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Voltage-based storage control for distributed photovoltaic generation with battery systems

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ABSTRACT

Recent advances and continued research in energy storage systems suggest that storage management in grid-connected applications is an area of increasing importance. Hence, this paper proposes a novel voltage-based storage control scheme which reduces network stress and is capable of increasing customer remuneration where variable energy pricing schedules are implemented. The scheme charges the battery during instances of low load and discharges during peak load using only locally available data. The scheme is also capable of adapting to changes in load behaviour throughout the year and is capable of identifying whether local load is dependent on the working week. The scheme is verified both in the small-signal environment and in the steady-state load flow environment using MATLAB. Two case studies covering a typical residential and commercial load profile are conducted to investigate the performance of the proposed scheme.

1. Introduction

Effective energy storage and management systems in distribution networks are integral to the continued proliferation of renewable energy resources in a free market [1]. The intermittent nature of renewable energy resources, coupled with the peakiness of load behaviour, necessitates the presence of energy storage; preferably close to the load [2]. Through judicious energy pricing, government incentives during the infancy of battery technology development and the reduced cost of distributed generation (DG) units, private investment in DG will expand until technical considerations preclude any further investment. These technical considerations, including power quality and reliability, in addition to violating technical standards, also impose cost burdens on DG proprietors and their neighbours – however, the cost may not be immediately evident. The costs manifest in reduced lifetime of appliances and network infrastructure, as well as increased instances of nuisance anti-islanding tripping [3]. Both costs are a result of over-voltage.

Instances of over-voltage can be mitigated by installing larger cables or voltage regulating devices, but these options are often prohibitively expensive [4]. Voltage issues associated with DG can also be remedied through the control of active power, reactive power, energy storage or a composite of these [5]. Real power curtailment reduces the remuneration for the customer; reactive power absorption unnecessarily stresses the network and reduces network efficiency. A study of the various DG control schemes (using locally available information only) concluded that real power curtailment has the minimal negative impact on network efficiency and the voltage profile, especially where line drop compensation is used in zone substations [6]. Hence, an ideal control mechanism would vary the real power export according to the conditions of the grid and store any excess power for use during heavy loading. Thus, the authors propose a novel control scheme adopting battery energy storage in DG applications. It is important to note that batteries are typically expensive and require a significant amount of space. Furthermore, financial incentives to encourage DG customers to invest in storage systems have not been introduced by Australian governments at present, with an exception of a rebate scheme in Adelaide which commenced in 2015 [7].

A surge in the number of orders for grid-connected storage has demonstrated growth in commercial interest [8]. Such interest will drive research and improvements in energy density and cost effectiveness of battery technology, rendering large scale distributed energy storage more attractive for investors in the future. Hence, storage management schemes for DG systems may become very valuable in maximising customer return, minimising the

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impact of peak loading and the management of renewable energy resource intermittency. An increase in the level of grid-connected energy storage may allow energy storage devices to participate in volatile energy and reserve markets [9]. Such a development would greatly improve the business case for energy storage devices.

The connection of DG can be useful in reducing the power demand from large-scale generation. Furthermore, because DG is connected proximate to the point of consumption, network losses are usually reduced [10]. Hence, in theory, the addition of DG can lower peak demand and thus defer the requirement of generation plants and the utility to engage in infrastructure upgrade [11]. However, the ability of DG to reduce peak demand is significantly hindered by the mismatch of renewable power availability and customer demand. Solar power, which is quotidian in nature, peaks in the middle of the day, whereas residential load typically peaks in morning and in the evening [12]. Hence, energy storage is vital in order to maximise the benefit of DG from the perspective of the utility.

A hybrid super-capacitor/battery/photovoltaic system was proposed in [13]. The super-capacitor and battery are controlled to maintain a constant DC voltage between the maximum power point tracker and inverter. The control signal to the battery contains a low pass filter, allowing the super-capacitor to correct any short-term deviations from the DC voltage reference and the battery to correct any long term deviations. The weaknesses of the proposed hybrid control scheme are the cost as well as the scheme's inability to adapt to the power quality and economic requisites of grid inter-connection. The ability to maintain a constant DC power throughout the night during low load can cause significant over-voltages as well undesired power export during off-peak timings.

