Optimal scheduling of a grid-connected hydrokinetic-battery system under Time of Use tariff

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Abstract— In this work, the optimal power scheduling for a grid-connected hydrokinetic-battery hybrid system is proposed to sufficiently explore hidrokinetic energy and to benefit customers at demand side. The developed model for the hybrid system's optimal power flow management aims to minimize electricity cost subject to the power balance, hydrokinetic and battery storage outputs as well as other operational constraints. With respect to demand side management, an optimal control method is developed to schedule the power flow of hybrid system over 24-h. Simulation are performed using MATLAB, and the results demonstrate that operating the proposed hybrid system under the developed optimal energy management model can reduce the operation cost and allow consumers to generate substantial income by selling power to the grid.

***Index Terms*—Hydrokinetic energy, hybrid system, Time of Use, Optimal control**

1 INTRODUCTION

Renewable energy (RE) technologies, such as wind, solar, hydropower and their combinations in hybrid systems, have become attractive alternatives of producing energy in comparison to traditional fossil fuels due to low cost, no pollutant emission, energy security as well as their modularity [1-2]. Renewable energy sources can be used as standalone to supply isolated load or as grid-connected for selling power to the utility company [3]. Because of the instable and variable nature of their resources; renewable systems are often used in conjunction with storage systems [4-5]. Battery storage systems can reduce the risk of renewable systems' intermittent power supply, and always ensure that the load demand is continuously met [6-7].

In general, grid-connected renewable systems do not require battery storage therefore advanced energy management strategies are also not required. Maximizing use of the renewable power is the only strategy adopted when the generation is less than the instantaneous load demand [8]. On the contrary, battery storage makes the energy management more difficult, as more complicated operation strategies must be taken into account, such as charging the battery from the grid or renewable source and discharging into the grid or to the load when necessary [9]. As a result, controllers are required for hybrid renewable-battery systems, such that the use of the renewable system can be considerably improved and the grid regulation can be enhanced in terms of safety, reliability and efficiency.

For grid-connected hybrid renewable-battery systems, the varying electricity price imposed by the grid, the instant of power transaction, and the difference between renewable power generation and load demand are main challenges encountered [10]. From the demand side management (DSM) point of view, energy from the renewable source or from the grid can be stored when the generation is higher than the demand or when the electricity price from the grid is very low. The stored energy can then be used when the electricity price from the grid is high, during peak power demand, or when the renewable power is unavailable [11-12]. Well managed grid-connected hybrid system with DSM can assist customers in reducing their electricity cost, and also can assist utility companies to control the grid in terms of security and efficiency issues while increasing the reliability.

Several research works have reported on the benefit of applying energy management on hybrid solar photovoltaic (PV) and wind systems as standalone or connected to the grid. However very few works have been conducted on the use of standalone hydrokinetic system (HKT) combined with other energy sources and storage systems [13-19]. From the available literature, it appears that the grid-connected hydrokinetic with battery has not yet been investigated. Therefore, the focus of this paper will be on analyzing a grid-connected HKT-battery system under the Time of Use (TOU) program with contracted selling as an example. An optimal power flow management algorithm of the proposed hybrid system is developed aiming to minimize the electricity cost within the DSM framework. It will be shown how consumers can optimally schedule the hybrid system's operation to earn cost savings with changing prices in the TOU program, and how they can manage their generation, consumption and storage to sell surplus power to the grid over peak period.

