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

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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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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.

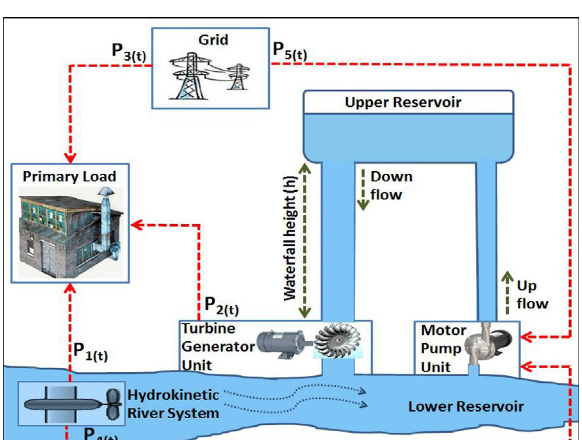

Fig. 1. Power flow layout of the proposed grid-connected MHK-PHS system.

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]:

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

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 (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]:

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

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]:

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

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]:

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

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

3. Methodology

The energy management of the proposed system is critical to ensure a continuous supply of electricity to the load at a minimum cost. This is achievable through optimal use of the PHS and MHK river systems. To evaluate the operation of the proposed model, water resource data, load demand profile, system size as well as the TOU tariff prices for weekdays and weekend days are to be used.

3.1. Load demand profile

A typical industrial load profile consuming an average of 60 kWh per day as shown in Fig. 2 has been used in this study [11]. At around 12h00, the industrial load demand drops at a high rate when compared to other business hours. The reason is because other industries allow their employees to simultaneously take a lunch break instead of allowing different break shifts to take place. However, from practical perspective, it is impossible for the load to consume the same amount of energy every day. Hence, to create a more reasonable load profile, HOMER software was used to synthesize the load profile by adding randomness for different days. From the created randomness of 10% daily and hourly variation, eight days load profile has been considered for simulation purpose as shown in Fig. 5A. The behaviour of the proposed energy management model will be analysed for a period of 8 days (192 h) in order investigate the behaviour during week days and weekend days.

3.2. Hydrokinetic resource data

The flowing water resource data of the typical river situated in Kwazulu Natal has been used during the simulations [7,11,12]. Fig. 3 shows the monthly average water speed of the selected site. The water speed of a high demand season month, June has been selected and will be used during the simulations. In this study, a standard deviation was set to 0.2% since the hydrokinetic resources proved not to vary rapidly within a short period of time [9–11]. Hence, the variation of the used water speed for the month of June resulted into the hourly water speed profile shown in Fig. 5A. It can be seen that the water speed is around 2.18 m/s on average for the entire 192 h period.

3.3. TOU tariffs rates

The high demand season TOU tariff rates as charged by the South African utility company (Eskom) will be applied during the simulations [28]. Ruraflex Gen tariff rates shown in Table 1 are expressed in South African currency (ZAR) and will be applied during the simulations. During the study, 1 US$ is equivalent to 13.49 ZAR. Fig. 4 shows the TOU periods during high demand season for weekdays, Saturday and Sunday, respectively. It can be noted that the electricity prices changes over different time intervals according to the costs imposed by Eskom [28].

3.4. Simulation parameters

The optimal size of the proposed grid-connected MHK-PHS system was obtained through the use of the HOMER software [11]. A 5.98 kWh PHS system size was obtained and will be used in this study. A 1.5 kW MHK turbine generating a maximum of 1.5 kW when driven at a water speed of 2 m/s or above was used as an input to the HOMER software. However, HOMER led to the oversizing constraint since the PHS was not utilized at all. Hence, to simplify the analysis and to minimize the initial capital cost, a 3 kW MHK turbine (two MHK turbines) was selected in this study. The selected MHK turbines can generate up to a maximum output power of 3 kW at a water speed of 2 m/s or above. The overall simulation parameters of the proposed grid-connected MHK-PHS system are as shown in Table 2.

The efficiency of the PHS plants ranges from 70 to 85% [29]. The motor-pump and the turbine-generator units are assumed to have the efficiency of 84% respectively [30]. Hence, the round trip efficiency of the PHS system used in this study is 70.6% which is typical for PHS plants.

4. Discrete model formulation and the proposed algorithm

The optimization outline comprises of the objective function and constraints as to be discussed below.

