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Model Predictive Control for Energy Dispatch of a Photovoltaic-Diesel-Battery Hybrid Power System

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Abstract: The photovoltaic-diesel-battery (PDB) hybrid system is proposed previously to satisfy power requirements in some remote areas locating out of national power grid. However, to dispatch the uses of different components in PDB hybrid system remains a problem. In this paper, mathematical model of the PDB hybrid system is transformed into an MIMO linear state-space form, and model predictive control (MPC) is applied to its energy dispatching problem. In the MPC design, an objective function is constructed to penalize the use of diesel generator and battery bank, while the use of photovoltaic array is encouraged. Constraints of the system are modeled according to its practical limitations, and are expressed in a compact form. The proposed MPC is designed by using the standard receding horizontal technique. Performances of the closed-loop system is demonstrated by simulation examples, where disturbances in load demand and photovoltaic (PV) power are considered.

Keywords: Energy dispatch, model predictive control, photovoltaic-diesel-battery hybrid system, optimization, receding horizontal control.

1. INTRODUCTION

Renewable energy sources are significant for remote rural areas which locate out of national power grid (Deshmukh and Deshmukh (2008)). Among all renewable energy sources, solar photovoltaic energy is quite advantageous for its easy maintenance and free of greenhouse gas emission (Hong and Lian (2012)). Consequently, solar photovoltaic (PV) energy has been adopted in many countries as a complement for national power grid (Shaahid and Elhadidy (2008)). However, the main disadvantage of PV generator is that it provides discontinuous energy flows, since solar energy is subject to daily and seasonal variations (Belfkira et al. (2011)). To this end, hybrid power systems are usually constructed by combining PV arrays with other types of generators to provide consistent energy flows.

Photovoltaic-diesel-battery (PDB) hybrid systems are proposed in a previous research (Tazvinga et al. (2013a)) to satisfy the daily requirements of power in a rural Zimbabwean site. In this hybrid system, the battery bank is used to store the surplus energy generated by PV arrays for future use. The diesel generator is used to cover the imbalance whenever load demands cannot be satisfied by the PV arrays and the battery. Although the diesel generator consumes expensive fossil fuels and emits greenhouse gases, it is useful because it can be started whenever it is required (Koutroulis et al. (2006)). A dispatching problem arises on how to schedule uses of different components of the PDB hybrid system, such that load demands are supplied, and fuel consumption is reduced.

Optimization techniques are explored to solve the dispatching problem of hybrid power system, and are shown to be effective in energy saving (Tazvinga et al. (2013a); Dufo-Lopez and Bernal-Augustin (2005); Kamaruzzaman et al. (2008)). Other than traditional optimization techniques, the model predictive control (MPC) (Wang (2009)) approach is quite suitable for dispatching problems. The main difference between the MPC and other optimization techniques is that, MPC is a closed-loop approach that could contribute to better performances during a relatively long period when disturbances would occur. MPC approaches have been used previously in many other dispatching problems, such as optimal dynamic resource allocation problem (Zhang and Xia (2011)), cost-optimal operation of water pump station (Zhuan and Xia (2013)), fuel cost minimization of electric power generation (Xia et al. (2011)), current management for hybrid fuel cell power system (Vahidi et al. (2006)), and so on.

In this paper, an MPC approach is applied to the dispatching problem of a PDB hybrid systems. The aim is to satisfy the load demands while reduce the use of diesel generator. *Highlights* of this paper include 1) the PDB model is restated in an MIMO linear state-space form to facilitate control design; 2) the objective function and constraints for optimization are established respectively according to the cost and limitations of the PDB hybrid system, and are expressed into a compact form for MIMO MPC design; 3) an MIMO MPC algorithm is then designed by using receding horizontal control, where the predicted control in the next sampling time is exerted, and controls in other future sampling times are discarded. Some simulation examples with disturbances in load demand and PV power are presented to illustrate the performances of the closed-loop system. Compared with open loop optimization system,

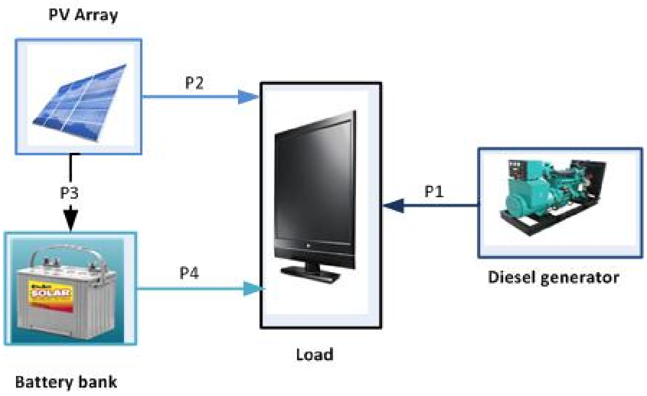

Fig. 1. Configuration of the PDB hybrid system

the closed-loop MPC system is superior in reducing the use of the diesel generator.

