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Optimal capacity design for hybrid energy storage system supporting dispatch of large-scale photovoltaic power plant

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ABSTRACT

This paper presents a methodology to evaluate the optimal capacity and economic viability of a hybrid energy storage system (HESS) supporting the dispatch of a 30 MW photovoltaic (PV) power plant. The optimal capacity design is achieved through a comprehensive analysis of the PV power plant performance under numerous HESS capacity scenarios. The analysis has been conducted using a high performance computing cluster which generated a large amount of simulation data based on a PV power profile of one month. The HESS, consisting of a vanadium redox battery and a supercapacitor bank with a power rating ratio between the two energy storage technologies of 5:1, is connected at the point of common coupling to support the PV power plant to comply with the dispatch rules in the Australian national electricity market. A quantitative relation is developed based on surface fitting, which relates the HESS capacity with the dispatch performance of the PV power plant in terms of energy yield and required ancillary services. The paper concludes the optimal capacity of HESS which will provide the maximum profit improvement under the actual market conditions.

1. Introduction

In the last five years, the worldwide photovoltaic (PV) installations have increased dramatically as the manufacturing cost of PV modules dropped continuously (e.g. more than 50% drop since 2010) [1]. Especially, large-scale PV power plants take a significant place of the new PV installations. Capacity records of individual PV power plant have been frequently renewed. For instance, the 550 MW Topaz PV power plant holds the current capacity record since it started operation in 2014 [2]. The largest PV power plant in the southern hemisphere with a peak capacity of 102 megawatts is currently under construction at Nyngan, Australia and will start its operation in 2015 [3].

The large-scale PV power plants naturally generate intermittent power, as the daily power profile illustrated in Fig. 1. As a consequence, these PV power plants do not have the same level of controllability as conventional fossil-fuel power plants. Therefore, the increasing penetration of large-scale PV power plants can affect the power quality of the electricity grid [4–7]. For the stability of the electricity grid, the Australian energy market operator requires any large-scale PV power plants to comply with dispatch instructions regarding the delivery of active power to the grid [8,9]. Specifically, a constant dispatch target should be assigned to the PV power plants before each dispatch interval.

An illustration regarding a daily power profile of a particular PV power plant and the set dispatch target is presented in Fig. 1. In order to compensate such mismatch, a possible solution that has been proposed in the technical literature [6,7,10–12] is to integrate an energy storage system (ESS) with the PV power plant. In other words, the virtual PV power plant including the PV system and the ESS is required to follow the dispatch target set by the Australian energy market operator. Ideally, an ESS with the same power capacity as the PV power plant is required to compensate the power mismatch under all scenarios of the PV power fluctuation. Potential ESS technologies, which can provide a power capacity from tens to hundreds of megawatts for grid-support application, include pumped hydro, flywheels, compressed air energy storage, batteries, superconducting magnetic energy storage, just to mention a few [6,7,13].

Batteries feature the flexibility of location and scalability of capacity, thus making them the most suitable ESS technology for integration with PV power plants [14]. In the USA, an 8 MW lithium-ion battery (commissioned in 2014) and a 25 MW flow battery (expected to be commissioned in 2015) are designed and

Abbreviations: ESS, energy storage system; HESS, hybrid energy storage system; MPP, maximum power point; PV, photovoltaic; SCB, supercapacitor bank; VRB, vanadium redox battery.

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Nomenclature

C	Profit improvement by using the HESS
$d\%$	Power reserve of the delta-balance control
G	Historical solar irradiance measurement
P_{DT}	Power dispatch target
P_{PV}	Actual power generated by the PV system
P^{*}_{HESS}	Power reference of HESS
ΔE_{HESS}	Difference of energy stored in the HESS between the beginning and the end of simulation
P^{MPP}_{PV}	Maximum instantaneous power of PV system based on the actual solar irradiance
$P_{capHESS}$	Power capacity of HESS
P_{capVRB}	Power capacity of VRB
P_{capSCB}	Power capacity of SCB
E_{grid}	Energy yield for the investigated time period;
E^{loss}_{HESS}	Energy loss of HESS
α	Market price of electricity
δ_{kwl-2}	Unit cost of VRB and SCB related to power capacities
C_{HESS}	Cost of HESS
e_{fc}	Maximum forecasting error of PV power output in each dispatch interval
P_{nom}	Nominal power capacity of PV system
P_G	Power delivered to the grid
ΔP_{PV}	Curtailment of PV output power
P_{HESS}	Actual power absorbed or supplied by HESS
ΔE_{PV}	PV energy curtailment
E^{MPP}_{PV}	Maximum available PV energy based on the actual solar irradiance
$E_{capHESS}$	Energy capacity of HESS
E_{capVRB}	Energy capacity of VRB
E_{capSCB}	Energy capacity of SCB
E_{AS}	Required ancillary services for the investigated time period
λ_{1-12}	Coefficients of the developed equations between E_{grid},E_{AS} and VRB capacities
β	Market price of ancillary services
δ_{kwhl-2}	Unit cost of VRB and SCB related to energy capacities

