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An Optimization Sizing Model for Solar Photovoltaic Power Generation System with Pumped Storage

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Abstract

In this study, a novel sizing model for the solar photovoltaic system with pumped storage is proposed, to optimize the capacity of the PV generator and pumped storage system for power supply in remote areas. The genetic algorithm is then employed to optimize sizing system with respect to the system total cost. The variables considered in the optimization process include PV module number, upper reservoir size and water pump size. With the developed model, a technically and economically feasible power supply solution can be achieved easily. The proposed model is finally applied to a case study on renewable energy power generation system for an island, and the optimization performance has been demonstrated.

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Key words: Optimization sizing; cost of energy; renewable energy power generation; remote area

1. Introduction

Off-grid power systems number in the thousands, and most of them are still powered by diesel generators. They are typically either remote, islanded systems or special zones designed to disconnect from the main utility grid for economic or power supply quality reasons. Standalone renewable energy technologies present great potential for energy generation and supply in remote areas, since the renewables have a reputation for being omnipresent, inexhaustible, environmentally benign, and now is becoming cost-effective when compared to diesel generation in those areas. However, the most significant feature limiting the wide spread deployment of renewables is their inherent intermittency [1]. Energy storage system appears to be the only solution to the intermittent production [2], which can ramp the fluctuating output from renewables, and ensure that power produced by renewables can be released and dispatched reliably to better fit demand. In this study, the solar photovoltaic system with pumped storage is proposed for the off-gird power supply, the sizing models are developed, and the capacity of the PV

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generator, upper reservoir (UR) and solar pumps are optimized in terms of levelized cost of energy (COE). The performance of the optimized system is finally analyzed.

2. System sizing models

The proposed hybrid solar and wind system is illustrated in Fig. 1. The system is designed to supply power for a remote island. Based on the collected data, the solar energy distribution matches well with electricity consumption, and thus PV module is used as the major power generator. The surplus energy after meeting the load is stored using a scheme called pumped storage, which can keep potential energy using the excess power from solar PV system to elevate water from a lower to a higher reservoir. When PV system cannot meet the load, the stored water is released to flow downhill through a turbine to produce power. The pumped storage system can operate flexibly and respond quickly therefore sustainable power supply can be provided for isolated places.

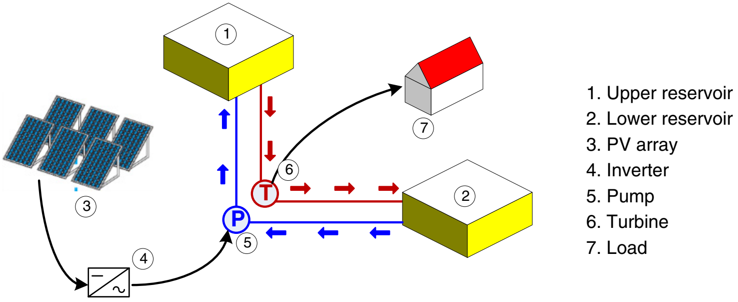

Fig. 1 System schematic

2.1. Simulation models

To size the system capacity and predict power from PV generator, the energy models for the PV module and pumped storage system are developed [3].

The five-parameter model [4] is deployed to simulate the power from PV system:

$$P = N_p I_{ph} V - N_p I_0 V\left(e^{\frac{1}{V_t}\left(\frac{V}{N_s}+\frac{I}{N_p}R_s\right)} - 1\right) - \frac{N_p}{R_p} V\left(\frac{V}{N_s}+\frac{I}{N_p}R_s\right) \tag{1}$$

The simulation of the pumped storage system includes two parts. During the charging process, the flow rate of water sucked from lower reservoir to UR can be expressed as:

$$q_P = \frac{\eta_P \cdot P_P}{\rho \cdot g \cdot h} \tag{2}$$

During the charging process, the power produced by hydro turbine-generator is:

$$P_T = \eta_T \cdot \rho \cdot g \cdot h \cdot q_T \tag{3}$$

Therefore, the water stored in the UR is

$$Q_{UR} = Q'_{UR} + q_P \Delta t - q_T \Delta t \tag{4}$$

2.2. Economic models

The economical approach is the best benchmark of system optimization. In literature [5, 6], levelized cost of energy (COE) is usually employed as a preferred indicator to evaluate different system configuration and options. In this study, the economic model for cost analysis is developed based on the COE concept.

The levelized cost of energy is defined as:

$$COE = \frac{NPV * CRF}{Load} \tag{5}$$

Where *TPV* is the total net present value of actual cost of all system components (PV panels, solar pumps, reservoirs, turbines, pipes, and others), and *CRF* is the capital recovery factor, which depends on the annual discount rate and the system life.

