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Development of a three-phase battery energy storage scheduling and operation system for low voltage distribution networks

Christopher J. Bennett, Rodney A. Stewart *, Jun Wei Lu

Griffith School of Engineering, Griffith University, Gold Coast Campus 4222, Australia

HIGHLIGHTS

- Forecast based 3-phase energy storage scheduling system for the LV network.
- Reduces peak demand through peak shaving and valley filling.
- Better manages distributed supply from solar PV through optimal battery charging.
- Load balances through intelligent charging and discharging.
- Developed system was tested using actual LV distribution network transformer data.

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ABSTRACT

Three phase battery energy storage (BES) installed in the residential low voltage (LV) distribution network can provide functions such as peak shaving and valley filling (i.e. charge when demand is low and discharge when demand is high), load balancing (i.e. charge more from phases with lower loads and discharge more to phases with higher loads) and management of distributed renewable energy generation (i.e. charge when rooftop solar photovoltaics are generating). To accrue and enable these functions an intelligent scheduling system was developed. The scheduling system can reliably schedule the charge and discharge cycles and operate the BES in real time. The scheduling system is composed of three integrated modules: (1) a load forecast system to generate next-day load profile forecasts; (2) a scheduler to derive an initial charge and discharge schedule based on load profile forecasts; and (3) an online control algorithm to mitigate forecast error through continuous schedule adjustments. The scheduling system was applied to an LV distribution network servicing 128 residential customers located in an urban region of South East Queensland, Australia.

1. Introduction

There has been a substantial push by governments to promote the installation of residential solar photovoltaic (PV) array installations in the low voltage (LV) distribution network through subsidies and feed-in-tariffs. In Australia, residential solar PV installations have been promoted by the Renewable Energy Target and the feed-in tariff schemes [1]. As of the 2012–13 financial year, the Australian Energy Regulator [1] reports that Australia's combined rooftop solar PV capacity is 2300 megawatts (MW). In South East Queensland (SEQ) the distribution network operator, Energex, noted that the number of customers with solar PV increased from 2000 to 221,000 installations from 2009 to June 2013, with 74,000 installations taking place between June 2012 and June 2013 [2]. The increase of customers with solar PV installations contributed to an increase price of energy, which led to a slight reduction in energy consumption from conventional sources and a shift in the SEQ network peak to later in the day [2,3].

Daily peak demand in residential networks typically occurs in the evenings in summer and both late morning and evening in winter [4]. Solar PV generation is dependent on the inclination of incoming solar radiation; hence, peak generation occurs during the middle of the day, typically when demand in the residential distribution network is low. Due to the behaviour of residential customers (i.e. concentrated energy demand activities in the evening) and the nature of solar PV generation, there is an incongruity between when energy is generated and when it is required. This can lead to power quality issues in the LV distribution network, such as overvoltage at points of common coupling and instances of reverse power flow to the distribution feeders [5]. In some

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* Corresponding author. Tel.: +61 7 5552 8778.
E-mail addresses: christopher.bennett2@griffithuni.edu.au (C.J. Bennett), r.stewart@griffith.edu.au (R.A. Stewart), j.lu@griffith.edu.au (J.W. Lu).

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Nomenclature

adj	loop adjustment constant
BE	battery bank efficiency (%)
C	capacity (kW h)
CT	charge target (W)
CR	charge rating (W)
e_a	energy available (kW h)
e_r	energy required (kW h)
edp	end of discharge period
EP	evening peak
DoD	depth of discharge (kW h)
DR	discharge rating (W)
DT	discharge target vector (W)
fe	finish element number
i	inverter or phase
iCR	inverter charge rating (W)
iDR	inverter discharge rating (W)
IE	inverter efficiency (%)
L	historical load (W)
Lf	load forecast (W)
LP	load profile (W)
LPf	forecasted load profile
m	gradient (W/t)
m_r	actual rate of energy use (W/t)
m_s	scheduler's rate of energy use (W/t)
min_r	estimated end of discharge period
min_s	scheduler's end of discharge period
MP	morning peak
np	next peak
pp	previous peak
se	start element number
SoC	state of charge (kW h)
SoC_s	scheduler's state of charge (kW h)
t	time iteration
t_α	amplitude threshold
TC	total charge (kW h)
t_m	gradient threshold (W/t)
α	amplitude (W)
δ_t	charge in charge (kW h)
ω	number of time intervals

