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Optimal power dispatch of a grid-interactive micro-hydrokinetic -pumped hydro storage system

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A B S T R A C T

Developing nations around the world are facing energy deficit crisis due to an increasing energy demand and slow exploitation of renewable energy (RE) technologies. Among different RE technologies, hydrokinetic is a promising technology that has proved to generate electricity cheaper than solar and wind technologies. Among different energy storage devices, pumped hydro storage (PHS) has proved to be the most cost-effective option. Due to rising electricity price, domestic farm-houses situated in close proximity to the flowing water resource can make use of a hydrokinetic-PHS system to reduce the electricity cost and to sell excess energy into the grid through feed-in tariff (FIT) scheme. This paper introduces an optimal energy management model for power dispatching within a grid-interactive micro-hydrokinetic pumped hydro storage (MHK-PHS) system. The aim is to minimize the grid consumption costs and to maximize the energy sales revenue by considering the weekdays and weekend time-of-use (TOU) tariffs. The simulation results have shown the effectiveness of the model since it allows most of the load power demand to be met by the RE systems during expensive peak-period as a means of minimizing the grid consumption costs. Most of the energy sales took place during standard and expensive peak periods as a means of maximizing the energy sales revenue. Additionally, the simulation results have shown that an energy saving potential of 100.1% and 104.23% can be achieved during high demand and low demand seasons, respectively.

1. Introduction

The ever increasing electricity demand brings significant challenge of installing new fossil fuel-based power plants in order to mitigate power deficit crisis [1]. Such solution results into electricity price increase for end-users as well as an increased greenhouse gases (GHG's) emission. Hence, the rising electricity price, power deficit and global warming have led to significant interest in renewable energy (RE) sources [2].

Due to the rising electricity demand, measures such as the use of energy efficiency appliances and demand response (DR) are applied by electrical utility companies [1], [3–5]. The aim is to reduce the electricity consumption during peak demand periods in order to match the supply and the demand. DR program includes different price-based methods such as real time pricing (RTP), time-of-use (TOU), critical peak pricing (CPP), or incentive-based program. TOU has being the most widely applied DR method [3], [6]. Through TOU tariff scheme, the price of electricity differs seasonally and timely. Consumers who are willing to reduce their grid consumption during peak demand periods will reap the benefit of reduced electricity bills.

However, the use of price-based signaling methods such as TOU tariffs may not change the consumer behavior, especially the residential consumers [4]. The reason is because unlike the commercial and industrial sectors, residential sector such as small residential houses consume the least amount of energy that may lead to little or unnoticed financial savings. Residential consumers can be encouraged to have an onsite RE system to notice the financial savings benefits. To improve the reliability of a RE system, it needs to be integrated with energy storage system to store the excess energy for later use [7]. However, the inclusion of a storage system may lead to a higher investment cost. Nevertheless, to minimize the investment cost, the size of the RE hybrid system can be reduced once integrated with a grid network [8]. The storage system needs to be fully charged for later use and the excess power from the hybrid system can be supplied into the grid via feed-in tariff (FIT) scheme instead of being dissipated into the dummy load. This will generate revenue for the consumer. Additionally, the consumer can utilize the grid

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power during the cheaper-to-buy off-peak periods while utilizing the stored energy during costly peak periods.

RE technologies such as solar and wind are not reliable due to the drawback of their intermittent nature. Hydrokinetic is a promising RE technology that can overcome such drawback. It is easily predictable since its resources proved to vary seasonally instead of varying rapidly in a short period of time [9–11]. It generates electricity using the kinetic energy of the flowing water resource moving at a speed of 0.5 m/s or more within river streams, tidal current or other artificial water channels. It has proved to generate electricity cheaper than solar and wind systems [12,13]. It has proved to generate electricity more economically if used in combination with a pumped hydro storage (PHS) instead of battery storage system [14]. PHS system has proved to be the most efficient (70–85%) and cost-effective storage system to be used in RE powered micro-grid than battery storage system [7,15]. As a result, consumers such as residential farm houses situated in close proximity to the flowing water resources can make use of a hydrokinetic-PHS system to minimize the grid consumption costs.

Optimal integration of a hydrokinetic-PHS system with the grid can provide the most cost-effective solution. Optimal control strategy can be achieved through the application of the optimization computational techniques. There have been very few research efforts by various authors in developing an optimization model for hydrokinetic-based hybrid systems.

In Ref. [16], a grid-connected hydrokinetic-battery based system under the TOU tariff program was analyzed for 24 h period. The aim is to minimize the electricity cost within the DSM framework.

