Using PV with Borehole Pumped Hydro Storage Systems for Small Farming Activities in South Africa

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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 system can be implemented in real-time to investigate the impact of the proposed model on the electricity cost reduction of small loads in the South African farming sector.

Index Terms--Demand response, Dynamic pricing, Optimal Scheduling, Pumped hydro storage.

I. 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 hydro power 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 underground water through boreholes 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 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.

II. SYSTEM DESCRIPTION

A. 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 \( P_{MP} \). 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 \( P_{TG} \), 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.

![Figure 1. Set-up of the studied microgrid](image)

B. Simplified photovoltaic model

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

\[
P_{PV} = A \times \eta_{PV} \times I
\]

(1)

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

C. Pumped hydro storage

1) Pumping system

The power used to pump water from the lower reservoir to the upper reservoir is given using Eq. (1).

\[
P_{MP} = \frac{P \times g \times h \times Q_{MP}}{\eta_{MP}}
\]

(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\(^2\)), \( \eta_{MP} \) is the efficiency of the pumping system.

2) Hydro generator

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

\[
P_{TG} = \frac{P \times g \times h \times Q_{TG} \times \eta_{TG}}{t}
\]

(3)

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

3) Upper reservoir

The potential energy stored in the reservoir is given by:

\[
E_R = \rho \times V \times g \times h
\]

(4)

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

D. 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].

\[
\rho(t) = \begin{cases} 
\rho_k, & t \in T_k, T_k = [7,10) \cup [18,20) \\
\rho_0, & t \in T_0, T_0 = [0,6) \cup [22,24) \\
\rho_s, & t \in T_s, T_s = [6,7) \cup [10,18) \cup [20,22) 
\end{cases}
\]

(5)

Where \( \rho_k = 0.20538 \) $/kWh for peak periods; \( \rho_0 = 0.03558 \) $/kWh for off-peak periods; \( \rho_s = 0.05948 \) $/kWh for standard periods.

III. OPTIMISATION MODEL AND PROPOSED ALGORITHM

A. Objective function

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

\[
f = \sum_{j=1}^{N} \rho_j (P_{G-PHS(j)} + P_{G-L(j)}) \Delta t
\]

(6)
B. Variable constraints

1) PV system
The sum of instantaneous PV power for pumping water and for supplying the load must be less than the total PV power generated.

\[ P_{PV-PHS}(j) + P_{PV-L}(j) \leq P_{PV}(j) \] (7)

2) Grid constraints
For each sampling interval \( j \), the sum of powers from the grid to fill in the reservoir and to supply the load must be less than the instantaneous that is allowed to be drawn from the grid.

\[ P_{G-L}(j) + P_{G-PHS} \leq P_{G}(j) \] (8)

3) Power balance
For any sampling interval \( j \), the sum of the power from the PHS turbine-generator set and from the utility must be equal to load power requirement.

\[ P_{Load}(j) = P_{PV-L} + P_{PHS-L}(j) + P_{G-L}(j) \] (9)

4) Variable boundaries
The grid and PHS systems are modelled as variables which can be controlled from a minimum to a maximum set range for each sampling time of the simulation horizon. These constraints can be expressed as:

\[ 0 \leq P_{G-L}(j) \leq P_{max}^{G-L} \quad (1 \leq j \leq N) \] (10)
\[ 0 \leq P_{PV}(j) \leq P_{max}^{PV} \quad (1 \leq j \leq N) \] (11)
\[ 0 \leq P_{PHS-L}(j) \leq P_{max}^{PHS} \quad (1 \leq j \leq N) \] (12)

\[ V_{R}^{min} \leq V_{R}(j) \leq V_{R}^{max} \] (13)

Equations (6) - (13) are the constraints on the different power sources as well as on the storage size. Equation (14) describes the potential energy dynamics linked to the change of stored water volume, where:

- \( V_{R(0)} \) is the volume of water stored at the beginning of every sampling time.
- \( \delta \) is the loss in the reservoir linked to evaporation or leakage.

\[ V_{R}(j) = V_{R(0)} \times (1 - \delta) + \eta_{TG} \sum_{i=1}^{j} \left( P_{PV-PHS(i)} + P_{G-PHS(i)} \right) \] (14)

C. Solver selection
The developed objective function and constraints are linear; therefore, the optimization problem can be solved using linear programming in Matlab:

\[ \begin{align*}
\min g(x) & \text{ s.t. } \begin{cases}
Ax \leq b \\
A_{eq}x = b_{eq} \\
b \leq x \leq ub
\end{cases}
\end{align*} \] (15)

With: \( g(x) \) represents the objective function; \( A_{eq} \) and \( b_{eq} \) represent the equality constraint parameters; \( A \) and \( b \) represent the inequality constraint parameters; \( l_b \) and \( u_b \) represent the inferior and superior limits of the variables.

IV. APPLICATION RELATIVE TO BLOEMFONTEIN CASE (SOUTH AFRICA)

A. Input data and control system settings
In this work, a representative commercial daily load profile (Fig. 2) is obtained by adding the respective demand profiles of different equipment available in a typical small sized farm in Bloemfontein such as bulk milk cooler, milking machine, fan, water pump, freezer, electric heater and light.

