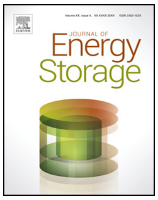
Journal of Energy Storage 14 (2017) 8–15

Contents lists available at ScienceDirect

Journal of Energy Storage

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



# Optimal energy management of a grid-connected micro-hydrokinetic with pumped hydro storage system

S.P. Koko[a], K. Kusakana[b,*], H.J. Vermaak[b]

[a] Department of Maths, Science and Technology Education, Central University of Technology, Private Bag X20539, Bloemfontein 9300, South Africa
[b] Department of Electrical, Electronic and Computer Engineering, Central University of Technology, Private Bag X20539, Bloemfontein 9300, South Africa

ARTICLE INFO

*Article history:*
Received 11 June 2017
Received in revised form 22 August 2017
Accepted 9 September 2017
Available online xxx

ABSTRACT

Renewable energy sources are the key alternatives to mitigate the issue of greenhouse gases (GHGs) and to meet the ever increasing electricity demand. In South Africa, most energy is consumed by the industrial sectors when discretely compared to other sectors. Industrial consumers can reduce their electricity costs by creating an optimally managed onsite renewable energy system. Hydrokinetic is a promising renewable technology that has proved to offer a cost-effective electrification solution in areas with flowing water resources when compared to solar and wind technologies.

This paper proposes an optimal energy management model for a grid-connected micro-hydrokinetic pumped hydro storage (MHK-PHS) system supplying the industrial load profile. The aim of the study is to investigate the behavior of model when minimizing the grid energy costs through power-flow control variables and time-of-use (TOU) tariff scheme. The optimization problem has been solved through the use of the *linprog* solver in the MATLAB's optimization toolbox for a period of 192 h as a means of including week days and weekend days. The simulation results show that the developed model can assist the onsite MHK-PHS system to optimally reduce the electricity cost for the industrial load profile. An 86% grid cost saving has been achieved through the optimally managed MHK-PHS system.

## 1. Introduction

More than 80% of the world energy supply is mainly generated from fossil fuels resulting into a climatic change due to carbon emissions [1]. Globally, the ever increasing electricity demand brings significant challenge of installing new fossil fuel power plant which results into electricity price increase for end-users [2]. This trend is expected to continue due to population growth leading to energy shortage and demand supply imbalance. To guarantee grid stability, popular approaches such as promoting energy efficiency as well as demand side management are applied.

Consumers are encouraged by the electric utility companies to reduce their energy consumption through demand response [3]. Time-of-use (TOU) pricing scheme is a commonly used effective method to influence the consumer consumption behavior [4]. Through TOU pricing scheme, consumers are encouraged to reduce their electricity usage during peak periods by shifting their demands to off-peak or standard periods.

Similar to energy efficiency and demand side management approaches, an approach such as clean alternative energy generation can also be used to boost the grid stability [5,6]. Such approach warrants a reduced reliance on fossil fuels. However, the intermittent nature of renewable energy sources such as solar and wind makes this approach less competitive. Hence, by incorporating the energy storage system to a hybrid renewable energy system will make the system to be more reliable and economical. Nevertheless, the initial capital cost as well as the maintenance cost will be high. Therefore, to ensure a good investment return, proper power flow usage and storage of excess energy are critical. This leads to the requirement for an optimal energy management method of the hybrid system.

Hydrokinetic technology is a promising renewable energy technology that has proved to generate electricity markedly better and cheaper than solar and wind systems [7,8]. Unlike the traditional hydropower generation, hydrokinetic does not require water head to generate electricity. It generates electricity by making use of kinetic energy of the flowing water within river streams, tidal current or other artificial water channels [9–11]. It can generate electricity when the speed of the flowing water resources ranges from 0.50 m/s and above [9]. It has proved to generate electricity more economically if used in combination with

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* Corresponding author.
*E-mail addresses:* skoko@cut.ac.za (S.P. Koko), kkusakana@cut.ac.za (K. Kusakana), hvermaak@cut.ac.za (H.J. Vermaak).

http://dx.doi.org/10.1016/j.est.2017.09.007

a pumped hydro storage (PHS) instead of battery storage system [12]. PHS system has proved to be the most durable, cost-effective and efficient energy storage system when compared to other energy storage systems [13]. The required capital cost of building a PHS system is less than 100 US$ per kWh [13,14]. If an industrial business is situated in close proximity to the flowing water resource, it can make use of the hydrokinetic-PHS system to rip the energy savings benefit.

In South Africa, about 40% of the end-use energy consumption is associated with industrial activities [15]. As a result, it is of significant importance for the industrial consumers to reduce their demand as a means of reducing their electricity bills. This will also help in minimizing probability of grid instability. Many studies have been carried out to develop an optimal energy management model for the renewable energy hybrid systems under TOU tariff scheme [16–21]. However, during optimization model simulations, 24-h load profiles were considered by assuming that the load consumption is constant for all other days. Consequently, it is practically impossible for the load demand to remain constant throughout the week. Additionally, the studies also ignored the behaviors of the optimization models under weekend (Saturday and Sunday) TOU tariffs.

