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A Scheduling Model of Household Application with a Battery Storage System Based on Charge/Discharge Characteristics of Lithium-ion Battery

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Due to over-consumption of fossil fuel and aggravation of greenhouse effects, renewable power system is one of the viable solutions for household application. Lithium-ion batteries are widely used for energy storage and constant energy supply for the excellent electrochemical performances. This work demonstrates a stand-alone renewable power system with battery storage for a household application. An integrated approach is proposed for optimal scheduling of household application, coordinated with the battery storage performances based on battery charge/discharge characteristics. A mixed integer nonlinear programming (MINLP) model for scheduling of application and battery in household is established to minimize the levelized cost of energy (LCOE) of the system. Battery characteristics are optimized by considering the LCOE of the entire system. The strategies for application and battery scheduling in multiple periods are embedded into the model. Results show that the LCOE of the system obtained by the proposed model is reduced by optimizing the battery characteristics and multi-period scheduling schemes. The LCOE of the system depends intensively on the charge/discharge characteristics of battery. These results provide deep insights into design and operation of the battery storage system and the corresponding household power supply system.

1. Introduction

Residential energy use makes up a sizeable portion of the total energy demand (Abedi et al., 2012). Renewable energy is one of the appropriate solutions to supply energy to household without altering climate behaviour (Yu et al., 2013). Batteries are well-functioning facilities to provide peak shaving/valley filling in household power supply systems. Lithium-ion batteries are one of the most promising technologies available for energy storage and constant energy supply in stand-alone household power systems.

Optimal scheduling of household power supply systems has been recently investigated. Various optimal scheduling models have been formulated, which are mostly demonstrated in mathematical programming (Setlhaolo and Xia, 2015). Although the charge/discharge characteristics of battery have strong effects on battery storage system and even the entire power system for the fact that the operation performances depend on batteries intensively (Leadbetter and Swan, 2012), these features are rarely included in the scheduling models in literature. Moreover, these optimal scheduling models available are often for stable operations, ignoring the initial states of battery in the start-up period, which are crucial to determine the battery performance and the operational state of the entire power supply system.

In this paper, an optimal scheduling model of a hybrid power supply system for household application is established, in which the battery charge/discharge characteristics and the start-up period are involved. The battery charge rate and depth of discharge (DOD) are taken into consideration. The proposed model is a mixed integer nonlinear programming (MINLP) model, and the objective function is the levelized cost of energy (LCOE) of the system. The impacts of battery characteristics on the scheduling schemes are investigated. Moreover, the effects of solar radiation in different regions on the scheduling schemes of battery are also studied.

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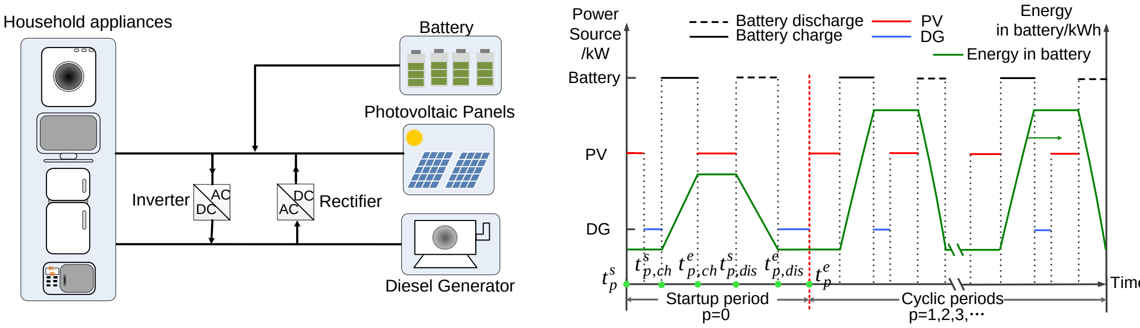
2. Scheduling strategies of a hybrid power supply system

Figure 1(a) presents a hybrid power supply system for stand-alone household application, which is composed of photovoltaic panels (PV), a diesel generator (DG) and a lithium-ion battery. To minimize the LCOE of the system, the scheduling strategies are proposed as follows: 1) the start-up period and cyclic periods are distinguished to determine the initial state of battery during the cyclic periods. Based on the performance of battery, the start-up period and cyclic periods are shown in Figure 1 (b). When the system starts, the first period is defined as start-up period, denoted by p=0. The initial state of battery in the start-up period is different from that in the cyclic periods. The cyclic periods is denoted by p = 1,2,3,…. 2) Influences of battery charge rate and DOD are involved. 3) The battery is charged when the energy produced by the PV panels is more than the user load. 4) When the energy produced by the PV panels is less than the user load, the battery discharges, and the diesel generator starts for the energy supplement.



