Applied Energy 167 (2016) 377–384

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Multi-objective optimization for integrated hydro–photovoltaic power system

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HIGHLIGHTS

- A model optimizing both quality and quantity of hydro/PV power was proposed.
- The dimension was reduced by decoupling hydropower and PV power in time scales.
- Reservoir operations have been optimized for different typical hydrological years.
- Hydropower was proved to be an ideal compensating resource for PV power in nature.

ARTICLE INFO

Article history:
Received 29 May 2015
Received in revised form 20 August 2015
Accepted 3 September 2015
Available online 16 September 2015

Keywords:
Hydro–photovoltaic power system
Multi-objective optimization
NSGA-II
Longyangxia hydro/PV project

ABSTRACT

The most striking feature of the solar energy is its intermittency and instability resulting from environmental influence. Hydropower can be an ideal choice to compensate photovoltaic (PV) power since it is easy to adjust and responds rapidly with low cost. This study proposed a long-term multi-objective optimization model for integrated hydro/PV power system considering the smoothness of power output process and the total amount of annual power generation of the system simultaneously. The PV power output is firstly calculated by hourly solar radiation and temperature data, which is then taken as the boundary condition for reservoir optimization. For hydropower, due to its great adjustable capability, a month is taken as the time step to balance the simulation cost. The problem dimension is thus reduced by decoupling hydropower and PV power in time scales. The modified version of Non-dominated Sorting Genetic Algorithm (NSGA-II) is adopted to optimize the multi-objective problem. The proposed model was applied to the Longyangxia hydro/PV hybrid power system in Qinghai province of China, which is supposed to be the largest hydro/PV hydropower station in the world. The results verified that the hydropower is an ideal compensation resource for the PV power in nature, especially in wet years, when the solar radiation decreases due to rainfalls while the water resource is abundant to be allocated. The power generation potential is provided for different hydrologic years, which can be taken to evaluate the actual operations. The proposed methodology is general in that it can be used for other hydro/PV power systems than those studied here.

1. Introduction

China's energy demand will continue to grow rapidly in the early 21st century. According to the prediction of Chinese Academy of Sciences, the annual energy consumption of China may increase to 7 billion tonnes of coal equivalent (1 tce corresponds to 7.500 kW h) in 2050 from 3.84 billion tce in the year of 2014, and the total installed capacity of power generation will rise to 3 billion kW in 2050 from 1.36 billion kW in 2014. To utilize the energy resources sustainably and limit the environment pollution and greenhouse gas emissions, the portion of coal energy should be decreased, and the share of clean renewable energy needs to be greatly increased. 40% of the 3 billion kW installed capacity in the year 2050 is taken by coal energy, and the hydropower, nuclear power and the gas power take up to about 15%, 11%, and 4%, respectively. Hence, there are about 30% of the power needs to be provided by non-hydro renewable resources, corresponding to about 900 million kW installed capacity.

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http://dx.doi.org/10.1016/j.apenergy.2015.09.018
0306-2619/

China has a large area of desert Gobi, which offers the probability of large-scale development of photovoltaic (PV) industry. It is estimated that the gross area of desert Gobi in China is about 1,280,000 km^2, and the corresponding potential PV power output can be as high as about 130 billion kW. By the end of 2014, the accumulative installed capacity of PV power is 28.05 million kW, with annual power generation of 25 billion kWh. In the year of 2014, China added 10.6 million kW of the PV capacity, taking up to 1/5 of the global increment. Only for Qinghai province, the PV capacity integrated into power grid is increased by 1.01 million kW in 2014, and it has accomplished annual growth of over 1 million kW integration of PV capacity for consecutive four years.

Qinghai Province locates in high latitudes with intense solar radiation, and long-time sunshine. The annual radiation is up to 56–74 MJ/m^2, in which the direct radiation accounts for more than 60%, only ranking behind Tibet in China. Most of the Qinghai Province is sparsely populated with flat terrain. The population density is lower than 1 person/km^2. The area of available desertificated land is more than 200,000 km^2, mainly distributed in the Qaidam Basin and Sanjiangyuan region with rich radiation. Besides, a lot of desert is near electric power lines and load centers, facilitating electrical connection. For these reasons, Qinghai region is preferable for the construction of large-scale PV power plants.