4.1. TOU tariffs

As stated in the methodology, the daily electricity cost price (C) to be used for high demand season under the TOU tariff scheme is given as follows:

$$C(t) = \left\{ \begin{array}{l} C_p = ZAR3.21/kWh \\ C_s = ZAR0.97/kWh \\ C_o = ZAR0.53/kWh \end{array} \right\} \quad (5)$$

where: C_P is the tariff price during peak period; C_S is the tariff price during standard period and C_O is the tariff price during off-peak period.

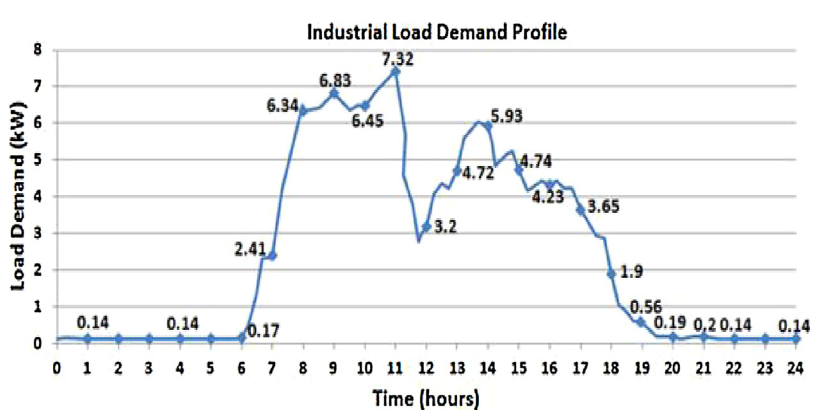

Fig. 2. Industrial load profile [11].

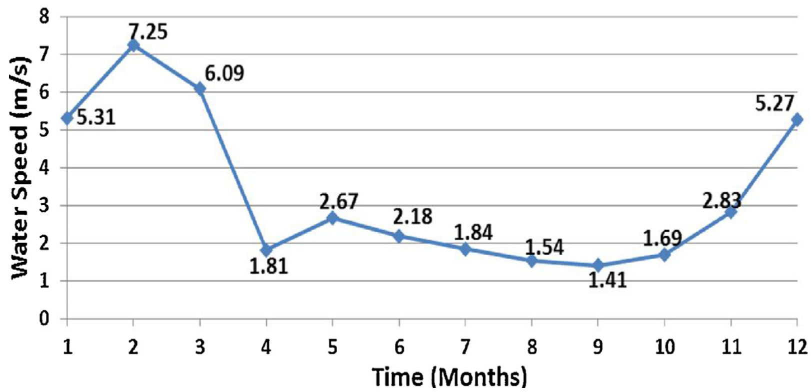

Fig. 3. Monthly Average Water Velocity (Kwazulu Natal) [7,11,12].

Table 1
Eskom Ruraflex Gen TOU Tariffs for high demand season [28].

TOU periods	High-demand season (Jun to Aug)	Period range
Peak periods	ZAR3.21/kWh	06:00–09:00, 17:00–19:00
Standard periods	ZAR0.97/kWh	09:00–17:00, 19:00–22:00
Off-peak periods	ZAR0.53/kWh	22:00–06:00

4.2. Objective function

As stated in the introduction, the optimization problem in this study is addressed to minimize the energy costs through power-flow control variable constraints and TOU tariff scheme for 192 h. Minimization of the grid cost can be achieved by minimizing the pumping energy demand from the grid as well as the load energy demand from the grid. Hence, the discrete cost objective function (F) at any sampling interval (j) is expressed as follow:

$$F = \sum_{j=1}^{N} C_j \cdot (P_{3(j)} + P_{5(j)}) \cdot \Delta t \qquad (6)$$

where: N is the total number of sample intervals, Δt is the sampling time (i.e. the time between the sampling points), C_j is the TOU electricity price at the j^{th} sampling time (ZAR/kWh), $P_{3(j)}$ is the power flow from the utility grid to the primary load (kW), and $P_{5(j)}$ is power flow from the utility grid to the motor-pump unit (kW). Since the control horizon is for 192 h with a sampling time of 30 min, the total number of sampling intervals is 384. The formulated objective has been optimized under the following constraints.