This paper is arranged as following: the mathematical model of the PDB hybrid system is proposed in Section 2; the detailed MPC design for energy dispatch of the PDB hybrid system is presented in Section 3; simulation results for a specific site in Zimbabwe are displayed in Section 4; and the conclusion is drawn in the final section.

2. PROBLEM FORMULATION

2.1 Configuration of the PDB hybrid system

As is displayed in Fig. 1, the PDB hybrid system is proposed in Tazvinga et al. (2013a) by combining a diesel generator, a photovoltaic array (PV), and a battery bank. The proposed hybrid system is used to supply the daily requirements of a remote area which is out of the national power grid. In this paper, an hourly load profile of a typical Zimbabwe site is given in Table 1.

Generally, power from PV array (P_{pv}) is less expensive than that from battery (P_4) and diesel generator (P_1); consequently, as an intuitive strategy, if the sunlight is sufficient, PV array is used (P_2) to satisfy the load demand (P_L) as a priority. The PV array is also used for charging the battery (P_3) in case of sufficient supply for the load demand. When sunlight is insufficient, the battery bank discharges to satisfy the load demand as a second choice, since power from the battery bank is cheaper than that from the diesel generator. Finally, if the load demand is too large for PV array and battery bank to supply, the diesel generator is operated to cover the imbalance.

2.2 Photovoltaic array

In this paper, data of energy flow from the PV array is given for each hour in a single summer or winter weekday, as are shown in Table 2. It is supposed that, the power from PV array relates only with sunlight at each sampling time. As is shown in Fig. 1, energy from PV is used for supplying the load demand and charging the battery.

PV powers for supplying the load demand and charging the battery are denoted by P_2 and P_3, respectively. They should be subject to the following constraints:

Table 1. Load demand profiles ($P_L(k)$, kW)

time	summer demand	winter demand
00:30	1.5	1.5
01:30	1.5	1.5
02:30	1.85	1.5
03:30	1.95	1.5
04:30	1.85	1.5
05:30	1.5	1.65
06:30	1.15	1.65
07:30	1.25	1.35
08:30	1.3	1.35
09:30	1.32	3.0
10:30	1.35	3.0
11:30	1.32	1.95
12:30	1.25	1.95
13:30	1.32	1.95
14:30	1.35	1.95
15:30	1.35	1.95
16:30	1.45	1.65
17:30	2.15	1.65
18:30	2.31	3.25
19:30	3.25	3.25
20:30	3.25	2.31
21:30	2.0	2.15
22:30	1.95	2.15
23:30	1.65	1.35

Table 2. Power provided by PV ($P_{pv}(k)$, kW)

time	summer supply	winter supply
00:30	0.00	0.00
01:30	0.00	0.00
02:30	0.00	0.00
03:30	0.00	0.00
04:30	0.00	0.00
05:30	0.00	0.00
06:30	0.09	0.19
07:30	2.30	1.21
08:30	3.98	2.66
09:30	5.42	3.95
10:30	6.45	4.89
11:30	6.75	5.25
12:30	6.59	5.14
13:30	5.84	4.50
14:30	4.84	3.56
15:30	3.47	2.33
16:30	2.07	1.11
17:30	0.09	0.13
18:30	0.00	0.00
19:30	0.00	0.00
20:30	0.00	0.00
21:30	0.00	0.00
22:30	0.00	0.00
23:30	0.00	0.00

$$0 \le P_2(k) \le P_2^{max},\ 0 \le P_3(k) \le P_3^{max},$$
$$0 \le P_2(k) + P_3(k) \le P_{pv}(k),$$

where P_2^{max} denotes the maximum amount of power that can be directly transmitted to the load from PV array, and P_3^{max} is the maximum amount of power allowed to charge the battery during one hour.