2 DESCRIPTION OF THE GRID CONNECTED HKT-BATTERY HYBRID SYSTEM

The hybrid system analyzed in this work is composed of a HKT system and battery bank that are both connected to the grid. The output power of the HKT feeds the load demand directly. If the demand is less than the HKT's output, the surplus HKT power will be charged into the battery bank. If the load power requirement is larger than the HKT's output, the deficit of power will be supplied by the battery or the grid. The grid plays a major function in the hybrid system for charging the battery and directly supplying the load demand. The battery can be charged by the grid in the off-peak period, and then discharged in the

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peak period to save electricity cost. The grid provides electricity directly when the load cannot be entirely met by the HKT and the battery. The schematic of this hybrid system is shown in Fig. 1, in which arrows represent directions of power flows in the hybrid system. P_{HKT-B} is the HKT power used for charging the battery; P_{B-L} is the discharging power of battery for load demand; P_{G-B} is the grid power for charging the battery; P_{G-L} is the grid power for load demand; P_{HKT-L} is the HKT power directly supplying load demand; P_{SOLD} is the battery discharge for selling power to the grid.

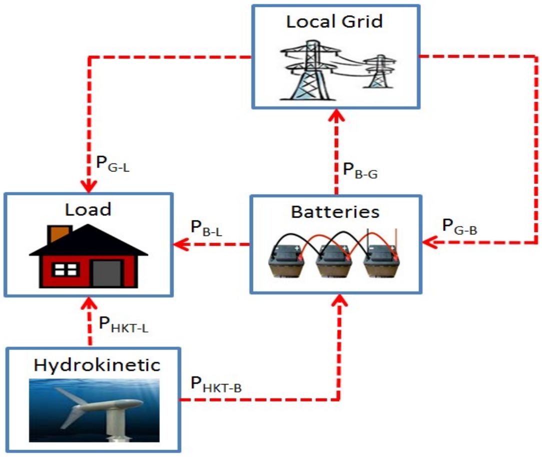

Figure 1: Hybrid system layout (power flow)

2.1 Hydrokinetic system

Hydrokinetic energy systems convert kinetic energy from flowing water without using a dam, barrage or penstock. Hydrokinetic systems can produce energy from water flowing at very low velocities with nearly no environmental impact, over a larger range of potential sites than those offered by traditional hydropower systems [20].

The energy extraction principle used by hydrokinetic systems is similar to the one used in wind conversion systems. However, given that water is approximately 800 times denser than air, the corresponding energy produced by a hydrokinetic system is much higher than the one produced by a wind system of equal diameter under equal water and wind velocity. The other advantages of hydrokinetic system are that the water resource does not vary randomly as the wind resource does, and the direction of the flowing water does not change direction as the wind does.

The power generated by the hydrokinetic system is expressed as:

$$P_{HKT} = \frac{1}{2} \times \rho_W \times A \times v^3 \times C_{p,HKT} \times \eta_{HKT} \tag{1}$$

Where: ρ_W is the density of water (kg/m^3), $C_{p,HKT}$ is the coefficient of the hydrokinetic turbine performance, η_{HKT} is the combined efficiency of the hydrokinetic turbine and the generator, A is the turbine area (m^2), ρ the water density (1000kg/m^3), v is the water current velocity (m/s).

2.2 Battery storage system

The power flows from the HKT, the grid and the load demand at any given sampling interval j, determine whether the battery is charging or discharging. The dynamics of the battery state of charge (SOC) can be expressed in discrete-time domain by a first order difference equation as follows [21-22]:

$$\begin{aligned} SOC_{(j+1)} = (1-d_b) \times SOC_{(j)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times (P_{HKT-B(j)} + \\ P_{G-B(j)} - \frac{\Delta t}{E_{nom}\eta_D} \times (P_{B-L(j)} + P_{SOLD(j)}) \end{aligned} \tag{2}$$

Where: SOC is the state of charge of the battery; d_b is the self-discharging rate of the battery storage system; η_C is the battery charging efficiency; η_D is the battery discharging efficiency and E_{nom} is the battery system nominal energy.