In Ref. [17], a model was developed to find the optimal daily operation schedule for a hydrokinetic-diesel-PHS hybrid system. The aim is to minimize the fuel cost, to maximize the hydrokinetic and PHS utilization. The gap is that the TOU tariffs were not considered since the system was not connected to the grid.

In Ref. [18], a model was developed to optimize the operation of a hydrokinetic-PV-wind-diesel-battery hybrid system. The aim is to minimize the use of the diesel generator (DG) while maximizing the use of the renewable energy sources as a means of reducing the cost function. The gap is that the TOU tariffs were not considered since the system was not connected to the grid.

In Ref. [19], a model was developed for optimal control of a connected hydrokinetic-powered pump back system for hydropower plant. The aim is to maximize the use of hydrokinetic energy for pumping purpose, to minimize the grid pumping energy and to minimize the restoration of the dam volume through the pump back operation. However, even though the system was connected to the grid, the utility tariffs were not considered.

In Ref. [20], a model was developed for optimal control of a conventional hydropower plant retrofitted with a cascaded pump back system powered by a hydrokinetic-system for 24 h horizon. The aim is to minimize the pumping energy demand and the wear and tear of the pumping system in addition to maximizing the use of hydrokinetic energy for pumping purpose. However, the utility tariffs were not considered during simulations.

From the above-mentioned hydrokinetic literatures, only one study has considered to evaluate the optimal model performance under the consideration of the time varying electricity price [16]. However, the study only considered the weekday TOU tariffs by ignoring the model evaluation under weekend TOU tariffs. Additionally, none of the above literatures have evaluated the model performance by considering the random variability of the load profile. The simulations were carried out using 24 h horizon with the exclusion of the weekend. In addition to the above-mentioned hydrokinetic literatures, several other studies has developed optimization models for hybrid systems consisting of other types of RE sources and power back-up systems under TOU tariff scheme [21–26]. Similar to the hydrokinetic literatures, none of these studies have considered the variability of the load profile as well as the weekend TOU tariffs since the simulations were performed for 24 h.

This study aims to develop an optimal energy management model for a grid-interactive micro-hydrokinetic-pumped hydro storage (MHK-PHS) system. The aim of the model is to effectively reduce the grid consumption costs for residential consumer as well as to maximize the RE sales revenue into the grid. TOU electricity tariff for both weekdays and weekend will be considered as one of the control parameters in addition to power-flow control variables. Random variability will be added to the load profile through the use of HOMER (Hybrid Optimization Model for Electric Renewables) software in order to create a reasonable load profile.

2. System description and mathematical presentation

The configuration/power flow layout of the proposed grid-interactive MHK-PHS system is shown in Fig. 1. The system consists of a micro-hydrokinetic (MHK) river system, a PHS system as well as a primary residential load. The selected PHS consists of the two separated penstocks used for pumping the water up and for generating electricity, respectively. Therefore, both charging and discharging processes can occur at the same time. The double-penstock offers a much easier way of power-frequency regulation as required by the grid, although this may lead to a higher system cost [27,28].

The residential load can be simultaneously served by the MHK system, PHS system and the grid depending on the TOU tariffs. The PHS is used as storage of excess energy from the MHK system. It can also be used to store the cheaper-to-buy grid energy during off-peak periods. The MHK system is used to supply the load, recharge the upper reservoir and to sell the excess energy into the grid.

The MHK system can supply power $P_{1(t)}$ directly to the load, $P_{4(t)}$ to the motor-pump unit to recharge the upper reservoir and $P_{6(t)}$ to the grid for energy sales. The PHS system can generate electricity by making use of the turbine- generator unit to supply power $P_{2(t)}$ to the load and $P_{7(t)}$ to the grid for energy sales. The grid can supply power $P_{3(t)}$ to the load and $P_{5(t)}$ to the motor-pump unit to assist in refilling the upper reservoir depending on the pumping demand and TOU tariffs.

2.1. Hydrokinetic system

Unlike the conventional hydro turbines requiring a water head, hydrokinetic turbines generates electricity at low to zero hydraulic heads [9,20].They are designed to capture the kinetic energy of the flowing water resource instead of the potential energy of the falling water. Their operation principle is similar to the one of the wind turbines. Unlike the wind energy resource, hydrokinetic resources are easily predictable and can generate electricity even at low speed since the water is 800 times denser than air [29–31]. The energy generated by a hydrokinetic system is expressed as follows [14,17]:

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

Where: ρ_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 performance (Betz limit), η_{HKT-G} is the overall efficiency of a hydrokinetic turbine-generator unit and t is the time (s).

2.2. Conversional pumped-hydro storage system

When storing potential energy in the upper reservoir, the motor-pump unit elevates certain volume of water (m^3) from the