4.2.1. Power balance constraint

Power balance constraint is critical to ensure that the primary load demand is satisfied at all times to warrant power reliability. Based on the power flow layout, the load demand must be satisfied by the MHK river system, PHS system and the grid at any sampling interval. Therefore, the power balancing can be discretised as follows:

$$P_{Load(j)} = P_{1(j)} + P_{2(j)} + P_{3(j)} \quad (1 \leq j \leq N) \qquad (7)$$

where: $P_{1(j)}$ is the power flow from the MHK river system to the primary load (kW) and $P_{2(j)}$ is the power flow from the turbine-generator unit to the primary load (kW).

4.2.2. Inequality power constraint

The sum of the instantaneous output powers consumed from the MHK river system for meeting the load demand and supplying the motor-pump unit must not exceed the MHK's generated output

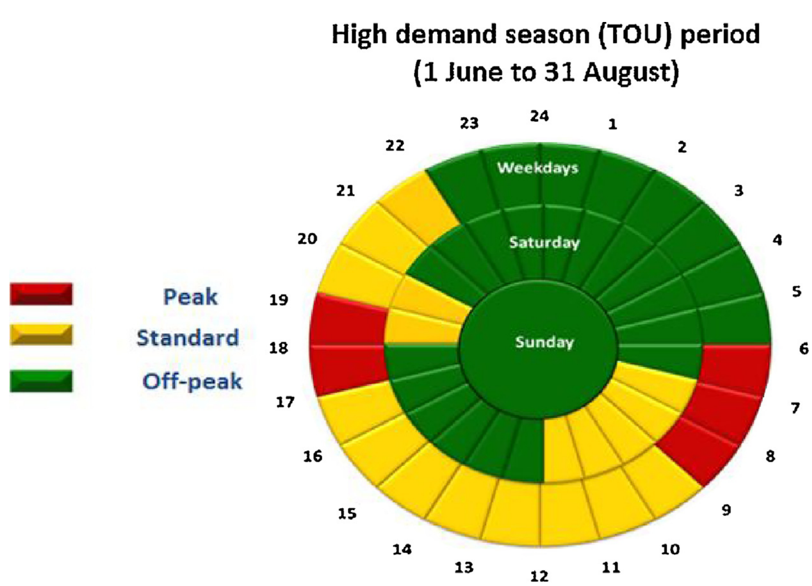

Fig. 4. TOU period for high demand season [28].

Table 2
Simulation parameters.

Item	Value
Sampling time (Δt)	30 min
PHS nominal capacity	5.98 kWh
PHS maximum volume	100%
PHS minimum volume	5%
Initial upper reservoir capacity	80%
Overall efficiency of the Turbine-generator unit.	84%
Overall efficiency of the Motor-pump unit.	84%
MHK system rating	3 kW

power as shown by Eq. (8). Additionally, to refill the upper reservoir, the pumping demand is met by the MHK system and/or the grid as shown by Eq. (9).

$$P_{1(j)} + P_{4(j)} \le P^{\max}_{MHK(j)} \quad (1 \le j \le N) \tag{8}$$

$$P_{4(j)} + P_{5(j)} \le P^{rated}_{M:P(j)} \quad (1 \le j \le N) \tag{9}$$

where: $P_{4(j)}$ is the power flow from the MHK river system to the motor-pump unit (kW) and $P^{rated}_{M:P(j)}$ is the rated power of the motor-pump unit (kW).

4.2.3. Control variable limits constraints

Each power source (control variable) needs to be firmly limited to operate within its minimum and maximum electrical power capacities at any point in time. These power sources are controllable from zero minimum limits to a maximum limit of their rated or available instantaneous power. Therefore, five power control variables are then expressed as follows:

$$0 \le P_{1(j)} \le P^{\max}_{1(j)} \quad (1 \le j \le N) \tag{10}$$

$$0 \le P_{2(j)} \le P^{rated}_{2} \quad (1 \le j \le N) \tag{11}$$

$$0 \le P_{3(j)} \le P^{rated}_{3} \quad (1 \le j \le N) \tag{12}$$

$$0 \le P_{4(j)} \le P^{\max}_{4(j)} \quad (1 \le j \le N) \tag{13}$$

$$0 \le P_{5(j)} \le P^{rated}_{5} \quad (1 \le j \le N) \tag{14}$$

4.2.4. Storage constraints

In each time interval, the excess energy from the MHK river system and the energy from the grid when its price is low are to be stored. However, the storage level is constraint due to the natural limit of the upper reservoir. Hence, the upper reservoir water level state $Cap_{(j)}$ will be used as a decision variable for preventing overcharging. In cases whereby the upper reservoir is completely full, the maximum capacity equals 1. Therefore, the storage limit level constraint has been imposed on the upper reservoir as follows:

$$Cap^{\min} \le Cap_{(j)} \le Cap^{\max} \tag{15}$$

where: Cap^{min} is the minimum allowable capacity of the upper reservoir and Cap^{max} is the maximum allowable capacity of the upper reservoir.