The solar resources have been used as input to the More information the solar resource and the system sizing can be found in ref. [14,15]. The main simulation data are given in Table 1.

![Figure 2. Proposed commercial load profile](image)

Table 2: Simulation parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time (Δt)</td>
<td>30 min</td>
</tr>
<tr>
<td>PV rated power</td>
<td>4.5 kW</td>
</tr>
<tr>
<td>Pump rated power</td>
<td>4 kW</td>
</tr>
<tr>
<td>Pico hydro rated power</td>
<td>4 kW</td>
</tr>
<tr>
<td>Pumping efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>Pico turbine efficiency</td>
<td>70%</td>
</tr>
<tr>
<td>PH S maximum Volume</td>
<td>100%</td>
</tr>
<tr>
<td>PH S minimum Volume</td>
<td>20%</td>
</tr>
</tbody>
</table>

B. Simulation results and discussion

1) Load exclusively supplied by the grid
Fig. 3 shows the simulation results of the case where the grid is used exclusively to supply the load demand of Fig. 2. It can be seen that the power profile drawn from the grid and the load profile have the exact same pattern. The analysis of this figure reveals that the peak load demand coincides with the peak pricing period from the grid; this will result in high cost of electricity consumed.
C. Load supplied by the grid-connected PHS

In this case, we consider that at the beginning of the simulation, the state of volume in the water tank is set at its minimum.

- Power flow during first off-peak pricing period \( (0, 6) \)
  
  Given the fact that the initial water level in the tank is at its highest as shown on Fig. 4, the potential energy stored in the upper reservoir of the PHS can be used successfully responds to the load demand as shown on Fig. 5. During this pricing period, there is no solar resource, therefore, the PV system does not generate any power as shown on Fig. 6 and Fig. 7. The grid is not used to supply the load or to pump water as shown on Fig. 8 and Fig. 9 respectively.
• Power flow during first standard pricing period (6, 7)
  During this standard pricing period, the grid is used to supply the load as well as to pump water into the upper reservoir as shown on Fig. 8 and Fig. 9 respectively. This is to have enough energy stored to cater for the peak pricing period; this results in an increase of the PHS state of volume as shown on Fig. 4.

  It can be noticed that there is a small output power from the PV system, this is used to supply the load as well as to contribute to the power supplied to the pump as shown on Fig. 6 and Fig. 7.

• Power flow during first peak pricing period (7, 10)
  During this peak pricing period, the load demand is mainly supplied by the whole available PV system. However, the solar resource is decreasing, therefore, water from the reservoir is released to generate the deficit of power needed by the load on Fig. 5 and Fig. 6; the corresponding state of stored water in the reservoir decreases as shown on Fig. 4. Because of the high electricity price during this period, the grid is not used to reduce the operation cost.

• Power flow during second standard pricing period (10, 18)
  During this standard pricing period, the load is mainly supplied by the PV as shown in Fig. 6. The PV system is also used to pump water in the reservoir as shown in Fig. 7. Because the electricity price is reasonable during this period, a small contribution form the grid power is used to supply the load as well as to pump water into the upper reservoir as shown on Fig. 8 and Fig. 9.

• Power flow during second peak pricing period (18, 20)
  As for the first peak pricing period, the load demand is mainly supplied by the whole available PV power produced seconded by the pico hydro turbine form the PHS as shown on Fig. 5 and Fig. 6. The corresponding water level in the reservoir is empty and there is no power generated from the PV system as shown on Fig. 4 and Fig. 6 respectively. Therefore, the grid is the only option that can be used to supply the load as shown on Fig. 8. However, the power from the grid is not used to pump water in the upper reservoir as shown on Fig. 9.

• Power flow during second off-peak pricing period (22, 24)
  In this case, the exact same operating mode is observed as for the third standard pricing period.

D. Daily economic analysis

Table 2 gives a summary on the cost saving that can be realized by using the proposed grid connected PV pumped hydro storage instead of supplying the load exclusively by the grid. These results also show the importance to the pumped hydro initial state of water stored in the upper reservoir in achieving cost reduction.

<table>
<thead>
<tr>
<th>Supply option</th>
<th>Daily operation cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load exclusively supplied by the grid</td>
<td>$6.24</td>
</tr>
<tr>
<td>Load supplied by the grid-connected PHS (Minimal initial volume)</td>
<td>$3.47</td>
</tr>
<tr>
<td>Load supplied by the grid-connected PHS (Maximal initial volume)</td>
<td>$0.95</td>
</tr>
</tbody>
</table>

V. Conclusion

In this paper, a novel to minimize the electricity cost of proposed farming activities in South Africa is proposed. The system integrates a PV system with pumped hydro storage and pico hydro using borehole water. From the simulation results, the following conclusion can be drawn:

• The developed model effectively utilizes the PV as well as underground water resources available on site.

• The simulation performed using the real data shows that the daily electricity cost has been reduced for the proposed farming load profile with the use of the PV, storage as well as pico hydro.

• The power from the grid can be used for pumping during off-peak pricing period.
• The proposed model minimizes the consumer grid power consumption during peak hours by maximizing the use of the PV and PHS.
• The initial state of the water stored in the tank has an influence on the cost reduction.
• The developed model can be implemented in a smart grid environment with dynamic electricity pricing.

REFERENCES