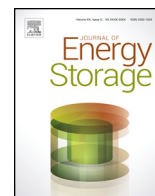




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Research paper

## Energy storage system utilisation to increase photovoltaic penetration in low voltage distribution feeders

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### ABSTRACT

This work introduces a new droop control for energy storage system (ESS) dispatch commands generation. The droop characteristic generates the ESS dispatch commands as a function of the power surplus at the substation transformer. The ESS with the new droop control aims to increase the level of Photovoltaic (PV) penetration in low voltage (LV) distribution networks, for the most economical solution in terms of ESS placement and sizing. The new droop control maintains two independent modes of operation; the first mode is fixed droop (FD) control, and the second mode is variable droop (VD) control. When FD control is employed, the droop characteristic remains invariable during hours of excessive PV generation, while the dispatch commands maintain the total of the grid parameters within the allowable range at all times. When VD control is performed, the slope of the droop characteristic was modified hourly, providing a sound grid operation at all times, while the accuracy of the dispatch commands was enhanced compared to the FD control mode. For the research, a real-life LV network case study that maintains a loop arrangement was utilised for modelling purposes. The operational grid constraints include transmission lines loading, terminal voltage variation, and substation transformer loading. Simulation results revealed that both of the proposed control modes maintain a sound grid operation for 70% PV penetration. The VD control performed better resulting in a lower cost ESS. The study demonstrated that an ESS located in the LV network performed a number of positive functions, including load management, peak load levelling and voltage support.

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## 1. Introduction

### 1.1. Advent of renewable energy

To tackle climate change, global efforts are in progress, aiming to increase the volume of Renewable Energy Sources (RESs) in the energy mix [1–3]. This is particularly so in Australia, which has the target of 23.5% for renewably-generated energy by 2020 [4], and records a sustained growth in the installed capacity of Photovoltaic (PV) installations which is presented in Fig. 1 [5]. Mainly due to economic incentives associated with the feed-in tariff (FIT), the PV installed capacity from 0.121 GW in 2009 reached 4.7 GW by the end of 2015.

The energy production from the plethora of the RESs, including PVs, wind turbines (WTs), biogas, wave and tidal energy, etc. can significantly benefit public health in the near term, as well as it can

mitigate climate disruption. For example by replacing a portion of the electricity produced from fossil fuels with electricity produced by RESs, there is a considerable benefit in public health accruing from the improved breathing air of diminished particulate concentration. The reduced greenhouse gas emissions also help to mitigate the effects of climate change [6]. While RESs provide a number of environmental benefits, their introduction to the power grid has created a number of problems. For example, the unidirectional top-down power-flow becomes bidirectional including the bottom-up dimension. This reverse power-flow, coincides with a voltage rise at the feeder terminals, and often causes transmission line and transformer overloading. Furthermore, the renewable energy fluctuation affects the system's frequency, increases the probability of sudden power loss, requires increased spinning reserves and poses additional difficulties in the electricity market trading [7–12].

### 1.2. Literature review on grid support methods

As additional support to the grid due to excessive load demand or as a remedy to the aforementioned symptoms introduced by

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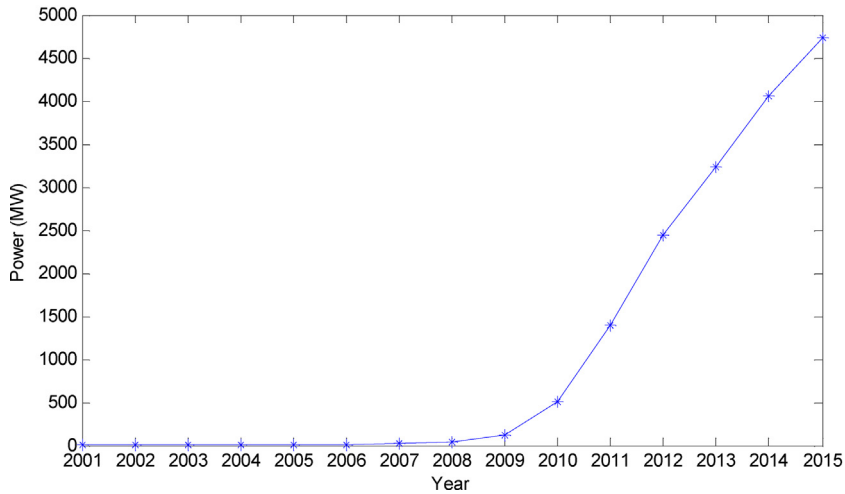


Fig. 1. Australian PV installed capacity.

RESs, a number of different approaches are proposed in the literature, including demand side management (DSM), grid infrastructure upgrade, PV power curtailment, and ESS utilisation among others [13–27].

