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Optimal sizing of utility-scale photovoltaic power generation complementarily operating with hydropower: A case study of the world's largest hydro-photovoltaic plant

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ABSTRACT

The high variability of solar energy makes utility-scale photovoltaic power generation confront huge challenges to penetrate into power system. In this paper, the complementary hydro-photovoltaic operation is explored, aiming at improving the power quality of photovoltaic and promoting the integration of photovoltaic into the system. First, solar-rich and hydro-rich regions across the world are revealed, which are suitable for implementing the complementary hydro-photovoltaic operation. Then, three practical scenarios of the novel operation mode are proposed for better satisfying different types of load demand. Moreover, a method for optimal sizing of a photovoltaic plant integrated into a hydropower plant is developed by maximizing the net revenue during lifetime. Longyangxia complementary hydro-photovoltaic project, the current world's largest hydro-photovoltaic power plant, is selected as a case study and its optimal photovoltaic capacities of different scenarios are calculated. Results indicate that hydropower installed capacity and annual solar curtailment rate play crucial roles in the size optimization of a photovoltaic plant and complementary hydro-photovoltaic operation exerts little adverse effect upon the water resources allocation of Longyangxia reservoir. The novel operation mode not only improves the penetration of utility-scale photovoltaic power generation but also can provide a valuable reference for the large-scale utilization of other kinds of renewable energy worldwide.

1. Introduction

Exploiting renewable energy resources (RES) is an effective approach to coping with the deteriorating ecological environment and satisfying the increasing energy demand. Owing to the favorable technological maturity and economic profitability, photovoltaic (PV) and wind power generation have prevailed amongst RES practices. They can be deployed either in distributed manners or at utility scale. However, for safety consideration and expensive spinning reserves, power system is reluctant to accommodate utility-scale PV and wind power due to the poor power quality caused by the random and intermittent nature of solar and wind energy [1]. The immense integration difficulty results in considerably high rates of solar and wind curtailment. Currently, the integration into the power system has become the major concern wherever variable RES is exploited at the large scale and one key to the pressing problem is the enhancement of the power quality of RES.

Being a kind of promptly-adjustable power sources, hydropower holds great potential as the real-time power compensator or stabilizer for the highly variable RES in addition to invariably providing the peaking service for the power system. In 2013, along with the successful commissioning of the world's largest complementary hydro-PV plant - Longyangxia hydro-PV plant (850 MW PV arrays + 1280 MW hydropower units) – in northwestern China, the complementary hydro-PV operation has become reality. In this novel operation mode, the utility-scale PV operating in combination with hydropower can be integrated into local power system. Now, the complementary hydro-PV operation is regarded as a promising option through which the power quality of PV will be obviously improved at supply side and can provide a valuable reference for other kinds of RES practices. But whether the novel operation mode is merely a particular case in China? Therefore, the feasibility of the complementary hydro-PV operation across the world should be explored at first.

Our previous study has preliminarily analyzed the complementarity between hydro and solar energy, explained the basic principle of complementary hydro-PV operation and formulated the capability of hydropower to compensate for PV in short-term

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scheduling [2]. Still, more scientific issues associated with the complementary hydro-PV operation need to be resolved, for instance, how to evaluate the optimal PV capacity integrated into hydropower and to what extent the complementary operation will alter the original process of water resources allocation of a reservoir.

With respect to the first proposition - sizing techniques for hybrid power generation systems, Kenfack et al. [3] proposed a hybrid microhydro-PV system to achieve the rural electrification. The system was sized according to the seasonal variations of both solar and hydro resources and a set of sensitivity variables are added to the cost-effectiveness model to choose the best technical, economical and environmental system architecture. Mohamed et al. [4] developed an iterative optimization program for sizing components of stand-alone hybrid PV-wind-diesel-battery energy systems suitable for remote areas. The program was designed to follow the limits on the loss of the load probability and dummy load at minimum levelized energy cost to satisfy the load demand. Portero et al. [5] presented a wind-hydro system using a reversible hydraulic facility with seawater for the Canary Islands. With given energy storage capacity of the upper tank in the hydraulic facility, the optimal number of wind turbines was selected by performing simulations considering the threshold conditions of the contribution of the wind-hydro system to the load demand, the energy surplus and the energy deficit. Maleki et al. [6] introduced a mathematical model for optimally sizing a hybrid PV-wind-battery system, whose objective function was to minimize the total annual cost. Different types of heuristic algorithms were employed to search for the optimal number of the system components. Ismail et al. [7] adopted genetic algorithm to optimize the sizes of a hybrid PV-microturbine-battery system. The objective aimed at minimizing the cost of energy production while considering global warming emissions costs. Taking advantage of ant colony optimization (ACO) and artificial bee colony (ABC) algorithm, Kefayat et al. [8] proposed a hybrid ACO-ABC algorithm for optimizing the location and size of a distributed energy network. The multi-objective optimization simultaneously considered technical, environmental and economic issues. Baghdadi et al. [9] optimized the components size of a hybrid PV–wind–diesel–battery system. The objective was to find the configuration offering the lowest energy cost consisting of the installing cost and operating cost of the system over its lifetime. Ma et al. [10] developed sizing methods and compared the economic performance of two energy storage technologies (batteries and pumped hydro storage) for a renewable energy powered island in Hong Kong. Results showed that the renewable energy system coupled with purely pumped storage outperformed the battery options in terms of life-cycle cost. Previous studies mainly focus on exploring sizing techniques for RES-dominant hybrid systems designed to meet the load demand of a microgrid or an isolated consumer. However, research concerning the size optimization of a utility-scale PV power plant integrated into the power system is rare.

