Optimal operation control of a grid-connected photovoltaic-battery hybrid system

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Abstract— **In this work, the optimal power scheduling for a grid-connected photovoltaic-battery hybrid system is proposed to sufficiently explore solar 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, photovoltaic 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 period. 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.**

Keywords— ***Photovoltaic energy, hybrid system, Time of Use, Optimal control***

I. 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]. Renewable energy sources can be used as standalone to supply isolated load or as grid-connected for selling power to the utility company [2]. Because of the instable and variable nature of their resources; renewable systems are often used in conjunction with storage systems [3]. Battery storage systems can reduce the risk of renewable systems' intermittent power supply, and always ensure that the load demand is continuously met [4].

In general, grid-connected renewable systems do not require battery storage therefore advanced energy management strategies are also not required [5]. Maximizing use of the renewable power is the only strategy adopted when the generation is less than the instantaneous load demand [6]. 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 [7]. 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 [8].

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 [9]. Several demand side management (DSM) programs can be implemented when renewable energy systems are connected to the grid such as peak shaving [10], direct load control [11], capacity market programs [12] and time-of-use (TOU) [13].

From 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 [14]. Well managed grid-connected hybrid system with DSM program 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. Therefore, at both supply and demand side, grid connected systems can bring in new opportunities to smart grid but also induce several challenges in the DSM programs.

Several works have already been conducted on grid-connected PV systems. However, most of these works have focused on energy management for large-scale integration of renewable energy at the utility side [15, 16]. Currently, there are very few studies reporting on the optimal energy management and DSM for small-scale grid connected hybrid systems at the demand side, because hybrid systems are installed for stand-alone or back-up usage without any contribution of DSM program [17 – 20].

Unlike the above-mentioned papers, the focus of this paper will be on analyzing a grid-connected PV-battery system under the time-of-use (TOU) program with contracted selling as an example using the South African context. An optimal power flow management algorithm of the proposed hybrid system is developed aiming to minimize the electricity cost within the DSM framework while satisfying the load demand. 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 in order to sell surplus power to the grid over peak period.

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II. DESCRIPTION OF THE GRID CONNECTED PV-BATTERY HYBRID SYSTEM

The hybrid system analyzed in this work is composed of a PV system and battery bank that are both connected to the grid. The output power of the PV feeds the load demand directly. If the demand is less than the PV's output, the surplus PV power will be charged into the battery bank. If the load power requirement is larger than the PV'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 peak period to save electricity cost. The grid provides electricity directly when the load cannot be entirely met by the PV and the battery. The schematic directions of power flows in the hybrid system. P_{PV-B} is the PV 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_{PV-L} is the PV power directly supplying load demand; P_{B-G} (P_{SOLD}) is the battery discharge for selling power to the grid.

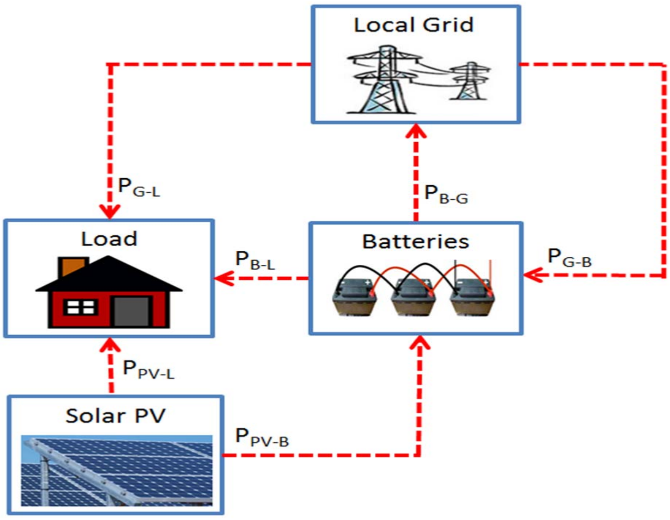

Fig. 1: Proposed hybrid system layout and power flow

A. Solar photovoltaic

Solar panels convert sunlight into electrical energy through the photovoltaic effect [11]. The output power of the solar PV system can be expressed as follows [12]:

$$P_{PV} = A_{PV} \times \eta_{PV} \times \int_{t_0}^{t} I(t) \times f(t) \times dt \qquad (1)$$

Where: A_{PV} is the total area of the photovoltaic generator (m^2); η_{PV} is the system's efficiency; I is the hourly irradiation (kWh/m^2) and $f(t)$ is the radiance density.

