Journal of Energy Storage 16 (2018) 133–138

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Optimal operation scheduling of grid-connected PV with ground pumped hydro storage system for cost reduction in small farming activities

Kanzumba Kusakana*

Department of Electrical, Electronic and Computer Engineering, Central University of Technology, Bloemfontein, South Africa

ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form 28 November 2017
Accepted 12 January 2018
Available online xxx

Keywords:
Demand response
Dynamic pricing
Optimal scheduling
Pumped hydro storage

ABSTRACT

A model of electricity cost minimization is proposed which can be implemented in small farming activities where boreholes are present for water supply. In this case, a hybrid system composed of solar photovoltaic and pico hydro supplied by a pumped storage system are used minimize the electricity cost in a dynamic electricity pricing environment. The varying price of electricity, the load demand, the reservoir state of water stored as well as the solar resource at any instant determine the optimal power flow from the different power sources to the load; these are the control variables to be optimised with the aim of reducing the power consumed from the grid. The optimization problem can be solved using linear programming. The simulation results can be used to investigate the impact and benefit of the proposed model on the electricity cost reduction of small loads in the South African farming sector.

1. Introduction

South Africa's energy sector has grown significantly in the past decade; this is due to the positive development occurring in the residential, commercial as well as industrial sectors [1]. Currently, almost 90% of the country's energy demand is met from fossil fuels. On March 31, 2017, the total installed power generation capacity was 52,811 GW, of which fossil fuels hold more than 80% of the total share [2]. However, the total share of solar, wind or hydropower energy sources is increasing due to the government commitment, and currently reaching 12% [3].

Nevertheless, despite the growth in the country's power generation capacity, South Africa is still not in a position to adequately meet the total energy demand of all the customers connected to the grid without implementing strategies such as demand-side management, Time-of-Use tariff or optimal management of available energy storages [4]. For residential, commercial and industrial consumers, this situation is most evident and translated by high cost of electricity during peak pricing period, which can be up to four times the price of electricity in off-peak periods; depending on the demand sectors as well as the seasons [5].

Apart from the mining and manufacturing sectors, South Africa's economy is also depending on agriculture. It has to be noted that the country is semi-arid, therefore a significant number of the small farmers heavily rely on underground water through boroholes for irrigation as well as other farming needs [6]. Underground water is usually pumped using electricity from the grid, standalone diesel generators or renewable energy such as wind and solar pumping systems which are currently seen as promising and sustainable options, especially in regions where other alternatives are not easy to be implemented and not cost effective [7].

Several research studies have analysed the performance of solar water pumping systems. In ref. [8] the research developments related to renewable energy technologies for water pumping systems are reviewed; discussing the different topologies, their advantages as well as limitations.

In Ref. [9] the design, development, and performance analysis of a solar system for water pumping is presented along with its technical, environmental, and economic benefits as compared to diesel generator or power grid.

The authors of Ref. [10] have compared performance of a directly connected photovoltaic pumping system and a scheme using a constant voltage maximum power point tracking algorithm. The results have demonstrated very good correlation with the numerical simulation of the systems.

However, the current renewable energy based options in rural areas involve batteries for storage of electricity, which have

* Corresponding author.
E-mail address: kkusakana@cut.ac.za (K. Kusakana).

https://doi.org/10.1016/j.est.2018.01.007
2352-152X/

negative impacts such as pollution and high lifecycle cost. These shortcomings can be overcome by using a novel energy storage system well suited for remote and isolated areas.

Renewable energy sources combined with the available pumping infrastructure can be used to generate clean electricity using the pumped hydro storage principle and pico hydro turbine. In reference [11] the author has described the operation principle of a novel system named Hydro Aeropower designed in Bloemfontein, South Africa. In this system, a windmill is used to drive a wind pump which extracts underground water via a borehole to be stored in a tank located at a reasonable height above the ground. The potential energy of the stored water is then released through a pico turbine to generate electricity.

Several farmers in South Africa draw water from boreholes and store it in the upper reservoirs for irrigation and other activities [12]. This same arrangement can be used for the implementation of pico-hydropower system. Therefore, local renewable energy sources can be combined to pumped hydro storage facilities and pico-hydro hydropower in a hybrid system configuration.