By induction reasoning, the dynamics of the battery state of charge at j^{th} sampling interval can be expressed in terms of its initial value $SOC_{(0)}$ of a day as follows:

$$\begin{aligned} SOC_{(j)} = (1-d_b) \times SOC_{(0)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times \sum_{i=0}^{j-1} (P_{HKT-B(j)} + \\ P_{G-B(j)}) - \frac{\Delta t}{E_{nom}\eta_D} \times \sum_{i=0}^{j-1} (P_{B-L(j)} + P_{SOLD(j)}) \end{aligned} \tag{3}$$

3 OPTIMIZATION MODEL AND PROPOSED OPTIMAL CONTROL METHOD

3.1 DSM model of the grid connected HKT-Battery hybrid system

As stated in the introduction, the optimization problem addressed in this work aims to minimize the electricity cost within the framework of TOU in which the electricity price changes over different time intervals according to cost imposed by the utility company, for instance a high price for peak load periods, medium price for standard periods and low price for off-peak periods. In this study, the daily electricity price at the selected region of South Africa can be given as [23]:

$$\rho(t) = \begin{cases} \rho_k ; t \in T_k, T_k = [7,10) \cup [18,20) \\ \rho_0 ; t \in T_0, T_0 = [0,6) \cup [22,24) \\ \rho_s ; t \in T_s, T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \tag{4}$$

Where ρ_k =0.20538 \$=kW h is the price for the peak load period;
ρ_0 =0.03558 \$=kW h is the price for the off-peak period;
ρ_s =0.05948 \$=kW h is the price for the standard period.

3.2 Objective function

The proposed cost function has three main components. The first component is the cost of purchasing electricity from the grid, which is used to supply the load demand and charge the battery. The component is the revenue generated from selling electricity to the grid. The third part is the wearing cost of hybrid system. The total function can be expressed as:

$$f = \sum_{j=1}^{N} \rho_j (P_{G-B(j)} + P_{G-L(j)})\Delta t - r_k \rho_k \sum_{j=1}^{N} P_{B-G(j)} \Delta t + \sum_{j=1}^{N} a(P_{B-L(j)} + P_{B-G(j)})\Delta t + 24b \quad (4)$$

Where r_k =0.65 is the contracted ratio of the peak price ρ_k for selling power during the peak load period; a is the coefficient of battery wearing cost and b is the hourly wearing cost of other components [23].

3.3 Constraints

The control variables in the objective function above have to satisfy the following constraints:

- HKT's output constraints:

The sum of instantaneous HKT's power for charging the battery and for supplying the load must be less than the HKT's output power generated.

$$P_{HKT-B(j)} + P_{HKT-L(j)} \leq P_{HKT(j)} \quad (5)$$

- Power balance constraint:

The required load demand must be exactly satisfied by the total power of HKT, the grid and the battery. This can be expressed as:

$$P_{B-L(j)} + P_{G-L(j)} + P_{HKT-L(j)} = P_{L(j)} \quad (6)$$

Each power source is modeled to be controllable in the range of zero to their rated power for the 24-hour period. Therefore, the variable limits are the output limits of these different power sources at any sampling interval j. These can be expressed as:

- Control variables limits

$$0 \leq P_{HKT-B(j)} \leq P_{HKT-B}^{\max} \quad (1 \leq j \leq N) \quad (7)$$

$$0 \leq P_{B-L(j)} \leq P_{B-L}^{\max} \quad (1 \leq j \leq N) \quad (8)$$

$$0 \leq P_{G-B(j)} \leq P_{G-B}^{\max} \quad (1 \leq j \leq N) \quad (9)$$

$$0 \leq P_{G-L(j)} \leq P_{G-L}^{\max} \quad (1 \leq j \leq N) \quad (10)$$

$$0 \leq P_{HKT-L(j)} \leq P_{HKT-L}^{\max} \quad (1 \leq j \leq N) \quad (11)$$

$$0 \leq P_{B-G(j)} \leq P_{B-G}^{\max} \quad (1 \leq j \leq N) \quad (12)$$

The available battery bank state of charge in any sampling internal must not be less than the minimum allowable and must not be higher than the maximum allowable state of charge. This can be expressed as:

$$SOC^{\min} \leq SOC_{(j)} \leq SOC^{\max} \quad (13)$$

3.4 Optimal control method

An optimal control method is used to manage the power flows P_i in all the sampling periods over a 24-h period to minimize the daily electricity cost, Eq. (4), subject to constraints, Eq. (5) to (13). Because the objective function and constraints are linear, this power flow control problem can be expressed as a linear programming problem as [24]:

$$\min f(x), s.t. \begin{cases} Ax \leq b \\ A_{eq} X = b_{eq} \\ lb \leq x \leq ub \end{cases} \quad (14)$$

where *f(x)* represents the objective function; A_{eq} and b_{eq} are the coefficients associated with equality constraints; A and b are the coefficients associated with inequality constraints; l_b and u_b are the lower and upper bounds of variables.

4 CASE STUDY

4.1 Control system settings

In this work, real load and water velocity have been used as input data to evaluate the performance of the system submitted to the developed optimal energy management system. These hourly data are available from [21]. It has to be highlighted that the HKT resource data have been collected for a day in September where the velocity is the lowest compared to the other days of year.

The sizing of HKT and battery bank is based on a sizing model in [25]. The parameters of this hybrid system are given in Table 1. The maximum power delivered by each source is given as 4 kW.

Therefore, the selected HKT system is sized in such a way to give a rated power of 4 kW at 1.4 m/s water velocity. The selected load demand from [21] reaches a peak demand of 8kW in winter; therefore, the hybrid system must be able to adequately respond to this demand.

Table 1: Simulation parameters [21]

Item	Household
Battery nominal capacity	5.6kWh
Battery maximum SOC	95%
Battery minimum SOC	40%
Battery charging efficiency	95%
Battery discharging efficiency	85%
HKT power	4 kW

4.2 Results of optimal control

The simulation results will be discussed and categorized according to the behavior of the proposed grid-connected hybrid system under the different pricing periods.

