Journal of Energy Storage 18 (2018) 84–89

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Hybrid DG-PV with groundwater pumped hydro storage for sustainable energy supply in arid areas

Kanzumba Kusakana

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

ARTICLE INFO

Keywords:
Demand response
Diesel generator
Groundwater
Optimal scheduling
Photovoltaic generation
Pumped hydro storage

ABSTRACT

This paper discusses the development of a model for the optimal operation of a hybrid diesel-photovoltaic pumping system using, groundwater in a pumped hydro storage scheme which can be used to minimize the daily electricity cost of a farm. The developed model can minimize the power produced from the diesel generator, while optimally managing the generated power flow from the PV and the groundwater pumped hydro storage given the variable load demand as well as the availability of solar resource. As a case study, the model has been used to simulate a small farming activity in South Africa, with the aim of evaluating the potential energy cost saving achievable using the proposed system when compared to exclusive power production using a diesel generator. The simulation results show that a potential 71.3% of energy cost saving can be achieved using the proposed hybrid system with the optimal control model rather, than supplying the load demand by the diesel generator exclusively.

1. Introduction

Agriculture is one of the main pillars of the South African economy [1]. However, most of the agricultural activities in the country are located in regions where there are severe techno-economic challenges in supplying water and electricity, especially through municipal channels. Among these challenges is the distance from the main municipal water pumping station, as well as the cost of the grid extension to remote farms can be cited [2]. Therefore, for irrigation purposes, as well as operating farming machineries and other electrical appliances, local farmers are currently looking at the possibilities of producing onsite electricity, as well as minimising the distance between the main water sources and the end users. Ideally, the energy produced, as well as water extracted, should be made available and stored near the point of use.

Most South African farmers in remote areas are relying on Diesel Generators (DGs) for electricity generation. These DGs are convenient in these circumstances because they have low capital costs. They generate electricity on demand, they are easily transportable to the point of use and generally have a high power-to-weight ratio [3]. DGs can also be integrated with other energy sources in hybrid systems to increase the reliability and availability of power supply, especially for standalone applications [4].

As a suitable onsite water supply option, pumping groundwater has been the preferred technology for South African farmers compared to surface water, due to the fact that it can be pumped near the point of use; it can be made available when needed using an appropriate reservoir.

The following energy sources are commonly used to supply electrical pumps extracting groundwater:

- Grid: This is the ideal option when there is a grid connection, especially to remote locations. There is no other set up needed as the pump is directly supplied from the electrical grid [5].
- Solar pump: A photovoltaic system can be adequately designed to provide energy to an electric pump that extract the groundwater through a borehole. A battery storage system can be incorporated into the design as a back-up power source, in case pumping activities are needed when there is not enough solar radiation [6].
- Wind pumps: These pumps can be further classified into Wind Energy Converting Systems where the wind turbine is used to generate electricity and then used to power an electric water pump [7]; Mechanical Wind Pumping Systems where the blade turning kinetic energy of the windmill is used directly to pump water [8].
- Diesel pumps: These pumps use DGs as main the source of electricity and can extract water on demand. However, they display all the technical, economic and environmental challenges associated with DGs operation [9].

Very few research works have been published in the literature, based on the use of groundwater for storage and electricity generation. The authors of Ref. [10] have developed a model to minimise the

E-mail address: kkusakana@cut.ac.za.

https://doi.org/10.1016/j.est.2018.04.012
Received 19 February 2018; Received in revised form 13 April 2018; Accepted 14 April 2018
2352-152X/

electricity cost of domestic consumers where open wells are available. In the study, a solar photovoltaic (PV) system with ground PHS is used for minimising the electricity bill in a dynamic electricity pricing environment. The objective function is solved using particle swarm optimization (PSO). The payback period for the proposed supply option, if realised, is also analyzed as a case study in India. A similar research was conducted by the authors of Ref. [11], where a wind energy converting system was used in conjunction with the PV.

The author of Ref. [12] has proposed a model to minimise the electricity consumed by a load from a grid-connected PV, using groundwater as a storage medium; this has been applied for farming communities in South Africa. The optimization problem has been solved using linear programming and the results have been used to investigate the impact and benefit of the proposed model on the electricity cost reduction in the South African farming sector.

The work in Ref. [12] has been extended in Ref. [13], where the author has used a mechanical wind pumping system for groundwater extraction. Water extracted from the borehole is stored in an upper reservoir and used later to generate electricity through a turbine connected to a generator.

An optimal energy management of a PV, DG, with a battery storage system, has been proposed in Ref. [14]. A PAT (Pump as Turbine) is also used as a hybrid system for supplying electricity and water, as well as storing groundwater in the upper water tank. The results have shown that the proposed controlled hybrid PV-PAT storing system is capable of supplying the water for irrigation and domestic requirements, as well as 9% of the electricity needed for the selected isolated load.