This study aims to develop an optimal energy management model for a grid-connected micro-hydrokinetic-pumped hydro storage (MHK-PHS) system to sufficiently benefit the industrial consumer at the demand side. The objective is formulated to minimize the electricity cost through the consideration of the TOU tariff pricing scheme. The proposed model will be used to manage the power flows in all sampling intervals for a period of 192 h (8 days) using high demand season as a worst case. Hence, the behavior of the model during the weekend will also be analyzed since the weekend TOU tariff schedule is different to the weekdays' one. The results of the study have shown the effectiveness of the model in ensuring minimal grid costs by utilizing the hydrokinetic power as a first preference for meeting the load demand.

## 2. Mathematical model formulation

The power flow layout of the proposed grid-connected MHK-PHS system is as shown in Fig. 1. The arrows represent the directions of the power flows. The system consists of the MHK river system, PHS system as well as the primary industrial load. The industrial load is fed directly by the MHK river system, PHS system and the grid. If a load demands less than the power generated by the MHK river system, the excess energy must be stored in the PHS system. If both the PHS system and the MHK river system cannot entirely meet the load demand, the grid must compensate the unmet demand. The PHS can be recharged by the grid and/or MHK river system to store energy during off-peak hours. The stored energy can be used during peak period to save on electricity costs. $P_{1(t)}$ is the electrical power flow (kW) from the MHK river system to the load at time $t$, $P_{2(t)}$ is the electrical power flow (kW) from the turbine-generator unit to the load at time $t$, $P_{3(t)}$ is the electrical power flow (kW) from the utility grid to the load at time $t$, $P_{4(t)}$ is the electrical power flow (kW) from the MHK river system to the motor-pump unit at time $t$, and $P_{5(t)}$ is the electrical power flow (kW) from the utility grid to the motor-pump unit at time $t$.

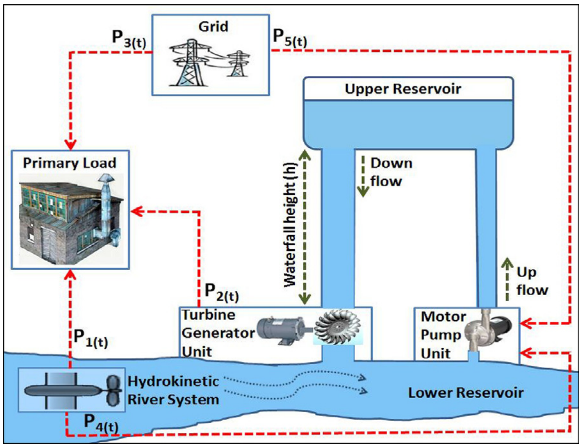

**Fig. 1.** Power flow layout of the proposed grid-connected MHK-PHS system.

### 2.1. Hydrokinetic system

Hydrokinetic turbines are designed to extract the kinetic energy of the flowing water instead of the potential energy of the falling water. As a result, no water head is required to convert the kinetic energy into electrical energy. Its operation principle is similar to the one of the wind turbine. However, unlike the wind energy resource, it is easily predictable and can generate electricity even at low water speed since the water is 800 times denser than air [22–24]. The energy generated by a hydrokinetic system is expressed as follows [8,12]:

$$E_{HK} = 0.5 \times \rho_W \times A \times v^3 \times C_p \times \eta_{HKT-G} \times t \tag{1}$$

where: $\rho_W$ is the water density (1000 kg/m$^3$), $A$ is the turbine swept area (m$^2$), $v$ is the water speed (m/s), $C_p$ is the power coefficient of a turbine (Betz limit), $\eta_{HKT\text{-}G}$ is the overall efficiency of a hydrokinetic turbine-generator unit and $t$ is the time (s).

### 2.2. Conversional pumped-hydro storage (PHS) system

In this study, a PHS system is used to store excess energy from the MHK river system and/or the energy from the grid during off-peak hours in the form of a potential energy. When storing energy, the motor-pump unit elevates a certain volume of water (m$^3$) from the lower reservoir (river) into the upper reservoir. The water flow rate is directly proportional to the supplied power. In pumping mode, the power supplied to the motor-pump unit to pump the water up to a certain height is then expressed as follows [25]:

$$P_{M:P} = \frac{\rho_W \times g \times H \times Q_{M:P}}{\eta_{M:P}} \tag{2}$$

where: $g$ is the gravitational acceleration (9.81 m/s$^2$), $H$ is the water-head height (m), $Q_{M:P}$ is volumetric flow rate of the water sucked from the lower reservoir by the motor-pump unit (m$^3$/s) and $\eta_{M:P}$ is the overall efficiency of the motor-pump unit.

During energy deficits, the upper reservoir water can be released to drive a hydro-turbine in order to generate electricity. Therefore, the power generated by the turbine-generator unit is expressed as follows [25]:

$$P_{T:G} = \rho_W \times g \times H \times Q_{T:G} \times \eta_{T:G} \tag{3}$$

where: $Q_{T:G}$ is the water volumetric flow rate into the turbine (m$^3$/s) and $\eta_{T:G}$ is the overall efficiency of the turbine-generator unit.

The amount of stored energy in the upper reservoir is proportional to the volume of the stored water as well as the waterfall height [26]. Hence, the gravitational potential energy of the stored water (kWh) can then be expressed as follows [25,27]:

$$E_S = \frac{V \times \rho_W \times g \times H \times \eta_{T:G}}{3.6 \times 10^6} \tag{4}$$

where: $V$ is the volumetric storage capacity of the upper reservoir (m$^3$).