.

The constraints on distribution networks can be described by two key effects:

1. *Voltage violation* – Distributed generators can increase the voltage in the network they are connected to when they supply power. In order to prevent damage to network connected infrastructure the voltage must lie within set limits (+10%, −6% for the LV network) [8] and as such distributed generators can cause violation of these limits. In addition, voltage violation can be caused by voltage unbalance when a variation of greater than 2% is seen in the voltage [8].
2. *Thermal overload* – The components of the distribution grid are required to transmit more power than they are designed for, hence, temperature increases and component failures can result, causing damage.

## 2. Theory

### 2.1. Voltage violation

In order to achieve the stated quality of service guaranteed standards [9] the voltage on the system must not go above or below set limits [8]. These regulations are in place in order to prevent damage to network connected infrastructure.

Voltage rise at the connection point of a distributed generator is caused by power injection. For a radial feeder layout it can be expressed by Eq. (1) [10].

$$\Delta V \approx \frac{(P_G - P_L)R + (Q_G - Q_L)X}{V} \tag{1}$$

$P_G$ and $Q_G$ are the real (kW) and reactive (kVA) powers of the distributed generator and $P_L$ and $Q_L$ are same for the line load. $R$ and $X$ are the line resistance and reactance (in Ohms) between the distributed generator and the substation and $V$ is the line voltage (V) at the connection point. As such it can be seen that the problem of voltage rise is exacerbated by low load power on the feeder and high line resistance and reactance or line length.

Voltage unbalance is caused by non-equal loads on each of the phases in the distribution system. Unbalance is one of the biggest problems facing LV networks [11]. It is stated in Engineering Recommendation P29 [12] that voltage unbalance be kept to within 2% for the entire network. This recommendation is in place to prevent damage to 3-phase equipment which can be caused by voltage unbalance [13]. Domestic PV installations, by their nature, provide a very inconsistent power injection onto a single phase in the network and as such greatly contribute to voltage unbalance [14]. It is possible that, within a feeder system, 70–90% of the PV installations are on the same phase and in this situation a very large voltage unbalance would be expected to occur under conditions of domestic solar power export [11] and this effect is increased with distance from the substation. The definition of voltage unbalance is, however, not always consistent.

The voltage unbalance rate (VUR) is calculated as:

$$VUR\,\% = \frac{\text{Maximum voltage deviation}}{\text{Average voltage}} \times 100 \tag{2}$$

This definition is open to interpretation and, as shown by Pillay and Manyage [15], there are a number of different definitions depending on whether the average voltage is taken from the line or the phase. However, in both of these definitions only the magnitude of the unbalance is considered. The voltage unbalance factor (VUF) is the true definition of voltage unbalance and accounts for the change in phase angle, it is defined as:

$$VUF\,\% = \frac{\text{negative sequence voltage component}}{\text{positive sequence voltage component}} \times 100 \tag{3}$$

Voltage unbalance figures presented in this work are stated as VUF.

### 2.2. Thermal overload

Thermal overload threatens the components of the distribution system through heating caused by the actual power exceeding equipment rated power levels.

Power transformers are the most expensive and important components in the electrical distribution network [16] and a power overload of this component can lead to multiple failure mechanisms [17]. Heating of the top oil in a power transformer, is often a precursor to failure. As heating above rated is proportional to the ratio of rated to actual load raised to the power of 1.4 [18], a failure from overheating becomes increasingly likely as the load increases.

The maximum current which overhead lines are permitted to carry is dependent on the overall heat transfer to the cable and the resistance as described in Eq. (4) [14].

$$I_{OL} = \sqrt{\frac{\Delta H}{R}} \tag{4}$$

$I_{OL}$ is the current in the overhead line (A), $R$ is the resistance ($\Omega$) of those lines and $\Delta H$ is the heat transfer from the cable to the surrounding environment (in Watts). Thus, it can be seen that, for increasing overload currents, reducing the resistance has a diminishing positive effect, and reducing the current has a squared effect on power loss and overload compared to resistance. Therefore, action to reduce the peak export current from distributed renewable generation with the inclusion of paired energy storage has a more positive effect on the network than peak shaving or demand side management at a distant point where cable connections are constrained.

With an after diversity maximum demand (ADMD) of roughly 2 kW (depending on location and inhabitants of homes) in the UK [19] the DNOs design and implement distribution networks assuming a peak power of 2 kW per home on the network. As such $I_{OL}$ (from Eq. (4) for the cables in the network and the rated power for the transformers are already set to these levels. The penetration of domestic solar and other distributed generation leads to immediate increases in the ADMD of the network. Rooftop PV arrays with capacity 0–4 kW account for 26% of UK solar deployment, of these, the average capacity is 2.92 kWp [6]. However, the tariff structure in place until March 2016, encouraged PV arrays of 4 kWp since these provide the largest return on investment [20]. As such, for a worst case scenario, it is assumed that a typical domestic PV array has a peak power of 4 kW (double the ADMD), and at high penetration levels where, due to the close geographical nature of most feeder systems, the arrays will be producing peak power at the same time, the export power (unless utilised to charge a battery) can quickly exceed the rated power of the feeder transformer or cause overheating of the distribution cables. Upgrading this infrastructure is a very costly and lengthy process and should be avoided where possible. As such, an energy