used to support the local wind farms [15,16]. Although the capital cost of large-scale battery energy storage system has been decreasing continuously, its cost is still significant with respect to the capital of the PV power plant. Therefore, a trade-off between the capacity of the battery energy storage system and its support for the PV system in the dispatch process should be considered in order to reduce the capital cost of the virtual PV power plant, thus generating price-competitive electricity.

Recently, numerous methods of optimizing the ESS capacity have been reported from different perspectives [17–24]. For smoothing wind power fluctuations, a battery capacity design scheme has been proposed based on the largest required capacity during the investigated intervals [18]. Also, the minimum size of an ESS has been defined in order to smooth the power fluctuations or to achieve specific technical requirement such as state of charge [21,22]. Apart from fulfilling the technical requirements, the optimal ESS capacity can also be defined from other perspectives, such as economic viability. In [23] and [24], stochastic and probabilistic approaches have been applied to explore the economic viability of using a battery energy storage system in a microgrid and a wind farm, respectively.

In the literature, detailed electricity market operations have not been considered when designing the ESS capacity. The electricity market operations may vary from country to country. For instance, Australia has a 5 min dispatch interval, but UK has 60 min interval [9,25,26]. The achievable forecast accuracies for different time horizons, e.g. 5 min and 60 min, can significantly affect the market operation constraints, thus affecting the optimization of the ESS capacity. Therefore, the optimal capacity of an ESS supporting PV power plants operating under the actual market rules needs to be investigated from both electrical and economic perspectives.

This paper proposes a methodology to evaluate the optimal capacity and economic viability of a hybrid ESS (HESS) assisting a 30 MW PV system to comply with the dispatch rules in the Australian national electricity market. Quantitative analyses based on a large amount of simulations performed on a high performance computing cluster are conducted to develop a mathematical relation between the HESS capacity and the dispatch performance of PV power plant (e.g. the energy yield and required ancillary services).

The rest of this paper is organized as follows. The system description of the virtual power plant is presented in Section 2. Section 3 describes the challenges associated with the optimal ESS capacity design. In Section 4, the quantitative analysis based on the simulation results is conducted. Based on the quantitative analysis, the optimal ESS capacity is defined in Section 5. Finally, Section 6 summarizes this paper and draws the conclusions.

2. Virtual PV power plant

This paper considers a virtual PV power plant consisting of a PV system coupled with a HESS, as shown in Fig. 2. From the perspective of the grid operator, the virtual PV power plant acts as a single generating plant at the point of common coupling. Specifically, the PV power plant is described as follows. Each PV array is connected to a common AC bus through a centralized DC/AC converter. Similar to the PV arrays, the vanadium redox battery (VRB) and the supercapacitor bank (SCB) are connected to common AC bus through DC/AC converters. The power management system reported in [27,28] is used to control all the power converters, thus supporting the dispatch of the virtual PV power plant.

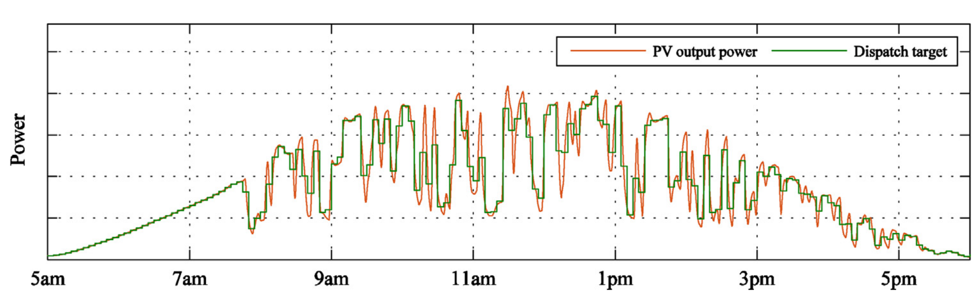

Fig. 1. Comparison of a typical daily power profile of a PV power plant and the assigned dispatch target by the Australian energy market operator.