(a) A hybrid power supply system

(b) The start-up period and the cyclic periods

Figure 1: Scheduling of a stand-alone power supply system for household

3. Optimal scheduling model by cooperating battery charge/discharge characteristics

3.1 Objective function

The objective of the proposed model is to minimize the LCOE of the hybrid power supply system, which can be expressed as

$$\min\left\{LCOE=\left[(LCC_{PV}+LCC_{DG}+LCC_{Bat})\cdot CRF\right]\Big/Q_{user}^{A}\right\} \tag{1}$$

where LCC_{PV}, LCC_{DG} and LCC_{Bat} denote the annualized life cycle costs of PV panels, diesel generator and battery, €·y^{-1}. Q_{user}^{A} is the annualized user load, kWh·y^{-1}. CRF is the capital recovery factor. The capital cost, operation cost, maintenance cost and replacement cost of battery can be calculated by referring to Malheiro' s work (Malheiro et al., 2015).

3.2 Constraints

(1) In the start-up period (p = 0)

In the system, the battery is composed of a great many Lithium-ion cells. In the beginning of the start-up period, the initial battery energy $Q_{Bat}^{p}(t_p^s)$ can be calculated by $Q_{Bat}^{p}(t_p^s)=S_{Bat}^{ins}\cdot SOC_i$, in which S_{Bat}^{ins} is the installed capacity of battery, and SOC_i is the initial state of charge. The battery energy at the initial moment of the start-up period and at the initial moment of the cyclic periods will be different due to different SOC.

At the end moment of the start-up period, the battery energy can be calculated by

$$Q_{Bat}^{p}(t_p^e)=Q_{Bat}^{p}(t_p^s)+(\eta_C\eta_{AD})\int_{t_{p,ch}^{s}}^{t_{p,ch}^{e}} f_{Bat}^{ch}dt-\int_{t_{p,dis}^{s}}^{t_{p,dis}^{e}} f_{Bat}^{dis}dt\Big/(\eta_D\eta_{DA}) \tag{2}$$

where t_p^s and t_p^e denote the start and end moment of the start-up period. f_{Bat}^{ch} is the power when the battery is charged, whereas f_{Bat}^{dis} is the power when the battery discharges. $t_{p,ch}^{s}$ and $t_{p,ch}^{e}$ are the start and end moments when the battery is charged during the period p. $t_{p,dis}^{s}$ and $t_{p,dis}^{e}$ are the start and end moments when battery discharges to users during the period p. η_C, η_D, η_{DA} and η_{AD} denote the charge efficiency, the discharge efficiency, the DC-AC efficiency and the AC-DC efficiency, respectively. The battery energy at

the end moment of the start-up period is equal to the battery energy at the initial moment of the cyclic period.
(2) In the cyclic period (p=1,2,3,…)
The total energy balance of the power supply system can be expressed as

$$Q_{PV,user}^{p} + Q_{Bat,user}^{p} + Q_{DG,user}^{p} = Q_{user}^{p} + Q_{L}^{p} \tag{3}$$

where $Q_{PV,user}$, $Q_{Bat,user}$ and $Q_{DG,user}$ denote the amount of energy supplied to users by PV panels, battery and diesel generator, respectively, kWh; Q_{user}^{p} denotes the user load in the period p , kWh; Q_L is energy loss.
To ensure battery operating in a steady state, there should be the same minimum residual energy $(Q_{Bat})_{min}$ during each cyclic period.
The energy balance of PV panels is expressed as

$$Q_{PV,user}^{p} + Q_{Bat,user}^{p} + Q_{PV,Bat}^{p} = Q_{PV}^{p} \tag{4}$$

where $Q_{PV,Bat}$ and Q_{PV} are the amount of energy charged to battery by PV and generated by PV, respectively, kWh.
At any moment t during the cyclic period p , the battery energy can be calculated as

$$Q_{Bat}^{p}(t) = Q_{Bat}^{p-1}(t_{p-1}^{e}) + (\eta_C \eta_{AD}) \int_{t_{p,ch}^{s}}^{t_{p,ch}^{e}} f_{Bat}^{ch} dt - \int_{t_{p,dis}^{s}}^{t_{p,dis}^{e}} f_{Bat}^{dis} dt \Big/ (\eta_D \eta_{DA}) \tag{5}$$

where $Q_{Bat}^{p}(t)$ denotes the battery energy in the period p at any moment t . t_{p-1}^{e} is equal to t_{p}^{s} .
The upper and lower bounds of the amount of energy in battery, energy charged to battery by PV panels and energy discharged to users by battery should be

$$Q_{Bat}^{p},\ Q_{PV,Bat}^{p},\ Q_{Bat,user}^{p} \in \left[0,\ S_{Bat}^{ins}(1 - SOC_{\min})\right] \tag{6}$$