2.3 Battery bank

Charging and discharging of battery bank can be described by a dynamic equation:

$$SOC(k+1) = SOC(k) + \eta_c P_3(k) - \eta_d P_4(k), \quad (1)$$

where $SOC(k)$ denotes the state of charge at sampling time k; P_3 and P_4 are charged power and discharged power, respectively; η_c and η_d are charging efficiency and discharging efficiency, respectively. It follows from (1) the state of charge at a given time τ could be expressed by

$$SOC(\tau) = SOC(0) + \eta_c \sum_{k=0}^{\tau} P_3(k) - \eta_d \sum_{k=0}^{\tau} P_4(k).$$

SOC is subject to the constraint:

$$B_C^{min} \leq SOC(k) \leq B_C^{max},$$

where B_C^{min} and B_C^{max} are the upper and lower limit of the state of charge.

The discharged power of the battery P_4 should satisfy

$$0 \leq P_4(k) \leq P_4^{max},$$

where P_4^{max} is the maximum power allowed for discharging during one hour.

2.4 Diesel generator

The diesel generator is used to cover the balance, when the load demand cannot be satisfied by PV array and battery bank altogether. It is the final choice in the hybrid system, because 1) the fuel is expensive, and 2) it generates greenhouse gas such as Carbon Dioxide (CO_2). The advantage of using diesel generator is that it can be operated at any time according to the demand.

In this paper, the energy flow from diesel generator is subject to the constraint:

$$0 \leq P_1(k) \leq P_1^{max},$$

where P_1^{max} is the maximum amount of power that can be generated by the diesel generator during one hour.

As is mentioned before, the diesel generator, photovoltaic array and battery bank should supply the daily requirements of power altogether:

$$P_1(k) + P_2(k) + P_4(k) = P_L(k).$$

2.5 Objective

The *objective* of this paper is to design the scheduling of P_1, P_2, P_3 and P_4, such that the usage of diesel generator is minimized. To this end, and objective function (cost function) can be given by

$$J = \sum_{k=0}^{T} c_1^2 P_1(k)^2 + \sum_{k=0}^{T} c_2^2 \left(P_3(k) + P_4(k)\right)^2 + \sum_{k=0}^{T} c_3^2 \left(P_{pv}(k) - P_2(k) - P_3(k)\right)^2, \quad (2)$$

where, on the right hand side, the first term is to penalize using diesel generator; the second term is to penalize charging and discharging the battery; and the third term is encourage using power generated by PV array. T denotes the finish time before which the PDB hybrid system is kept operating. Positive constants c_1, c_2 and c_3 are weight coefficients of different cost terms.

3. MODEL PREDICTIVE CONTROL DESIGN

In this section, a closed-loop MPC is proposed for the PDB hybrid system, such that: 1) load demand at each sampling time is satisfied, 2) the cost defined by (2) is minimized, and 3) the closed-loop system is robust with respect to disturbances in both load demand and PV energy.

3.1 MIMO linear state-space modeling

For typical MPC design, the PDB model proposed in Section 2 should be transformed into a linear state-space form. The energy flow from PV ($P_2(k)$), the charge of battery ($P_3(k)$) and the discharge of battery ($P_4(k)$) are considered as the control inputs. Energy flow from the diesel ($P_1(k)$), the practical use of PV energy ($P_2(k) + P_3(k)$), and the usage of battery ($P_3(k) + P_4(k)$) are regarded as outputs.

Define $x_m(k) \triangleq SOC(k)$ and $u(k) \triangleq [P_2(k), P_3(k), P_4(k)]^T$. The dynamic process of the battery can be expressed by

$$x_m(k) = x_m(k-1) + b_m u(k-1), \quad (3)$$

where $b_m = [0, \eta_c, -\eta_d]$. Define

$$y_m(k) = c_1 \left(P_L(k) - P_1(k)\right) = c_1 \left(P_2(k) + P_4(k)\right),$$

such that

$$y_m(k) = c_m x_m(k) + d_m u(k),$$

where $c_m = 0$ and $d_m = [c_1, 0, c_1]$. From the definition of y_m, it can be seen that minimizing $\sum c_1^2 P_1(k)^2$ is equal to minimizing $\sum \left(c_1 P_L(k) - y_m(k)\right)^2$.