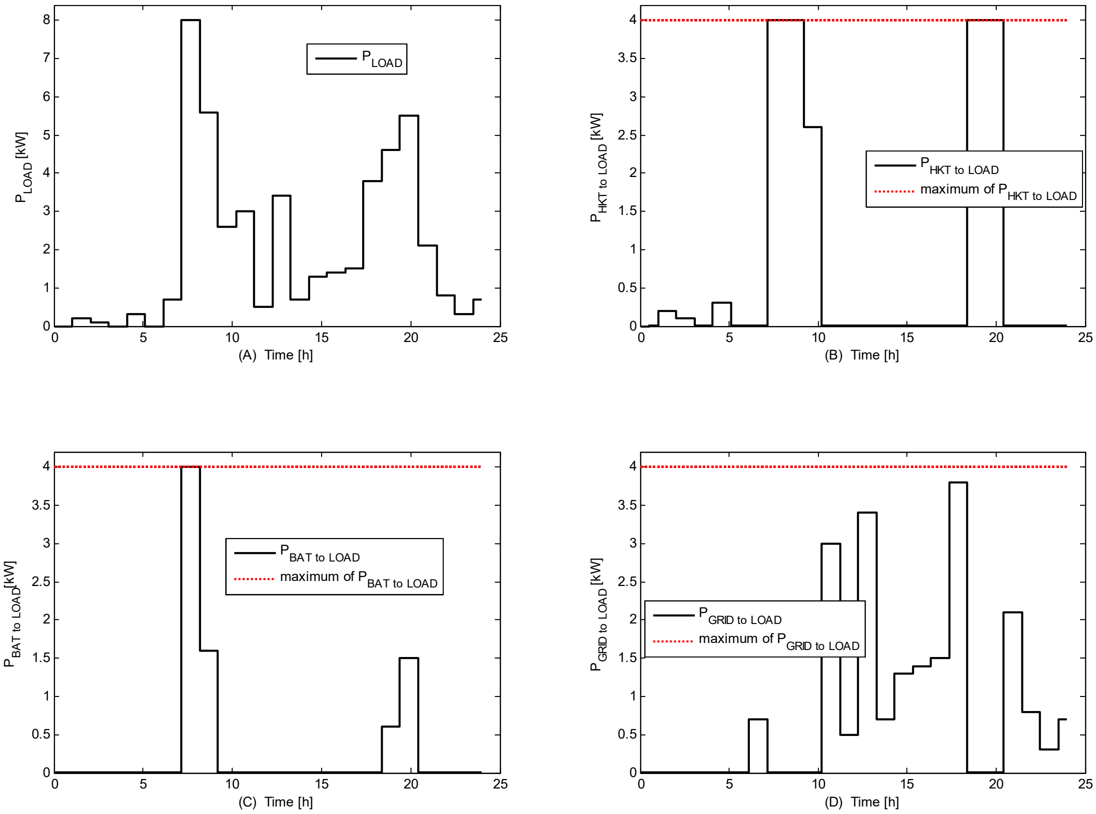

Figure 3: Load side power flow

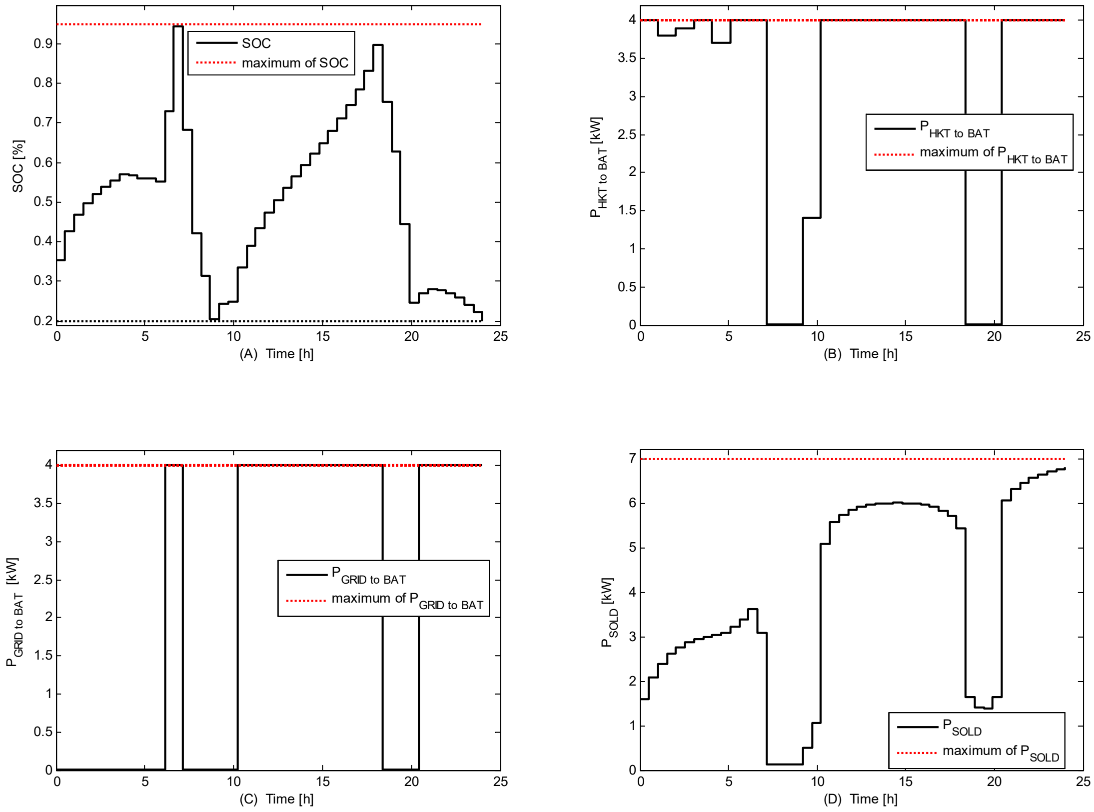

Figure 3: Battery side power flow

4.2.1. Power flow under off-peak load period [0,6) U (22,24]

Fig. 2(A) shows the load profile for the selected winter day. It can be observed that the demand is highly nonlinear; low during the night with high peaks in the morning and in the evening.