The charge and discharge rates of the battery should be restricted to the following range

$$(\eta_C \eta_{AD}) Q_{PV,Bat}^{p},\ Q_{Bat,user}^{p} \Big/ (\eta_D \eta_{DA}) \in \left[0,\ F_{\max} S_{Bat}^{ins} (t_{p+1}^{s} - t_{p}^{s})\right] \tag{7}$$

where F_{max} is the maximum charge/discharge percent per hour (Malheiro et al., 2015), %/h.
(3) Charge/discharge characteristics of battery
The relationship among battery charge rate I , DOD and the battery capacity C_{Bat} , is that (Hu et al., 2013)

$$C_{Bat} = c_1 I^2 + c_2 I + c_3 \tag{8}$$

$$C_{Bat} = c_4 DOD + c_5 \tag{9}$$

The relationship between the battery capacity and the installed capacity S_{Bat}^{ins} is

$$S_{Bat}^{ins} = V_{Bat} C_{Bat} \tag{10}$$

where V_{Bat} denotes the nominal voltage of battery, V. c_1 , c_2 , c_3 , c_4 and c_5 are constants, respectively.
The total capital cost of battery increases with the increase of DOD (Duggal and Venkatesh, 2015). The relationship between the total capital cost of battery TCC_{Bat} and DOD can be expressed as

$$TCC_{Bat}(DOD) = c_6 DOD^2 + c_7 DOD \tag{11}$$

where TCC_{Bat} should be put into life cycle cost of battery. c_6 and c_7 are constants.
(4) Power generation of PV panels and diesel generator
The power generated by PV panels and the diesel generators are calculated by using models in literature (Malheiro et al., 2015).

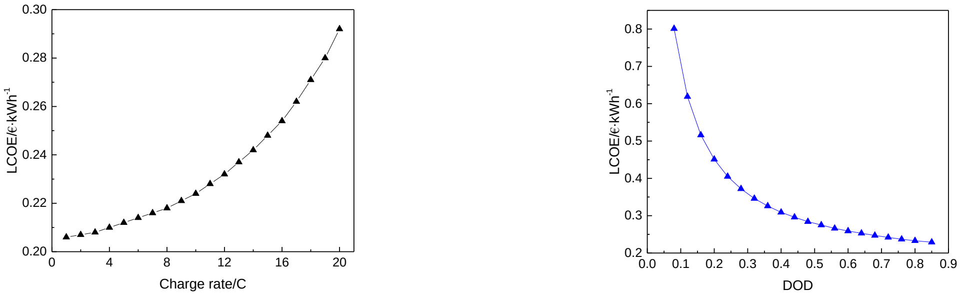
4. Case study

4.1 Fundamental data and model validation

A hybrid power supply system for household application is taken as a case study. The fundamental data of PV panels, diesel generator and battery used in the proposed model are all adopted from literature(Malheiro et al., 2015). The relevant data of the components in the system and the user load are applied to verify the model. The LCOE of the system calculated by this work is 0.213 €·kWh^{-1}, whereas it is 0.223 €·kWh^{-1} in Malheiro's work (Malheiro et al., 2015). Thus, the model proposed in this work is valid.

4.2 Impacts of battery charge/discharge characteristics on the hybrid power supply system

The relationship between battery charge rate, DOD and LCOE of the system is shown in Figure 2. The LCOE of the system increases slowly with the increase of charge rate and decreases sharply with the increase of DOD. The DOD of battery is selected as 0.85, which is usually the maximum allowable DOD of the battery in the system. In this case, the corresponding battery charge rate is 4C, where C is charge rate that equals to the charge current divided by the nominal capacity of battery.