Define $y_a(k) = c_3 \left(P_2(k) + P_3(k)\right) = c_a x_m(k) + d_a u(k)$, where $c_a = 0$ and $d_a = [c_3, c_3, 0]$. Usage of PV can be encouraged by minimizing $\sum \left(c_3 P_{pv}(k) - y_a(k)\right)^2$.

Define $y_b(k) = c_2 \left(P_3(k) + P_4(k)\right) = c_b x_m(k) + d_b u(k)$, where $c_b = 0$ and $d_b = [0, c_2, c_2]$. Utilization of the battery bank can be minimized by penalizing $\sum y_b(k)^2$.

Define the augmented system states

$$x(k) = [x_m(k), y_m(k-1), y_a(k-1), y_b(k-1)]^T,$$

and the augmented output

$$y(k) = [y_m(k-1), y_a(k-1), y_b(k-1)]^T.$$

An augmented linear state space model is then obtained:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k), \\ y(k) \;\; = Cx(k), \end{cases} \quad (4)$$

where

$$A = \begin{bmatrix} 1 & 0_{1\times3} \\ 0_{3\times1} & 0_{3\times3} \end{bmatrix}, \; B = \begin{bmatrix} 0 & \eta_c & -\eta_d \\ c_1 & 0 & c_1 \\ c_3 & c_3 & 0 \\ 0 & c_2 & c_2 \end{bmatrix}, \; C = \begin{bmatrix} 0_{3\times1} & I_{3\times3} \end{bmatrix}.$$

The augmented linear state-space equations are considered as the plant to be controlled via the MPC approach.

3.2 Objective function for MPC

The main objective of the MPC control system is to minimize the use of the diesel generator and the battery bank, and to encourage the use of PV generator. To this end, the objective function can be designed by the following three items:

(1) $\min J_1(k) = \min \sum_k^{k+N_p} \left(c_1 P_L(k) - y_m(k)\right)^2$, which indicates that usage of the diesel generator should be minimized;

(2) $\min J_2(k) = \min \sum_k^{k+N_p} y_b(k)^2$, which penalizes the use of the battery bank;

(3) $\min J_3(k) = \min \sum_k^{k+N_p} (c_3 P_{pv}(k) - y_a(k))^2$, which implies that usage of PV generator is encouraged.

In the above objective functions, N_p represents the predictive horizon for MPC design.

Define $Y(k) = [y^T(k), y^T(k+1|k), \ldots, y^T(k+N_p-1|k)]^T$, where $y(k+i|k)$ denotes the predicted value of y at step i $(i = 1, \ldots, N_p)$ from sampling time k. Define the reference value $R(k) = [c_1 P_L(k), c_3 P_{pv}(k), 0, c_1 P_L(k+1), c_3 P_{pv}(k+1), 0, \ldots, c_1 P_L(k+N_p-1), c_3 P_{pv}(k+N_p-1), 0]^T$. The overall objective function is then given by

$$\begin{aligned}\min J(k) &= \min(J_1(k) + J_2(k) + J_3(k)) \\ &= \min (Y(k) - R(k))^T (Y(k) - R(k)).\end{aligned} \tag{5}$$

3.3 Constraints for the MIMO linear system

As mentioned in Section 2, several types of constraints exist in this hybrid system:

(a) Energy flows from generators and battery are non-negative values and are subjected to their maximum values: $0 \le P_1(k) = P_L(k) - y_m(k) \le P_1^{max}$, $0 \le P_i(k) \le P_i^{max}$ $(i = 2,3,4)$, where P_i^{max} $(i = 1,2,3,4)$ denote the maximum values of energy flows.

(b) Energy flow from the PV generator $(P_{pv}(k))$ is no less than the sum of PV energy directly used on the load $(P_2(k))$ and the battery charge rate $(P_3(k))$, that is
$$P_{pv}(k) \ge P_2(k) + P_3(k).$$

(c) State of charge of the battery is confined between its minimum and maximum values:
$$B_C^{min} \le x_m(k) \le B_C^{max}.$$

The above constraints should be expressed into a compact form to facilitate MPC design for the MIMO system (4).

