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Flexible operation of shared energy storage at households to facilitate PV penetration

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ABSTRACT

This paper proposes a new methodology to enable high penetration of photovoltaic (PV) generation in low voltage (LV) distribution networks by using shared battery storage and variable tariffs. The battery installed at customer premises is shared between customers and local distribution network operators (DNOs) to achieve two goals-minimizing energy costs for customers and releasing distribution network constraints for DNOs. The two objectives are realised through a new concept - “charging envelope”, which dynamically allocates storage capacity between customers and the DNO. Charging envelope first reserves a portion of storage capacity for network operator's priority to mitigate network problems caused by either thermal or voltage limit violation in order to defer or even reduce network investment. Then, the remaining capacity is used by customers to respond to energy price variations to facilitate in-home PV penetration. Case study results show that the concept can provide an attractive solution to realise the dual conflicting objectives for network operators and customers. The proposed concept has been adopted by the Western Power Distribution (UK) in a smart grid demonstration project SoLa Bristol.

1. Introduction

The penetration of photovoltaic (PV) generation in low voltage (LV) networks is increasing across the UK, projected to be 22 GW by 2030. Along with benefits, the increasing PV also causes significant thermal and voltage violations for LV networks. Traditional approaches address these problems through network reinforcement, which is both expensive and time-consuming. Alternatively, demand side response (DSR), through sending economic signals, is an economic way to alter customer's energy use to ideally follow PV output [1–4]. From this aspect, energy storage empowers customers more flexibility in conducting DSR to maximise the benefits and help mitigate network issues caused by the increasing renewables [5].

Previous research [6–10] has been dedicated to using DSR and energy storage to tackle network issues with fluctuating renewable generation. Paper [11] proposes a novel active robust optimization dispatch by using robust optimization (RO) to study the impact of price responsive DSR, considering all possible wind power scenarios in a system. Papers [12,13] present an overview of challenges in integrating PV power into distribution networks and illustrates a variety of operational modes for battery storage systems to enable PV integration. In paper [14], a thermal unit commitment program is proposed which considers DSR for meeting system constraints, where electric vehicles (EVs) and heat pumps (HPs) are considered as controllable loads for enabling DSR. Paper [15] presents a multi-objective optimization method for evaluating the impact of energy storage costs on the net present value of installations in distribution substations. It uses a non-dominated sorting genetic algorithm (NSGA) optimization for load management to reduce costs. Paper [7] formulates a non-cooperative game model to analyse the existence of optimal strategies for customers with energy storage to reduce energy costs, where smart metering is considered. In paper [16], authors propose a method for coordinating multiple battery energy storage systems for voltage control in LV distribution networks. Generally, the existing work normally targets at either reducing energy costs for customers or releasing network pressures for Distribution Network Operators (DNOs), but the two problems are not resolved simultaneously.

In a low carbon energy system with substantial intermittent generation penetration, energy cost pressures may conform to network pressures (voltage or thermal problems), i.e. when demand is at peak (normally energy cost is high), renewable

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generation could also be at peak. Thus, energy storage is better not only used for reducing customers' energy costs but also for shaving system peak demand. The joint operation of DSR and energy storage can efficiently reduce energy cost and release network congestions. This is a dual-objective problem and papers [8,17] are the first effort to address it. They introduce a joint ownership of battery storage between customers and local DNOs to mitigate high energy costs and reduce network congestions. However, they assume a 'static' ownership sharing scheme, i.e. the share between customers and DNOs does not change with the variations of energy prices and network conditions.

In reality, PV output, customer energy consumption, and network conditions vary dramatically with time, and thus a flexible share of energy storage can maximise the potential benefits for both parties. The shared energy storage is invested by the DNO but can be operated by both the DNO and the customer at whose premise the storage installed. The primary target of DNO to operate it is to help manage the networks, i.e. resolving voltage and thermal limit violations. Then, the remaining capacity is utilised by the customers to manage their PV output and energy use in response to variable electricity tariffs. This problem could be modelled as a dual or multi-objective problem, but the simultaneous optimisation could not reflect the management sequence.