Whenever the power is supplied to the motor-pump, the upper reservoir water level will increase and whenever the turbine-generator unit generates electricity for the primary load, the water level will decrease. Hence, the dynamics of the upper reservoir water level state at j^{th} sampling interval is expressed in terms of the initial water level, $Cap_{(0)}$. This is expressed as follows:

$$Cap_{(j)} = Cap_{(0)} + \sum_{j=1}^{N}[(P_{4(j)} + P_{5(j)}) \cdot \frac{\eta_{M:P}}{E_{pot}} \cdot \Delta t] - \sum_{j=1}^{N} P_{2(j)} \cdot \frac{\Delta t}{\eta_{T:G} \cdot E_{pot}} \tag{16}$$

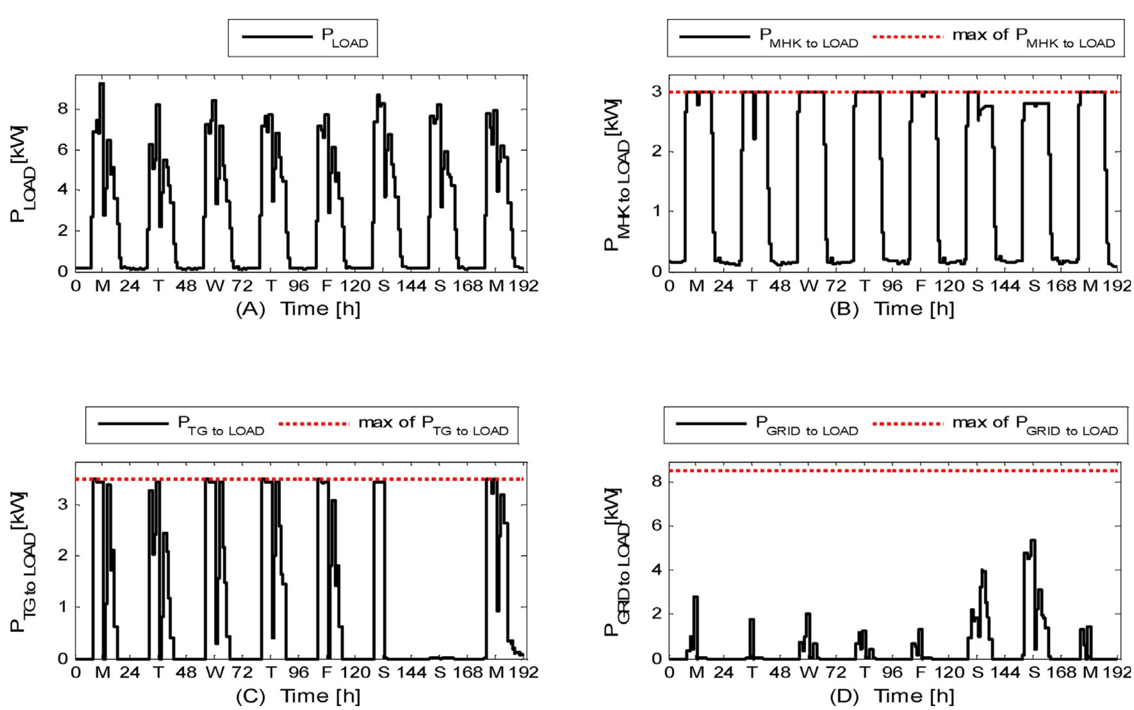

Fig. 5. Load side power flow.

where: E_{Pot} is the nominal potential energy in the upper reservoir (kWh).

4.3. Proposed algorithm

Linear programming (LP) optimization method has been selected since the objective functions and the constraints of the study appear to be linear functions of the decision variables. Therefore, the optimization problem will be solved using the "linprog" syntax from the MATLAB optimization toolbox. This solver is expressed in its canonical form as follows:

$$\min_{x}\left\{f^{T}x\right\} \text{ subjected to } \left\{\begin{array}{l} A\cdot x\leq b \\ A_{eq}\cdot x\leq b_{eq} \\ lb\leq x\leq ub \end{array}\right\} \quad (17)$$

where: A and b are the coefficients associated with inequality constraints, A_{eq} and b_{eq} are the coefficients associated with equality constraints, and lb and ub are the lower and upper bounds of the variables, respectively.