In this study, the system life is assumed as 25 years. A summary of the system components' cost and the corresponding lifespan is presented in Table 1.

Table 1 Basic information of the key components

Items	Unit	Cost (US$)	Lifetime (year)
PV array	W	2	25
Solar pump	0.8 kW	1,000	10
Turbines and pipes	kW	1,500	10
Reinforced concrete (reservoir)	m^3	170	35
Inverter	5 kW	4,480	15

3. Optimization methods

The objective of this study is to minimize the levelized COE, as expressed in Eq. (4). The problem to be solved in this study has a great number of possible solutions (different combination of solar panels, solar pumps and reservoirs), and hence it is difficult to solve such problem with classical mathematical techniques [7]. Genetic algorithm (GA) is a popular meta-heuristic that is particularly well suited for this class of problems. Therefore, the widely used GA is employed in this study to optimize system capacity.

4. Results and discussions

The proposed method is applied in a research project on power supply for a remote community, located in an island. The daily load consumption is about 45kWh/day. In this research, the 100% reliability of power supply should be guaranteed, which means that the system with any power deficit will be discarded, even though lower COE values could be achieved.

Table 2 Optimal sizing results for the solar PV system with pumped storage

Configurations	PV (kW)	Upper reservoir (m^3)	Solar pumps (kW)	COE (US$)
1	20.00	4880	15.2	0.594
2	21.60	3800	16.8	0.579
3	23.20	3903	17.6	0.570
4	24.80	2802	19.2	0.584
5	26.40	2702	20.8	0.605
6	28.00	2604	21.6	0.619

The optimal sizing result for the PV system with pumped storage system is summarized in Table 2. It is obvious that an increase in PV size can reduce the capacity of UR significantly, while the overall optimal solution is the configuration 3, which has the lowest COE of \$0.57, and the net present cost during the whole lifecycle is \$119,664. The optimal configuration is made up of 23.2kWp PV module, 3,093 m^3 UR and 17.6kWp solar pumps. With the simulation models, the energy contribution of PV panel and pumped storage system in the optimized case are investigated. As shown in Fig. 2, PV generator accounts for 46% of energy consumption, while the remaining parts are covered by the hydro turbine-generator. The PV output was extremely high in the summer months from June to September. This is a favorable characteristic since electricity demand is also strong in the summer due to high cooling load.

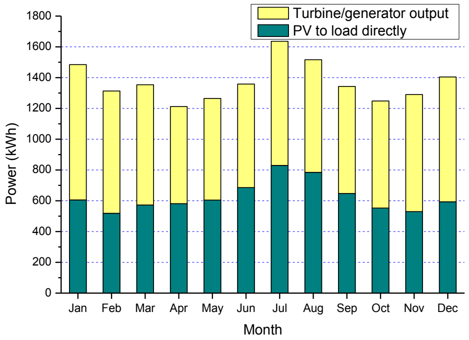

Fig. 2 Load consumption covered by PV and turbine

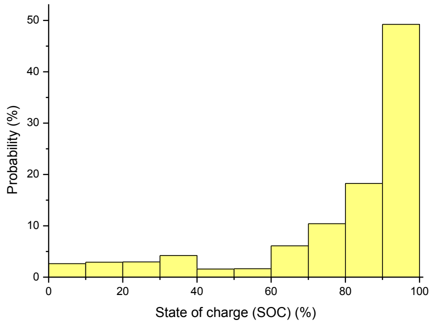

Fig. 3 state of charge of the pumped storage system

The probability distribution of the one-year state-of-charge of the pumped storage system is presented in Fig. 3, which indicates that about half of time is above 90% of the storage capacity. Thus about 16% of energy produced by the PV generator was lost when the UR is fully charged. An increase in the storage capacity can reduce the wasted energy, while the total cost will increase as well. It demonstrates that the case under study is the optimal system configuration with lowest cost and zero power supply failure.

5. Conclusions

In this study, the genetic algorithm is proposed to optimize the capacity of the PV generator and pumped storage system, and minimize the system cost. A remote island is used as a case-study to demonstrate the effectiveness of the algorithm. The results show that zero power failure hours could be reached with a low COE. The optimal system combination consists of 23.2kWp PV module, 3,093 m^3 upper reservoir and 17.6kWp solar pumps, and the corresponding COE is \$0.57. Finally, the optimal system configuration is simulated in hour basis and its performance is investigated.

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