This paper introduces a new solution to tackle the conflicts between the aims to address network pressures and energy costs simultaneously by utilising a shared energy storage. It proposes a novel concept of "charging envelope" to realise a joint storage ownership between DNOs and customers to achieve a dynamic share of the storage capacity in response to network conditions and energy prices. DNOs reserve a proportion of the capacity during projected network congestion periods to discharge energy for resolving voltage or thermal issues. Within the constraints of charging envelope, the remaining storage capacity is for customers to minimise energy costs via responding to energy tariffs and maximising PV penetration. The key advantages of the solutions are that they provide DNOs with greater certainty in mitigating network thermal or voltage violation problems. The concept has been utilised in a smart grid demonstration project in the UK. The major contributions are: i) a new approach to enable joint flexible battery share between DNOs and customers; ii) a new battery operation strategy based on time-of-use tariffs for customers to optimise energy costs.

2. Rationale of designing charging envelopes

This section briefly introduces the SoLa Bristol project which adopts the proposed approach, the concept of shared energy storage, and finally, charging envelops.

2.1. SoLa Bristol project

The SoLa Bristol project is an innovative combination of energy storage in customer premises, variable tariffs, and integrated LV network control techniques to overcome network constraints at key times of a day [18]. It is jointly sponsored by Western Power Distribution and UK market watchdog-the Office of Gas and Electricity Markets (Ofgem). This project supported 26 homes, 5 schools and an office block in Bristol to benefit from the new energy management concept [19]. It aims to address the technical constraints expected to arise on LV networks caused by increasing PV penetration with the assistance of energy storage. Through reducing network constraints and needed reinforcement, the trial techniques will facilitate PV penetration at a reduced cost. The sizes of PV and battery storaged installed are 3.5 kWp and 4.8 kWh respectively.

2.2. Shared energy storage

The trial project uses battery storage installed at customer households, invested by the DNO in this project, to provide benefits to customers and assist the DNO in network management. The battery is "virtually shared" between the customer and DNO. The DNO is able to communicate with the battery to operate it for network management. The DNO who invests the storage has the priority to use the battery storage. The main purposes are to resolve the thermal limit violation and voltage limit violation in the networks to reduce network investment. Then, the remained capacity of the storage not used by the DNO can be operated by the customer where the storage is installed. The customer is provided with variable tariffs to be encouraged to use electricity at the time of high PV generation and electricity from the storage when the network is heavily loaded. The customer who operates the remaining capacity mainly targets at maximising its PV output in order to reduce energy costs.

Through the storage, LV networks can be operated more actively with additional capacity to manage peak load and voltage rise [19]. For customers, the storage can enable high-density PV generation to be connected to the LV network more efficiently.

2.3. Charging envelope design

A charging envelope is to flexibly determine the capacity of battery storage operated by DNOs for addressing electricity network voltage and thermal issue. As given in Fig. 1, charging envelopes are the boundaries that define and constrain storage state of charge (SoC), including start time, duration and slope of charging/discharging. The upper and lower boundaries constrain the maximum and minimum SoC respectively for two purposes: i) resolving network pressures; ii) supplying DC load during discharging periods and accommodating PV penetration.

As seen in Fig. 1, the increasing slope of the upper boundary of the charging envelope limits the change of storage SoC, decided by the energy from PV and the grid. The decreasing, i.e. discharging, slope of the upper boundary represents the minimum drop of SoC. The decrement is discharged energy for mitigating network voltage or thermal problems. Similarly, the lower boundary of the charging envelope is the minimum energy required to charge for mitigating network congestions and avoiding energy released from the battery. Ultimately, the SoC should be within the upper and lower boundaries in order to flexibly respond to the variations of network conditions and energy prices.

Charging envelope design involves the following steps:

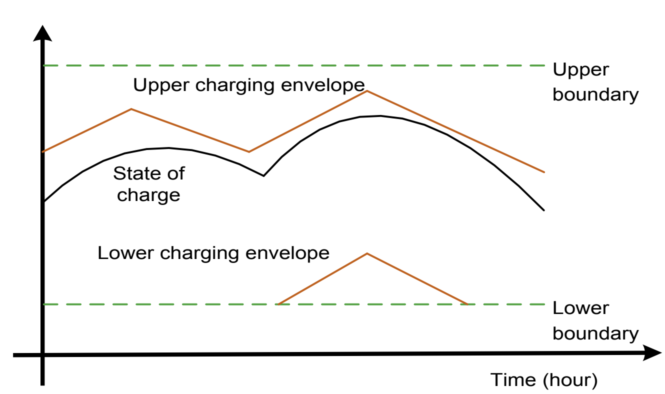

Fig. 1. The relation between charging envelope and real-time SOC.