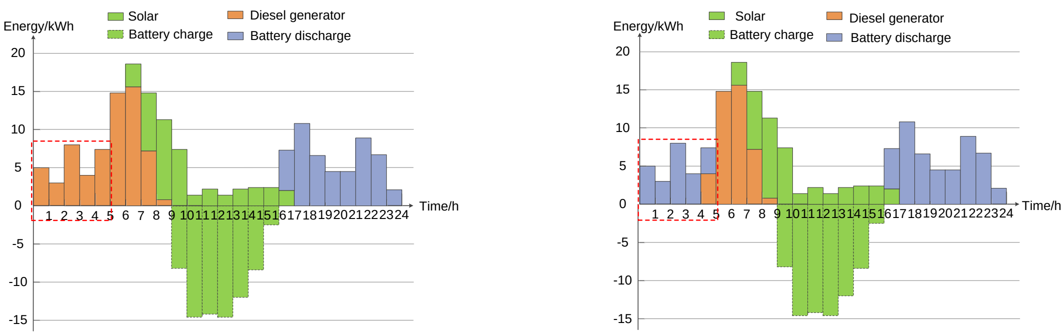


(a) Battery charge rate and LCOE (b) Battery DOD and LCOE

Figure 2: The relationship between battery charge rate, battery DOD and LCOE *of the system*

4.3 Scheduling scheme of the hybrid power supply system

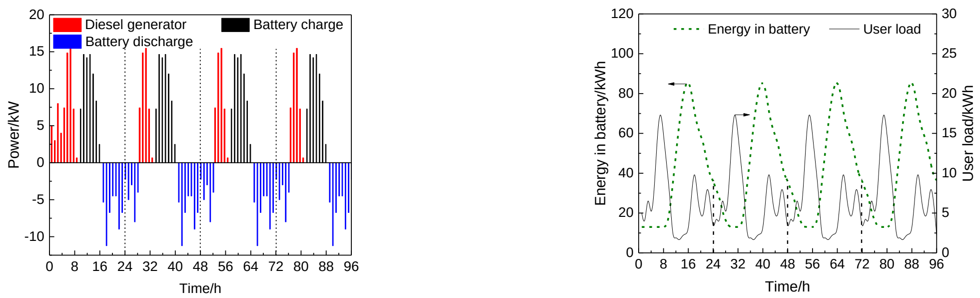
Figure 3 shows the scheduling scheme of the hybrid power system in the start-up period and the cyclic periods. The working hours and the output energy of each component in the system are presented. The summation of the energy bars above the abscissa is the user load, whereas the summation of the energy bars below abscissa is energy charged to battery. For the initial states of battery in cyclic periods are different with those in start-up period, battery supplied energy to users in 0 - 5 h, as shown in the dotted box in Figure 3(b), which corresponds to the fact that diesel generator supplies energy to users in 0 - 5 h, as shown in Figure 3(a).



(a) Start-up period (b) Cyclic period

Figure 3: Multi-period scheduling of power supply system (In this case, the power of photovoltaic panels is 40 kW; The power of diesel generator is 20 kW; The installed battery capacity is 86.64 kWh; Then LCOE of the system is 0.213 €·kWh^{-1})

Figure 4(a) shows the scheduling scheme of the diesel generator and the battery in 96 h, and Figure 4 (b) shows the energy in battery and user load variation in 96 h. It can be observed that the energy in battery at the beginning moments of the start-up period and the cyclic period are different. The total working hours of battery is 72 h which is greater than that of the diesel generator (24 h). In this case, the battery is dominant in the power supply system, while the diesel generator is auxiliary.

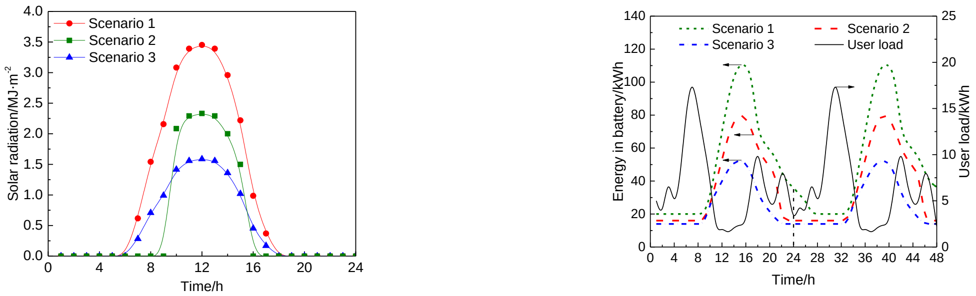


(a) Scheduling scheme (b) Energy in battery and user load

Figure 4: Scheduling schemes, energy in battery and user load of the system in 96 h operation

4.4 The impact of solar radiation on the scheduling scheme of battery

The impacts of solar radiation on the system are investigated through different locations of China. Scenario 1, 2 and 3 are the solar radiation cases of one day in June of Xinjiang, December of Xinjiang and June of Guizhou respectively, as shown in Figure 5 (a) (Yao et al., 2015). The impacts of the solar radiation on the system and the battery charge rate and DOD are investigated.