5. Results and discussion

The optimization model for the proposed grid-connected MHK-PHS system was evaluated through the use of the linprog solver. The proposed system is meant to ideally minimize grid electricity cost without involving the energy sales to the grid. Based on Eskom TOU tariff periods, it has being noticed that the peak periods do not exist on Saturday and Sunday. Hence, the simulations have been carried out for weekdays and weekend days using the high demand season tariff rates. Fig. 5 shows the system power flow on the load demand side only while Fig. 6 shows the power flow on the storage side. The selected MHK turbine generates a maximum output power of 3 kW throughout the week as denoted by the red dotted lines in Fig. 5B. The reason is because the speed of the water varies around 2.18 m/s as shown in Fig. 6A.

When applying the Eskom's TOU tariffs, the 8 days load profile shown in Fig. 5A will incur ZAR556.72 grid cost if solely supplied by the utility grid for the entire 192 h period. Through the inclusion of the MHK-PHS system and energy management model, the grid cost has been reduced to ZAR80.25. This is a massive savings of 86%.

5.1. Power flow during weekdays

Fig. 5B and C shows that during weekdays, the load demand is mostly met by the MHK system and the turbine-generator unit (PHS). Hence, the grid is used to supplement the slight unmet load demand. This mostly happens during morning business hours of the industry since the peak demand takes place in the morning than in the afternoon. As soon as the MHK system and the turbine-generator unit can supply the entire load demand, the grid is not allowed to supply the load as shown in Fig. 5D.

After business hours, the turbine-generator unit is not allowed to generate electricity. Hence, the small base load demand is met by the MHK system only. Fig. 6B shows that for each weekday the model allows the MHK system to refill the upper reservoir after 18:00 (after business hours) since the load demand is low. Hence, the upper reservoir's water level is increasing as shown in Fig. 6D. The refilling process stops after 08:00 in the morning since the business hours have started. Consequently, the upper reservoir's water level starts to decrease since the turbine-generator unit generates electricity to compensate the unmet load demand. Fig. 6C shows that the model does not encourage the utilization of the grid power for filling-up the upper reservoir during weekdays.

5.2. Power flow during the weekend days

In all subfigures of Figs. 5 and 6, the weekend starts after 120th hour to 168th hour. Hence, Saturday is after 120th hour to 144th hour while Sunday starts after 144th to 168th hour. Fig. 4 has highlighted that during early morning hours of Saturday, the standard TOU tariff rates are charged instead of the peak TOU tariff