Photovoltaic power generation converts the solar radiation directly into electrical power without fuel consumption or rotating machinery. Thus it is simple to maintain with high safety and reliability. Nevertheless, since PV generation uses solar radiation as the energy resources, it depends greatly on the uncertain natural conditions. The largest disadvantage of the PV power lies in its instability and discontinuity on account of season and weather, and such changes of power flow in long-distance power transmission leads to the difficulty for voltage control in power grid. As a result, there has to be enough spare capacity in the power system to make adjustment. The majority of studies and most systems in operation use a renewable source backed up by a conventional one such as a fossil fuel based generator [1], causing coal consumption and greenhouse gas emissions. Recently, the integrated hydro/PV/wind system has attracted interest of researchers, especially for the remote or isolated areas. Bekele and Tadesse studied the feasibility of small hydro/PV/wind hybrid system in Ethiopia [2]. Nfah and Ngundam contemplated pico–hydro and PV power systems in Cameroon [3], and Kenfack et al. suggested small hydro/PV hybrid system for rural electrification in developing countries as well [4]. Some pioneering resolutions have been put into operation, such as the PV–micro–hydro hybrid system in Taratak village of Indonesia, which was launched on June 10, 1989 [5]. As for the management of the existing hydro/PV hybrid systems, there also have been related studied. Meshram et al. developed an energy management system to improve the power quality of the hybrid system and to control the power distribution among the power generating systems [6]. A new approach to optimize the photovoltaic water pumping system for irrigation was presented by Campana et al. [7]. Campana et al. also developed a dynamic simulation tool combining the models of the water demand, the solar PV power and pumping system [8]. Many other studies on the hydro/PV hybrid system are published on its design [9], control strategies [10], as well as environmental effect [11,12].

Nevertheless, most of the studies are in view of the short-term operation for the small-scale system, or even off-grid power systems in some cases, where the quality requirements of power generation appear less important. Moreover, the PV power output depends on the solar radiation in hourly scale, while to estimate the long-term optimal operation by hours would result in a high-dimensional non-linear problem, to which none of the current optimization algorithms is capable. Hence, the optimization of the whole integrated hydro/PV power systems instead of the control techniques is seldom focus on, nor the analysis of the operational potential in a long term.

This study is intended to focus on the estimation of the annual power generation of the whole hydro/PV system considering both the quality and the quantity of the power output. To maintain the accuracy of calculation, the PV power output is firstly evaluated day by day with hourly solar radiation and temperature data, the results of which is taken as the boundary condition for the reservoir optimization. As to the hydropower, because of its great adjustable capability, a month is taken as the time step to balance the simulation cost. Such decoupling of hydropower and PV power in time scales effectively reduces the problem dimensions with respect to the computational accuracy. Taking reservoir release as decision variables, both maximizing the power generation of the integrated system and minimizing the fluctuation of its power output are set as objectives. With the addition of other operational constraints, a multi-objective optimization model for long-term operation of hydro/PV power system is established, and it is then optimized by the modified version of Non-dominated Sorting Genetic Algorithm (NSGA-II). The proposed method is applied on the Longyangxia project, which is the largest integrated hydro/PV power system in the world. The power generation potential in different typical hydrologic years is provided. The results prove that the hydropower and PV power are able to complement each other significantly, especially in wet years. Hydropower can make the power output process of the whole system much smoother with an increment of total power generation by reallocating the temporal distribution of water resources. The results can be used to either evaluate the practice or guide the reservoir operation. The proposed model can be promoted to other hydro/PV power systems than the case in this study.

2. Methodology

2.1. Calculation of PV power generation

PV grid-connected generation systems can be divided into two categories based on its function: one is unschedulable excluding energy storage components, and the other kind of PV systems is schedulable with energy storage elements. The energy storing device of the latter one introduces some operational defects, the primary of which is that the common storage battery has a short service life of about 3–5 years and is inconvenient to maintain. Besides, the battery will lead to environmental pollution. Due to the existence of these problems, the application of "schedulable type" of the PV system is far below that of the "unschedulable type". Hence, this study mainly aims at "unschedulable" PV grid-connected generation systems.

There is a typical PV power device in Fig. 1, a PV array with tracking stents. PV array is the key component of the device, formed by series–parallel connected PV solar cells. Its main function is to convert sunlight energy into electrical energy. The twin-shaft tracking stents bear the weight of the PV cells with controller, which is able to rotate the PV array to track the maximum energy point of incident rays. Detailedly, the angle of the solar wafer substrate is adjusted constantly to ensure that the substrate is always perpendicular to the incident solar rays so as to maximize the utilization of solar energy.

The electric current and voltage of PV power varies with different solar intensity and environmental temperature, and thus the output of PV power is unstable. If the PV array is incapable to real-timely track the change of external environment, the overall efficiency of PC power system will decrease inevitably. The technology of Maximum Power Point Tracking (MPPT) is developed to continuously obtain the maximum power output at any