The issue of voltage rise caused by large DG penetrations was addressed in [14] through centralised control of tap changers and energy storage. Upon detection of a voltage rise at the points of connection (POC) of DG units, the central controller will disseminate a signal to alter the tap setting of an on-load tap changer or voltage regulator to compensate. Furthermore, the central controller will signal the battery systems to commence charging in order to shave the peak load. The battery shall subsequently discharge according to the output of the peak load estimator. The scheme clearly has the ability to mitigate voltage rise and lower losses caused by reverse power flow through high impedance sections of the network. However, the robustness of the scheme requires evaluation. A detailed explanation of the peak load estimator is missing – the ability to approximate load behaviour is of critical importance. Furthermore, it is possible for voltage rise to occur during the night where there is no solar irradiance, but little load. The scheme does not account for such a situation.

Peak load smoothing was explored in [15] using a composite of battery and air conditioning control strategies. The control scheme is based on a target power export for the individual load; rather than the peak loading condition of the broader network. Hence, the control scheme does not necessarily minimise network stress unless the local load characteristics closely matches the behaviour of the broader distribution network. Similarly in [16], battery energy reserves are used to smooth the demand of electric vehicles, but is not optimally designed to minimise the stress of the overall network. A grid-connected photovoltaic and storage control scheme is developed in [17,18] which attempt to maximise the return of the DG unit based on predictions of solar and load behaviour. However, this scheme ignores the impacts of energy storage on the network efficiency and the voltage profile; hence, this scheme requires a careful analysis of the effects of interactions between DG units and voltage regulation devices. The value of including photovoltaics and energy storage with a cogeneration system is explored in [19], however most photovoltaic systems are not coupled with cogeneration technology and the proposed scheme does not consider the value of predicting power availability and demand. An analysis of extant literature reveals a research deficit for a grid-connected battery control scheme which passively mitigates the effects of distribution network load variations based on locally available data only. Hence, the scope for the voltage-based control scheme presented in this paper is apparent.

The voltage-based storage control scheme presents a novel method that smooths the demand from the mains by charging and discharging battery storage units according to the voltage measured at the POC of DG units. The proposed scheme requires only locally available data and will automatically calibrate itself using historical data. Furthermore, the scheme can operate even in the absence of an energy resource, as the scheme will absorb power from the grid during low load and export power during peak load. If variable pricing schedules are implemented, it may become cost effective to install such a system without an energy resource.

The motivation for the proposed voltage-based storage control scheme is the need for effective management of energy storage coupled with renewable energy resources in distribution networks. Implementation of the proposed scheme will result in smoother voltage profiles across distribution networks, lower line losses and reduced network stress during peak loading. Hence, network infrastructure upgrade may be deferred. Furthermore, as DG penetration rises with ample storage capacity, traditional voltage regulating devices such as on-load tap changers and autotransformers can be decommissioned as the voltage drops throughout the network will be reduced. It must be noted that all of these motivations benefit the utility; hence, consumer pricing schedule reform is an integral part of ensuring that strategic storage control practices also benefit the storage unit proprietor.

A detailed model of the battery and charger is outside the scope of this paper. It is assumed that the state of charge is known and that the *DC–DC* converter is capable of charging and discharging at any rate within the stipulated rated values. The effects of temperature and battery aging are ignored, but extant techniques can compensate for these effects [20–22]. More complicated models, such as the kinetic battery model developed by Manwell and Gowan in [23] may be implemented to represent the effects of the load current on the charge rate as well as the discharged capacity as a function of battery idle time. These effects will be minimised within the proposed model by imposing a low charge rate and allowing the user to restrict the discharge/charge range to preference. Alternatively, battery/supercapacitor hybrid technology as the Ecoult lead acid ultrabattery could be used, which is capable of high rate charge/discharge cycles without a significant decrease in life expectancy [24].

The business case for implementation of the control scheme proposed in this paper necessitates variable electricity pricing and low cost batteries. However, there is a strong economic case for consumer-side demand management through variable pricing due to the presence of advanced metering and the increasing cost of network infrastructure upgrades [25]. There also exists strong level of interest in the energy storage field due to technology developments such as the electrical vehicle. Thus, it is reasonable to assume that battery prices shall continue to fall and that battery energy density and lifetime may improve in the years ahead.

The rest of the paper is structured as follows: Section 2 introduces the proposed voltage-based storage controller, including the voltage set point calculating algorithm. Section 3 verifies the controller with a small-signal model by exposing the controller to significant network and irradiance disturbances. Section 4 defines a modification of a load flow solver incorporating the proposed scheme. Section 5 tests the voltage set point calculating