The power provided to the load includes the battery $P_{B\text{-}L}$, grid $P_{G\text{-}L}$ and $P_{HKT\text{-}L}$. During the off-peak period, only the HKT system provides power to the load as illustrated in Fig. 2(B); the battery and the grid do not supply the load during that period as shown in Fig. (C) and Fig.2(D) respectively.

The $P_{HKT\text{-}B}$ is the part of the hydrokinetic power not consumed by the load by the load and used to recharge the battery as it is shown in Fig. 3(B) and Fig. 3(C). There is enough power from the HKT to recharge the battery and to be sold to the grid to generate revenue. Even if the price is low during this period, excess power not used to supply the load or to recharge the battery is sold to the grid as shown in Fig. 2(D).

4.2.2. Power flow under standard load period [6,7) U [20,22)

During the standard price period, although the HKT system can fully satisfy the load demand, the grid power has been used. To store enough power for sale, the battery is not discharged during the standard period.

4.2.3. Power flow under peak load period [7,10)

During the peak load period, the power from the HKT as well as the one stored in the battery are used to satisfy the load demand (Fig. 2B, Fig. 2C) while there is no power flow from or to the grid. It can be seen from Fig. 3B how the state of charge decrease when the battery is giving its maximum power to the load. The power stored in the battery could have been sold to the grid during this period but because of the proposed hybrid system's size and the priority given to the load demand, there is no excess power to be sold during this peak power demand. Therefore, it can be seen for Fig. 3D that the power sold the grid is very small.

4.2.4. Power flow under off-peak load period [10,18)

During this off-peak load period, both the load demand and the price of electricity are low. Therefore, the power from the grid is used to principally supply the load and recharge the battery at the same time. This can be seen when looking at Fig. 2D and Fig.3C respectively. Fig. 2B and Fig. 2C confirm that no power from the HKT or the battery is used to supply the load; this power is sold to the grid as illustrated from Fig. 3D.

4.2.5. Power flow under peak load period [18,20)

During this second peak load period, all the power generated by the HKT system is used to supply the load with a small contribution from the battery as shown in Fig. 2B and Fig. 2C. The remainder of the power available from the battery is then sold to the grid to generate profit during this high demand pricing period as illustrated from Fig. 3D. Even if the amount of power sold is lower compared to the one from the off-peak period, the profit is high because of the high price of electricity in this period.

4.3 **4.2. Daily income generated**

On the selected day, if the load demand is supplied by the grid only without the HKT and battery storage system, the daily electricity cost would be \$4.32. When optimally operating the grid-connected HKT hybrid system, the daily income generated by selling electricity to the grid is \$9.39. In other words, when making the balance between what is purchased from the grind and what is sold to the grid, the customer can earn \$5.07. This income is function of the size of the hybrid system's components, the battery initial state of charge as well as on the load profile.

5 CONCLUSION

Demand side management has been applied in the optimal energy management of grid-connected HKT-battery hybrid system. The Time of Use operating tariff with power selling to the grid, has been studied for energy management in this work. A model for decreasing electricity charge at the consumer's side has been developed. The simulation results have demonstrated that the developed optimal operation model for the hybrid system results in the maximal use of HKT and battery storage system. The simulation results highlight the important role played by the battery which is storing power from the utility during off-peak periods and providing power to the load during peak periods. Consequently, by optimally operating the hybrid system, the load consumes nominal amount of power from the utility and the consumers can generate income by selling electricity to the grid. It has been demonstrated that optimal control is a powerful control method for power flow management in DSM.

For future work, Model Predictive Control will be developed to handle the control when the hybrid system experiences disturbances in HKT output and load demand. Also different load patterns as well as different renewable energy sources will be considered.

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