circumstances remedial measures such as tap changes or more costly network augmentations are required to manage the excess of power produced. Since solar PV generation rarely coincides with peak demand periods in the residential LV network, solar PV fails to contribute to supporting the network through reducing peak demand [6].

The installation of distribution energy storage (DES) may be cost-effective in LV distribution networks with high penetrations of solar PV, load during peak demand period nearing the ratings limits of the LV transformer or unbalanced loads. The general concept is that the DES will charge from the grid during low demand periods or when solar PV is generating surplus energy and discharge during peak demand periods—known as 'peak shaving and valley filling' [7]. This concept will serve to level the demand profile, reduce peak demand and mitigate overvoltage and reverse power flow issues induced by high solar PV penetrations. A proven consistent reduction in peak demand derives value for the utility through electricity network augmentation capital expenditure deferrals. While historically DES has been viewed as a cost prohibitive for application in the LV network, advances in battery technology, feed-in-tariff schemes and the economy of scale effect from electrical vehicles, energy storage will become less cost prohibited in the future [7–9].

To be effective, DES scheduling systems must optimally charge during periods of high solar PV generation or low demand and discharge during periods of peak demand. Many methods have been proposed in the literature to achieve this objective. The most common methods include the use of optimisation algorithms to minimise or maximise objective functions or through finding the optimal solution through dynamic programming [10–23]. These systems achieve optimal solutions but their implementations are relatively complex. Alternatively, a less complex heuristics-based DES scheduling system that has been purpose-built to cater for the characteristics of the LV network and battery energy storage (BES), as proposed herein. The proposed scheduling system comprises three core components: (1) an expert system to forecast next day load profiles (Section 4.3); (2) a scheduling algorithm that interprets the forecasts and provides a charge and discharge schedule (Section 4.4); and (3) an online control algorithm to adjust the charging and discharging in real time to mitigate scheduling error (Section 4.5).

The remainder of this paper is structured in an additional five sections. Section 2 contains the literature review which highlights methods of DES scheduling and formulates the method of this research. The nature of the data used in this research is described in Section 3. A detailed method for developing the scheduling system and constituent components is presented in Section 4. Section 5 presents the initial schedule results from the scheduler, the online control system's actions to mitigate scheduling error and the results for a 72 h simulation of the scheduling system as a whole. The paper concludes in Section 6.

2. Literature

2.1. Energy storage scheduling systems

The literature has proposed a number of different methods to construct DES scheduling systems to achieve one or more objectives such as engaging in valley fill and peak shaving operations, mitigating power quality issues and utilising distributed renewable energy generators, such as solar PV and wind turbines [5,10,24,11–16,25,17–23]. For scheduling systems to calculate a schedule for BES, they must rely on information that allows for charging and discharging periods to be identified or inferred. Types of information that are relied on may include historical load data, load forecasts, time-of-use tariffs, energy market prices and costs of production. Methods used to calculate schedules include time-based heuristics, voltage or frequency set points, fuzzy logic controllers, objective function optimisation and dynamic programming [5,10,24,11–16,25,17–23].

2.2. Price signal based systems

Marwali et al. [11], Lu and Shahidehpour [12] and Koutsopoulos et al. [17] developed scheduling systems that aimed to minimise the production cost of supplying electricity while attempting to peak shave and valley fill. The scheduling systems developed by Marwali et al. [11] and Lu and Shahidehpour [12] involve the coordination of thermal generators and co-located solar PV and BES. Marwali et al. [11] separate the scheduling problem into three steps. The first step involves anticipating solar PV generation,