Based on the facts discussed above, this paper presents a model which can be used to minimize the operation cost of a grid connected photovoltaic system with pico hydro and pumped hydro storage. This model can be implemented in small farming activities where boreholes are present for water supply. Therefore, the resources and facilities available in South African farms can be efficiently used for the proposed hybrid power generation scheme.

2. System description

2.1. Schematic diagram of the system

In this proposed hybrid system, the load P_L is mainly supplied by the photovoltaic system P_{PV} when the resource is available. The excess of energy from the PV is used to pump the water from the borehole to store it in an upper reservoir. When the solar resource is unavailable, the water stored in the reservoir is used to generate power through the pico turbine $P_{M\text{-}P}$. The load and the pump can also be supplied from the grid P_G when the electricity price is low. After the power is generated using the pico turbine $P_{T\text{-}G}$, water is allowed to flow back underground, thereby the borehole with its reservoirs is considered as an energy storage system. This operation is shown on Fig. 1.

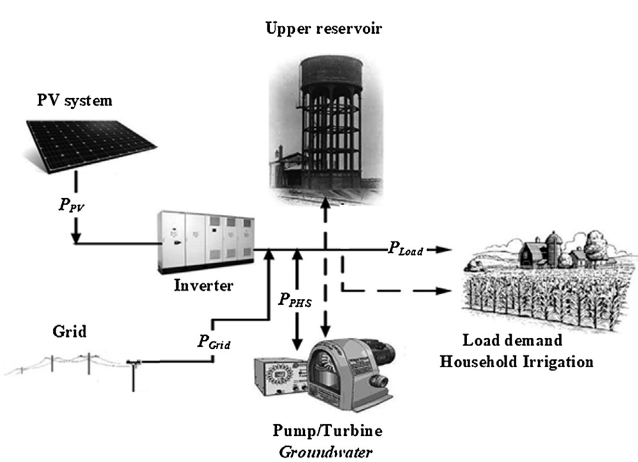

Fig. 1. Set-up of the studied microgrid.

2.2. Simplified photovoltaic model

For a given size, the output power from a PV system can be expressed as:

$$P_{PV} = A \times \eta_{PV} \times I \tag{1}$$

Where: A is the surface size of the PV array (m^2); η_{PV} is the efficiency PV system; and I is the solar irradiation (kWh/m^2).

2.3. Pumped hydro storage

1) Pumping system

The power used to pump water from the lower reservoir to the upper reservoir is given using Eq. (2).

$$P_{MP} = \frac{\rho_W \times g \times h \times Q_{MP}}{\eta_{MP} \times t} \tag{2}$$

Where P_{MP} the share of power from the grid used to supply the load (W); Q_{MP} is the pumping flow rate (m^3/s); h is the useful pumping head (m); g is the gravity (9.8 m/s^2), η_{MP} is the efficiency of the pumping system, t is the considered time.

1) Hydro generator

The electrical power generated from the hydropower system E_{TG} set is given as:

$$P_{TG} = \frac{\rho \times g \times h \times Q_{TG} \times \eta_{TG}}{t} \tag{3}$$

Where η_{TG} is the hydro generating power efficiency; Q_{TG} is turbine flow rate (m^3/s); h is the water head (m).

1) Upper reservoir

The potential energy stored in the reservoir is given by:

$$E_R = \rho \times V \times g \times h \tag{4}$$

Where E_R is potential energy (kWh); V is the size of the reservoir (m^3).

2.4. Power from the utility grid

The cost of power from the grid is dependent on the Time of Use. For South Africa, this structure is shown below with peak, standard, and off-peak pricing periods [13].

$$p(t) = \begin{cases} p_k; t \in T_k, T_k = [7,10) \cup [18,20) \\ p_0; t \in T_0, T_0 = [0,6 \cup [22,24) \\ p_S; t \in T_S, T_S = [6,7) \cup [10,18) \cup [20,22) \end{cases} \tag{5}$$

Where p_k = 0.20538 $/kWh for peak periods;
p_0 = 0.03558 $/kWh for off-peak periods;
p_s = 0.05948 $/kWh for standard periods.

3. Optimisation model and proposed algorithm

3.1. Objective function

The objective of this work are to minimize the amount of power drawn from the grid. This can be expressed as:

$$f_1 = \sum_{j=1}^{N} p_j (P_{G-PHS(j)} + P_{G-L(j)}) \Delta t \tag{6}$$

Where: N is the sampling time.