Given the fact that DGs are well spread in isolated farming activities to sustain livestock, poultry, plants, appropriate harvesting, storing and food conservation, the financial returns of the farm capital investments caused by the high operation costs of DGs can be reduced. Therefore, minimising the cost of electricity used on the farm is an important aspect to be taken into account when aiming to increase the financial benefit of the farm.

To decrease the operation cost of DG in isolated applications, renewable energy sources such as solar photovoltaic can be used in conjunction with a proper storage system in a hybrid system configuration [15]. In addition, the groundwater pumping arrangements, already available on most of the farms, can be redesigned to generate onsite electricity, that can be used to minimise the total amount and cost of electricity consumed when coupled to a DG.

Based on the review conducted in the above section, this paper develops a model for the optimal operation of a hybrid diesel-photovoltaic system, using groundwater in a pumped hydro storage scheme (PHS), which can be used to minimise the electricity cost of a farm. This model can minimise the power produced from the DG, while optimally scheduling the generated power flow from the PV and the PHS used to convert into electricity potential energy of the stored water in the reservoir, given the variable load demand as well as the availability of solar resources. This model can be implemented in small farming activities where groundwater is extracted. Therefore, the resources and facilities made available in South African farms can be efficiently used with the proposed hybrid power generation scheme.

2. Model development

2.1. System description

In this proposed supply option's architecture, the total load P_L is fed primarily by the photovoltaic system ($P_{PV\text{-}L}$) during the time of the day when there is adequate solar resource.

The photovoltaic system can also be used to supply the pump ($P_{PV\text{-}PHS}$), which is considered as a deferrable load, to store water in the reservoir for future power generation through the turbine and hydro generator set ($P_{PHS\text{-}L}$).

The diesel generator is also used to supply the load ($P_{DG\text{-}L}$), or to

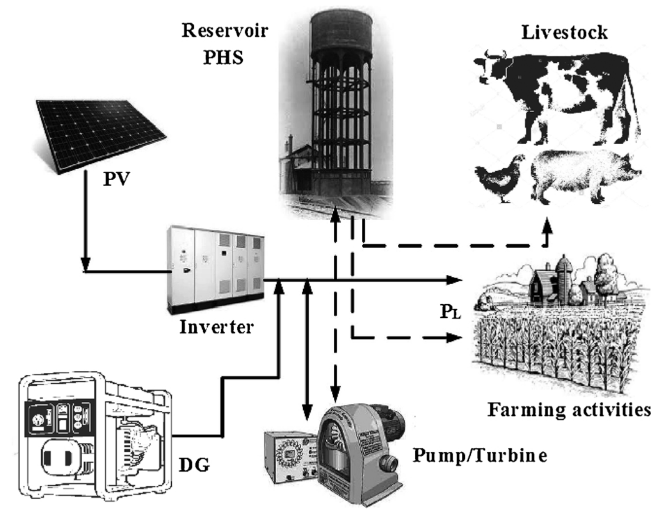

Fig. 1. Schematic diagram of the PV-DG with pump hydro storage system.

supply the pumped hydro storage ($P_{DG\text{-}PHS}$). However, the total output power from the DG is the control variable to be minimised. Therefore, the DG can be used in the following cases:

- When there is insufficient energy from the PV and the pumped hydro system to supply the load.
- When the reservoir needs to be at its final fixed state condition and the PV resource is not available.
- When the reservoir needs to be filled up before a peak power demand while most of the PV system's power is used to supply the load.

For the considered farming application, the main power flows related to the hybrid system described above can be graphically represented using Fig. 1.

2.2. Objective function

The main objective of the optimal energy management model developed is to minimise the daily operation cost function " f " under a considered period. For this specific case, it is defined as the total daily expense linked to the operation of the hybrid system. Given the short simulation time horizon, only the expenses linked to producing electricity linked to the DG are considered as the major operation costs. This can be mathematically expressed as follows:

$$f = \min C_f \sum_{j=1}^{N} (aP_{DG(j)}^2 + bP_{DG(j)} + c)\Delta t \tag{1}$$

Where C_f is the cost of diesel fuel per litre, j is the considered j^{th} optimisation sampling interval; N is the total number of sampling intervals; a, b and c are the parameters of the DG's fuel consumption curve available from the manufacturer; Δt the considered simulation sampling time.

2.3. Variable constraints

2.3.1. Power balance

The power balance is one of the main requirements in electrical circuits that need to be fulfilled. Eq. (2) represent a linear equality constraint. For this specific case, the power balance linked to the load demand is expressed as follows:

$$P_{Load(j)} = P_{PV-L(j)} + P_{PHS-L(j)} + P_{DG-L(j)} \tag{2}$$

This means that for each sampling J, the load demand must be met