B. Battery storage system

The power flows from the PV, 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 [22-23]:

$$SOC_{(j+1)} = (1-d_b) \times SOC_{(j)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times (P_{PV-B(j)} + P_{G-B(j)} - \frac{\Delta t}{E_{nom}\eta_D} \times (P_{B-L(j)} + P_{SOLD(j)}) \qquad (2a)$$

Where: SOC is the state of charge of the battery; db is the self-discharging rate of the battery storage system; ηC is the battery charging efficiency; ηD is the battery discharging efficiency and Enom is the battery system nominal energy.

By induction reasoning, the dynamics of the battery state of charge at jth sampling interval can be expressed in terms of its initial value SOC (0) of a day as follows:

$$SOC_{(j)} = (1-d_b) \times SOC_{(0)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times \sum_{i=0}^{j-1} (P_{PV-B(j)} + P_{G-B(j)}) - \frac{\Delta t}{E_{nom}\eta_D} \times \sum_{i=0}^{j-1} (P_{B-L(j)} + P_{SOLD(j)}) \qquad (2b)$$

III. OPTIMIZATION MODELS AND PROPOSED ALGORITHM

A. DSM model of the grid connected PV-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 loads 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 [24]:

$$\rho(t) = \begin{cases} \rho_k; t \in T_k, T_k = [7,10) \cup [18,20) \\ \rho_0; t \in T_0, T_0 = [0,6) \cup [22,24) \\ \rho_s; t \in T_s, T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \qquad (3)$$

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.

B. 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:

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

Where rk =0.65 is the contracted ratio of the peak price ρk 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 [24].

C. Constraints

- PV's output constraints:

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

$$P_{PV-B(j)} + P_{PV-L(j)} \le P_{PV(j)} \tag{5}$$

- Power balance constraint:

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

$$P_{B-L(j)} + P_{G-L(j)} + P_{PV-L(j)} \le P_{L(j)} \tag{6}$$

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

$$0 \le P_{PV-B(j)} \le P_{PV-B}^{\max} \quad (1 \le j \le N) \tag{7}$$

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

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

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

$$0 \le P_{PV-L(j)} \le P_{PV-L}^{\max} \quad (1 \le j \le N) \tag{11}$$

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

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:

$$SOC^{\min} \le SOC_{(j)} \le SOC^{\max} \tag{13}$$

D. Optimal control method

An optimal control method is used to manage the power flows 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 [25]:

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

where f(x) represents the objective function; *Aeq* and *beq* are the coefficients associated with equality constraints; *A* and *b* are the coefficients associated with inequality constraints; *lb* and *ub* are the lower and upper bounds of variables.

IV. CASE STUDY

A daily detailed load data is obtained from a typical household in Bloemfontein (South Africa) and the hybrid system is designed in such a way to provide electricity for low consumption electrical appliances. When scrutinizing this load profile, one can notice a general pattern arising from the daily activities of the users which changes depending on different seasons of the year. The selected load demand from ref. [22] reaches a peak demand of 8kW in winter; therefore, the hybrid system must be able to adequately respond to this demand.

A. 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 PB-L, grid PG-L and PPV-L. During the off-peak period, only the battery system provides power to the load as illustrated in Fig. 2(C); its corresponding state of charge decreases as shown in Fig. 3(A). The PV and the grid do not supply the load during that period as shown in Fig. 2(A) and Fig.2 (D) respectively.