As for the other proposition, owing to the increasing population, industrialization and changing climate, humans are now facing a more severe water crisis than ever before [11]. Rivers play crucial roles in the water supply for our human society and its water resources allocation mainly realized by controlling the discharge of reservoirs has drawn much more attention [12]. Therefore, whether adverse effects will be exerted upon the water resources allocation of a reservoir by the complementary hydro-PV operation becomes the major concern of watershed authorities. Previous studies concerning this issue, to the best of our knowledge, are scare. Only Ming et al. [13] investigated its influence on the short-term water resources allocation of Longyangxia reservoir under different meteorological conditions (sunny, cloudy and rainy days). Results showed that the maximum error of the daily discharge was merely 0.21% after implementing the novel operation mode. However, whether and to what extent the accumulation of the daily discharge error will affect the discharge of a reservoir at longer time scales, such as, the monthly and annual discharge, are still unknown and deserved to be further investigated in this study.

As for the above three issues related to the complementary hydro-PV operation, the objectives of this study are to: (1) explore the feasibility and prospect of implementing the complementary hydro-PV operation across the world; (2) develop a method for optimally sizing a PV plant integrated into a hydropower plant by maximizing the net revenue during lifetime; (3) investigate the influence of complementary hydro-PV operation upon water resources allocation of a reservoir.

The rest of paper is organized as follows. Section 2 locates the regions suitable for implementing the complementary hydro-PV operation across the world. In Section 3, three practical scenarios of the novel operation mode are proposed to satisfy different types of load demand and a maximum net revenue model as well as its solution is developed to optimally size the utility-scale PV integrated into hydropower. A brief introduction of the world's largest hydro-PV plant – Longyangxia hydro-PV plant – and the relevant data are presented in Section 4. Section 5 provides the results and discussion and is followed by conclusions in Section 6.

2. Feasibility and prospect of the complementary hydro-PV operation across the world

The basic process of complementary hydro-PV operation can be described as follows: (1) electricity generated by a PV plant is transmitted to a hydropower plant situated in its neighboring area; (2) the random and intermittent output of PV is tracked and compensated by the promptly-adjustable hydropower units in real time; (3) the PV plant complementarily operating with the hydropower plant serves as a hybrid power source to accomplish the generation scheme, whose electricity is packed together to be integrated into the power system. The complementary hydro-PV operation improving the power quality of PV at supply side, thus any other expensive energy storage facility or spinning reserve is no longer required. For economic considerations, the principle of local exploitation and utilization of RES is adopted by the complementary hydro-PV operation. Therefore, the regions endowed with both a wealth of solar and hydro energy are particularly suitable for the implementation of the novel operation mode.

Hydro energy is generally quantified by the theoretical hydropower potential. The theoretical hydropower potential can be explicitly represented by the potential energy E_W of the runoff W flowing along a specific reach L of a river and be calculated as follows

$$E_W = \rho g W H_L \tag{1}$$

where ρ is the density of the water (1000 kg/m^3); g denotes the gravitational acceleration (9.81 m/s^2); H_L is the elevation difference of a reach of the river.

The equation reveals that theoretical hydropower potential is basically dominated by the variables of W and H_L. Accordingly, hydropower potential concentrates in places where the abundant precipitation and considerable elevation difference in terrain are available. On the basis of Eq. (1), Pokhrel et al. [14] have depicted the global distribution of theoretical hydropower potential as is shown in Fig. 1.

Solar energy reaching the earth's surface is commonly quantified by the global horizontal irradiation (GHI). GHI is determined by a variety of factors including the latitude, elevation, landform and many other meteorological variables [15]. The annual sum of