(a) Solar radiation (b) Energy in battery and user load

Figure 5: Solar radiation and battery energy in Scenario 1, Scenario 2 and Scenario 3

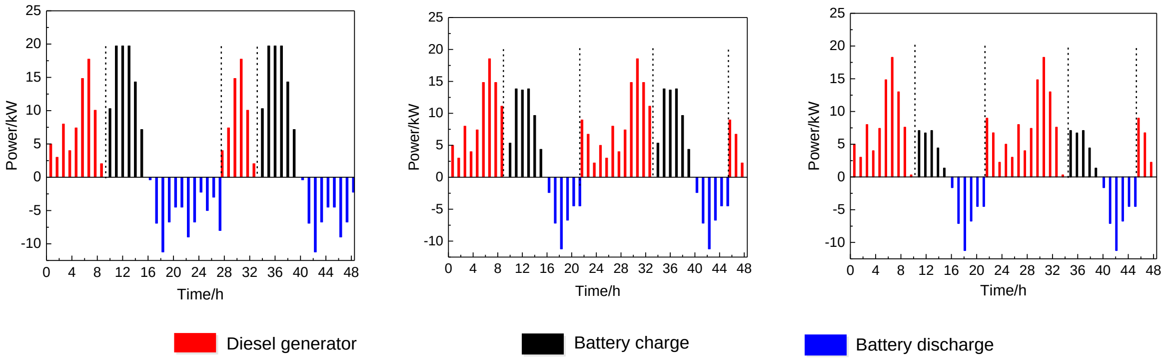
In Scenario 1, 2 and 3, the LCOE of the system can be calculated, as listed in Table 1. It can be seen from Table 1 that the LCOE of the system in Scenario 1 is the smallest, whereas the solar energy generation is the most. The LCOE in Scenario 3 is the largest, whereas the solar energy generation is the least. With the increase of solar radiation, the solar energy generation increases, and the LCOE of the system declines.

Table 1: The LCOE*, solar energy generation, cost and installed capacity of battery in Scenario 1, 2 and 3*

Items	Scenario 1	Scenario 2	Scenario 3
LCOE/€·kWh^{-1}	0.225	0.227	0.228
Solar power generation/kWh	124.862	77.664	49.843
Life cycle cost/€·y^{-1}	61,652.3	44,843.2	29,166.6
Capital cost/€·y^{-1}	23,639.6	17,198.4	11,154.3
Operation cost/€·y^{-1}	338.1	278.6	235.4
Maintenance cost/€·y^{-1}	1,250.1	909.5	589.8
Replacement cost/€·y^{-1}	34,315.7	24,965.6	16,191.9
Battery capacity/kWh	110.9	80.7	52.3

As shown in Table 1, the battery cost and the capacity installed in Scenario 1, 2 and 3 are different. They are the largest in Scenario 1, whereas they are the smallest in Scenario 3.

Figure 6 shows the scheduling schemes in Scenario 1, 2 and 3. In this figure, the working hours of the diesel generator and the battery are separated by the dashed line. As shown in Figure 6(a), the working hour of battery is longer, whereas the diesel generator is shorter. Thus, the battery is dominant in the power supply system. In contrast, as shown in Figure 6(c), the working hour of battery is shorter, whereas the diesel generator is longer. In this scenario, the diesel generator is dominant. As shown in Figure 5(b), the energy in battery is present. The end moment of the start-up period is represented by dot dash line. Compared with Scenario 1, the solar radiation in Scenario 2 and 3 declines. Hence, the battery changes from a continuous discharge state to an off-line state at the beginning moment in the cyclic period. The LCOE increases with the decrease of the solar radiation. Subsequently, in the local regions with poor solar radiation, the LCOE of the system increases greatly. The PV panels are not a favourable option.



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Figure 6: Scheduling schemes in Scenario 1, Scenario 2 and Scenario 3

5. Conclusions

Batteries can be used for energy storage in a household application. Determination of initial states of battery, charge/discharge characteristics and scheduling strategies are crucial to minimize the cost of the energy storage system. In this paper, a MINLP model is proposed to minimize the cost of a hybrid power supply system for household application with PV panels and diesel generator and battery as well. In this model, the start-up period and the cyclic periods are distinguished. The initial states of battery in the system can be determined. The constraints of battery charge rate and DOD are also integrated into the model. A case study shows that the proposed model is suitable for optimal scheduling of the hybrid power supply system. The LCOE of the system increases slowly with the increase of charge rate and decreases sharply with the increase of DOD. For different initial states of the battery, the running behaviours of the components in the system during the start-up and the cyclic periods are different. The influences of solar radiation in three scenarios are investigated. It indicates that in the local regions with poor solar radiation, the LCOE of the system increases greatly. The PV panels are not a favourable option.

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