There is enough power from the battery to supply the load 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 is sold to the grid as shown in Fig. 3(D).

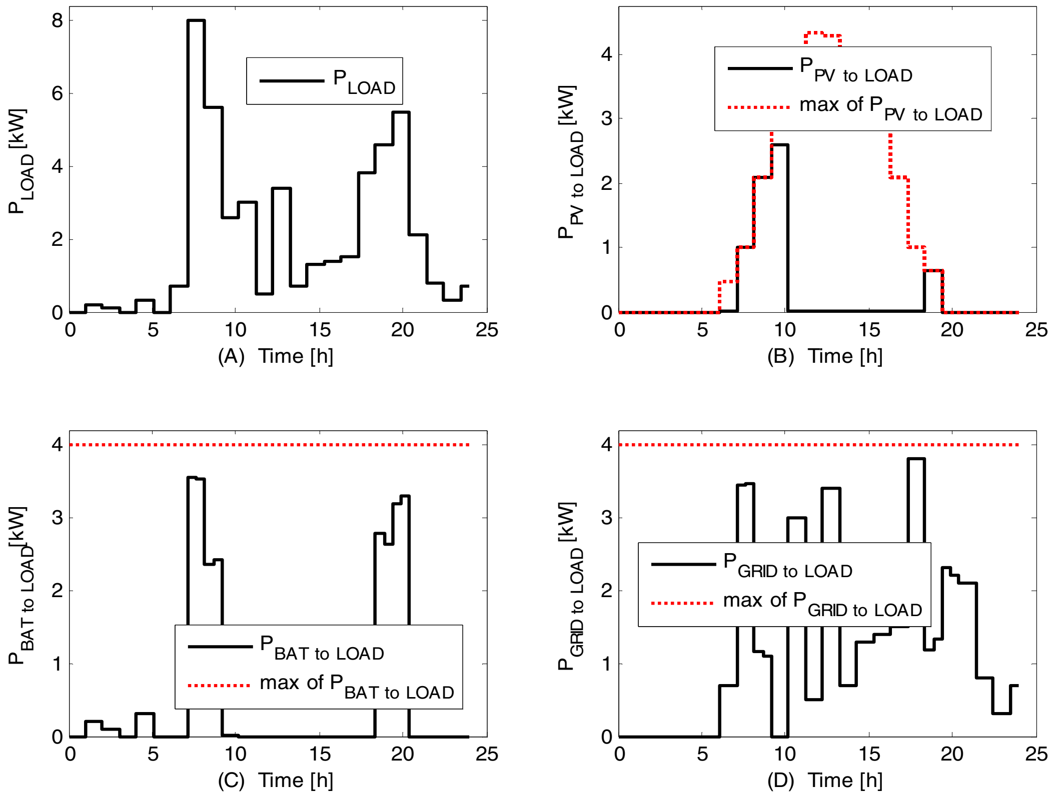

Figure 2: Load side power flow

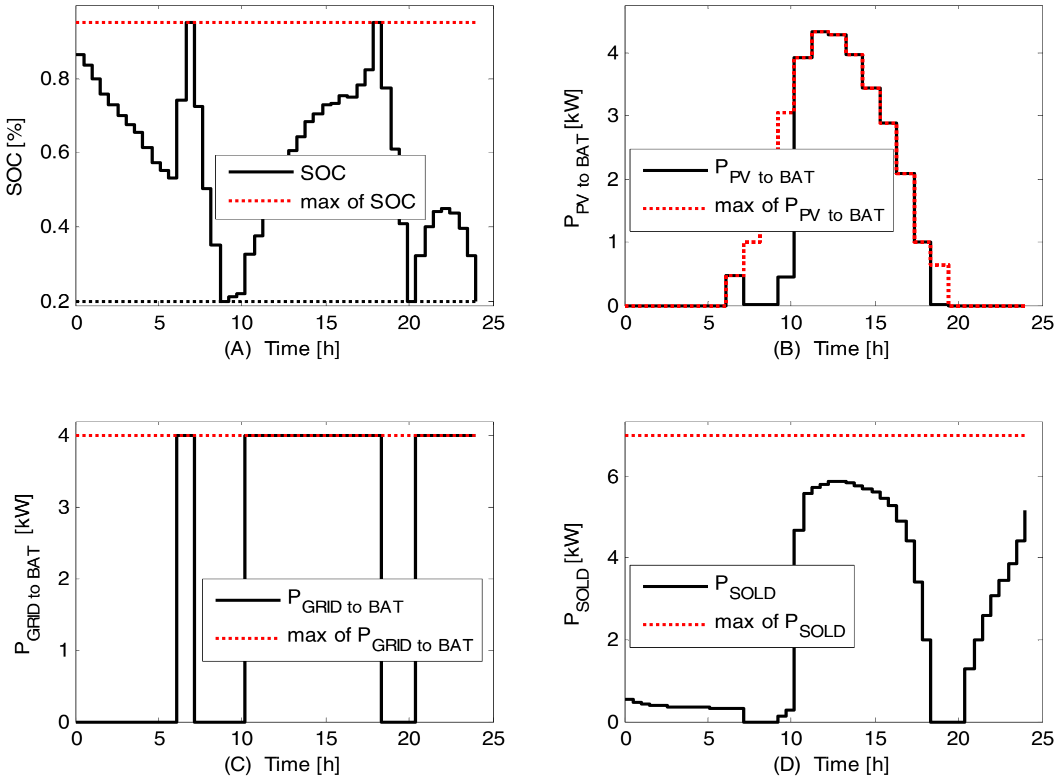

Figure 3: Battery side power flow (Household case)

B. Power flow under standard load period [(6, 7)U (20, 22)]

During the standard price period, although the battery system can fully satisfy the load demand, the grid power has been used as a main supply to the load as well as to recharge the battery. These can be seen from Fig. 2(D) and Fig.2 (C) respectively. There is a very small output from the PV; this is used to recharge the battery the battery as shown in Fig. 3(B).

C. Power flow under peak load period [(7, 10)]

During the peak load period, the load is principally met by the power from the PV, if there is any shortage in supply, the battery can then be used in conjunction with the PV system (Fig. 2(B), Fig. 2(C)). It can be seen from Fig. 3(B) how the state of charge decreases when the battery is giving power to the load. If the battery and the PV cannot adequately respond to the demand, the grid can be used to balance the power needed to satisfy the load demand as shown in Fig. 2 (D). 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 almost no excess power to be sold during this peak power demand period. Therefore, it can be seen from Fig. 3(D) that the power sold the grid at the end of this period is very small.

D. 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 by looking at Fig. 2(D) and Fig.3(C) respectively. Fig. 2(B) and Fig. 2(C) confirm that no power from the PV or the battery is used to supply the load; this power is sold to the grid as illustrated from Fig. 3(D).

E. Power flow under peak load period [(18, 20)]

During this second peak load period, there is a very small amount of power generated by the PV. All the power consumed by the load is coming from the battery and the grid as shown in Fig. 2(C) and Fig. 2(D) respectively. There is no power sold to the grid during this high demand pricing period as illustrated in Fig. 3(D).

F. Daily income generated

On the selected day, if the load demand is supplied by the grid only without the PV and battery storage system, the daily electricity cost would be \$4.32. When optimally operating the grid-connected PV hybrid system, the daily income generated by selling electricity to the grid is \$5.37. In other words, when making the balance between what is purchased from the grid and what is sold to the grid, the customer can earn \$1.05. 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.

V. CONCLUSION

Demand side management has been applied in the optimal energy management of grid-connected PV-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 of two case studies in South Africa have demonstrated that the developed optimal operation model for the hybrid system results in the maximal use of PV 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. 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. It has also been demonstrated that optimal control is a powerful control method for power flow management in DSM.

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

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