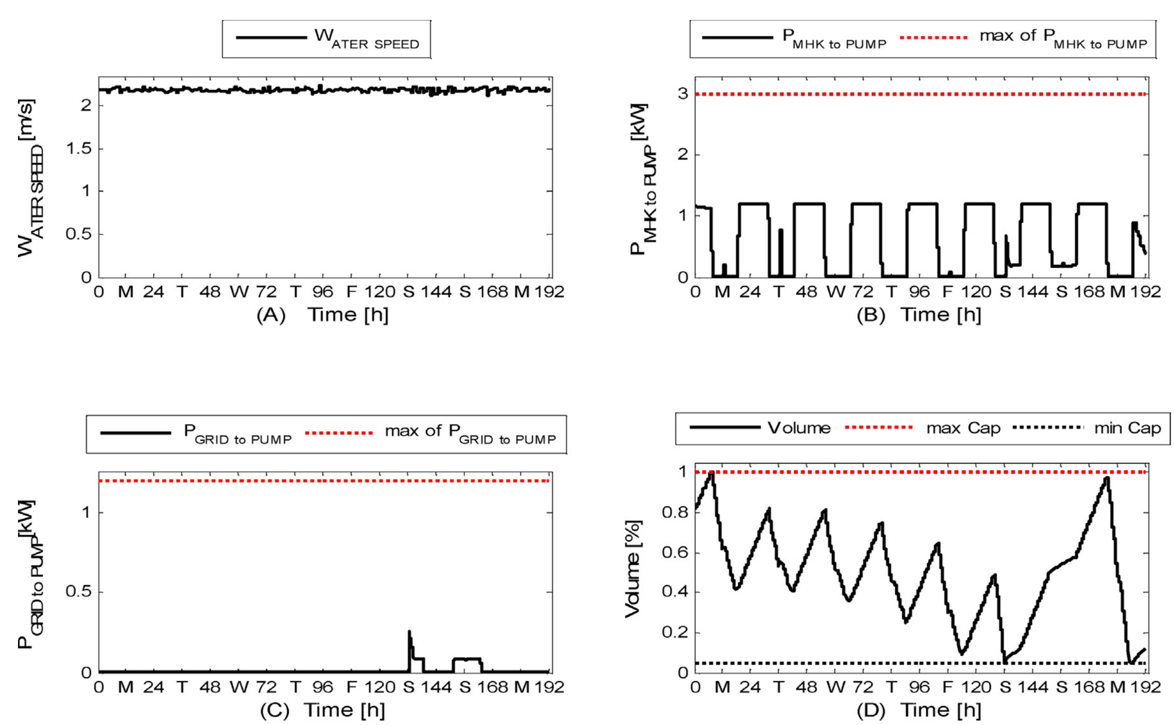

Fig. 6. Water speed and PHS side power flow.

rates. From 08:00 in the morning when the business have started, the load starts demanding more than 3 kW. As a result, both the hydrokinetic system and the turbine-generator unit are used to meet the load demand as shown in Fig. 5B and C. The grid is also used to compensate the unmet load demand. Hence, Saturday has led to the operation of all three power sources. Additionally, all power flow paths (P_1, P_2, P_3, P_4 and P_5) are operational on Saturday when compared to other days.

As soon as the inexpensive off-peak period (12:00-17h59) is approached during Saturday's business hours, the model discontinues the operation of a turbine-generator unit by allowing the load to demand power simply from the grid and the MHK system. Hence, the turbine-generator unit is not allowed to generate electricity in order to allow the upper-reservoir to be refilled. This leads to less operational hours of the turbine-generator unit when compared to the weekdays' operational hours. Additionally, Saturday allows the grid power to be used to refill the upper reservoir only during off-peak period of the business hours.

Fig. 5D shows that the total energy consumption from the grid is more during the weekend as compared to the energy consumption during weekdays. The reason is because the load demand is high during the inexpensive off-peak periods scheduled during the business hours. Fig. 6C shows that the grid power is utilised to refill the upper reservoir only during the weekend since off-peak TOU tariffs are applied during business hours. Fig. 4 has highlighted that both standard and peak periods do not exist on Sunday. Hence, the grid power is utilized to refill the upper reservoir for the entire business hours. Sunday also proved to lead to longer operational hours of the MHK system for refilling the upper reservoir. Finally, on Sunday the model disallowed the operation of a turbine-generator unit in order to refill the upper reservoir for the next day. Hence, the upper reservoir's water level is increasing at the highest rate.

6. Conclusions

This study has presented a TOU based optimal energy management model for the grid-connected MHK-PHS system. This was meant for minimizing the grid electricity cost for the industrial consumer without involving energy sales to the grid. Furthermore the flow of power at different TOU periods throughout the week (for 192 h) has been analysed to evaluate the performance of the proposed model during high demand season. The developed optimization model has revealed the cost saving benefit by maximizing the renewable energy usage (from the MHK and PHS systems) and by minimizing the grid energy usage especially during the costly standard and peak periods. The grid cost savings of 86% was achieved when the proposed system was optimally managed for meeting the industrial load demand.

The results have shown that the model allowed most of the load demand to be met by the PHS system and the MHK system during weekdays since the grid power was only considered to compensate the shortage. During weekdays, the refilling of the upper reservoir was solely accomplished through the use of the MHK system. Large amount of the grid power was used during the weekend to refill the upper reservoir and to supply the load during the entire business hours. The reason is because the peak demand of the industrial load takes place during inexpensive off-peak TOU period.

Sunday has proved to lead to the maximal operational hours of the motor-pump unit when compared to other days. Saturday has proved to lead to the concurrent use of all power sources to meet the load demand and all power flow paths are operational on Saturday.

The results of the study have led to the following recommendations:

- To investigate the performance of the system if the motor-pump unit is isolated from the grid. Hence, the storage system will only store the excess energy from the MHK system.
- To develop an optimal energy management model for the system when allowed to sell the energy to the grid under TOU tariff scheme.

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