The principle of DSM, by incentivising the shifting of load from the high consumption period of the day, to another with lower consumption, for example the morning hours, could facilitate higher PV penetration levels to be achieved by mitigating the PV impact. Economic incentives are often provided from the electrical utilities to the residential customers, such as the time-of-use (TOU) tariff, aiming to achieve the abovementioned load shifting within the DSM context. TOU tariffs have not yet been taken up by residential customers on any sizeable scale, meaning that TOU-based DSM cannot be relied upon to increase current PV penetration levels [13].

Alternatively, electrical appliances (e.g., clothes dryers) can be considered as deferrable loads, and the electrical utility could control them by sending on and off signals. By allowing the electrical utility to control the deferrable loads of the residential customer, the customer benefits from overall reduced electricity costs, while the electrical utility gains by mitigating the voltage rise caused by the rooftop PV installations [14]. The drawback of this method emerges, from the inconsistent availability of deferrable loads. For example, in the case where the total available utility controllable loads at a certain hour of the day, is less than the load that is required to counteract the impact of the generated PV power, then the secure grid operation is compromised.

The work in [15], highlights that the PV penetration limit of the electricity grid, can be reached by meeting the ampacity limits of the transmission lines existing in the feeder. As a remedy, line augmentation can be performed to increase the ampacity limits of the transmission lines. Grid reinforcement can allow higher PV penetration levels to be achieved, however it is a very costly solution, and it underutilises the upgraded grid equipment, since the higher ampacity limits of the upgraded equipment, are only met a few times a year. Above all, the flexibility of redirecting PV generated energy from morning hours to any other period of the day where it is needed the most (e.g., peak load period), is absent with grid reinforcement. Conversely, the additional degree of freedom of energy shifting, from the morning to any other period of the day where the grid needs support, is provided by ESS utilisation as demonstrated in this study.

Solar inverters have also been employed to perform voltage support without the presence of storage units. The author in [16], developed the  $\cos\varphi_{inv}(d, t) = f(P_{inv}(d, t), V_{grid}(d, t))$  droop control

method, where the power factor of the solar inverter,  $\cos\varphi_{inv}(d, t)$ , is a function of the active power of the inverter,  $P_{inv}(d, t)$ , and it also depends on the grid voltage,  $V_{grid}(d, t)$ . In the above formulation,  $d$  is the present day of the year, and  $t$  is the present time of the day. The author’s method was compared with the standard method of  $Q_{inv}(d, t) = f(V_{grid}(d, t))$ , where the reactive power of the inverter,  $Q_{inv}(d, t)$ , is as a function of  $V_{grid}(d, t)$ . The method proposed by the author, maintained a similar performance to the standard method of  $Q_{inv}(d, t) = f(V_{grid}(d, t))$  in terms of PV penetration levels, for transformer loading up to 100%. The droop control methods discussed above maintain two drawbacks. The first is the increased loading of the grid components (i.e., transmission lines and transformers) due to the reactive power-flow to be absorbed by the solar inverters required for the mitigation of the voltage rise. The second drawback is the oversized inverter requirement, to be able to inject the generated solar power into the grid and to absorb from the grid the required reactive power for the purpose of grid compensation.

Power curtailment as a measure for voltage rise mitigation is another application of droop control. The authors in [17,18] employed the droop characteristic of Eq. (1) to control voltage. When  $V_{grid}(d, t)$  is placed within the following range  $0.9pu \leq V_{grid}(d, t) \leq 1.06pu$ , then the total of the anticipated maximum power point power,  $P_{mpp}(d, t)$ , is inverted into AC and it is injected into the grid. In the case where the anticipated PV power generation results in  $V_{cri} < V_{grid}(d, t) < V_{max}$ , with the critical voltage to be  $V_{cri} = 1.06pu$  and the maximum voltage identified at  $V_{max} = 1.1 pu$ , then the droop characteristic of Eq. (1) is engaged for the reduction of the output power of the inverter,  $P_{inv}(d, t)$ , thereby  $V_{grid}(d, t)$  is maintained below  $V_{max}$ . Regarding the slope of the droop characteristic, it depends on the values of  $V_{cri}$  and  $V_{max}$ , as it can be observed in Eq. (1). At this stage it needs to be noted that since power curtailment results in less renewable energy injected into the grid, it exceeds the scope of this work.

$$P_{inv}(d, t) = P_{mpp}(d, t) - P_{mpp}(d, t) \cdot \underbrace{\frac{V_{grid}(d, t) - V_{cri}}{V_{max} - V_{cri}}}_{slope} \quad (1)$$

Coupling generated solar power and energy storage, enables the inherently stochastic renewable energy to be dispatchable. In [19], the author utilises the storage for voltage support, hence its optimal location is identified as the one resulting in the lowest voltage deviation at the feeder terminals. The approach includes application of sensitivity analysis, expressed by  $dV/dP$  and  $dV/dQ$

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