Constraints (a) and (b) can be rewritten by

$$M_1 u(k) \le \gamma_1, \tag{6}$$

where

$$M_1 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & 0 & -1 \end{bmatrix}, \ \gamma_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ P_L(k) \\ P_{pv}(k) \\ P_2^{max} \\ P_3^{max} \\ P_4^{max} \\ P_1^{max} - P_L(k) \end{bmatrix}.$$

Define the predictive control vector:

$$U(k) \triangleq [u^T(k), u^T(k+1|k), \cdots, u^T(k+N_c-1|k)]^T,$$

where $u(k+i|k)$ is the predicted value of u from the sampling time k, and N_c denotes the control horizon. Since each $u(k+i|k)$ in the predictive control vector $U(k)$ should satisfy (6), it follows that $U(k)$ should satisfy

$$\bar{M}_1 U(k) \le \bar{\gamma}_1, \tag{7}$$

where

$$\bar{M}_1 = \underbrace{\begin{bmatrix} M_1 & & \\ & \ddots & \\ & & M_1 \end{bmatrix}}_{N_c}, \ \bar{\gamma}_1 = \begin{bmatrix} \gamma_1 \\ \vdots \\ \gamma_1 \end{bmatrix}.$$

Constraint (c) is expressed with respect to state of charge; to facilitate the MPC design, it should be transformed into a form with respect to predictive control vector $U(k)$. Consider the battery dynamic equation (3), which can be written into

$$x_m(k+1) = x_m(k) + b_m u(k).$$

Consequently, predicted values of x_m can be given by

$$x_m(k+i|k) = x_m(k) + b_m \sum_{j=k}^{j \le k+i-1} u(j), \tag{8}$$

Define the predictive state of charge:

$$X_m(k) \triangleq [x_m(k), x_m(k+1|k), \cdots, x_m(k+N_c-1|k)]^T.$$

It follows from (8) that

$$X_m(k) = x_m(k)[1, 1, \cdots, 1]^T + B_m U(k),$$

where

$$B_m = \underbrace{\begin{bmatrix} b_m & 0 & \cdots & 0 \\ b_m & b_m & \ddots & \vdots \\ \vdots & & \ddots & 0 \\ b_m & b_m & \cdots & b_m \end{bmatrix}}_{N_c}.$$

Each $x_m(k+i|k)$ in the predictive state of charge $X_m(k)$ should satisfy Constraints (c); consequently,

$$B_{min} \underbrace{[1, 1, \cdots, 1]}_{N_c}^T \le X_m(k) \le B_{max} \underbrace{[1, 1, \cdots, 1]}_{N_c}^T$$

which can be further expressed by

$$\bar{M}_2 U(k) \le \bar{\gamma}_2, \tag{9}$$

where

$$\bar{M}_2 = \begin{bmatrix} -B_m \\ B_m \end{bmatrix}, \bar{\gamma}_2 = \begin{bmatrix} \left(x_m(k) - B_C^{min}\right) [1, 1, \cdots, 1]^T \\ \left(B_C^{max} - x_m(k)\right) [1, 1, \cdots, 1]^T \end{bmatrix}.$$

In (9), $x_m(k)$ can be obtained in real-time, and the constraint is expressed with respect to control series $U(k)$.

Combining constraints (7) and (9) yields

$$\bar{M} U(k) \le \bar{\gamma} \tag{10}$$

where $\bar{M} = [\bar{M}_1^T, \bar{M}_2^T]^T$, $\bar{\gamma} = [\bar{\gamma}_1^T, \bar{\gamma}_2^T]^T$.

3.4 MPC algorithm

With the linear state-space equations (4), the objective function (5) and the constraints (10), a standard MPC algorithm for MIMO linear system can be applied to the PDB hybrid system. For the principle of MPC design, please refer to Wang (2009).

i. Calculate MPC gains:

$$F = \left[(CA)^T, (CA^2)^T, \cdots, (CA^{N_p})^T \right]^T,$$

$$\Phi = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & & 0 \\ \vdots & & \ddots & \vdots \\ CA^{N_p-1}B & CA^{N_p-2}B & \cdots & CA^{N_p-N_c}B \end{bmatrix},$$

$E = \Phi^T \Phi$, and $H = (Fx(k) - R(k))^T \Phi$.

ii. According to standard MPC design, the predictive output vector can be expressed with respect to input

Table 3. Values of system parameters

Notations	Values	Notations	Values
P_1^{max}	5 kW	B_c^{max}	54.5 kWh
P_2^{max}	5 kW	B_c^{min}	27.25 kWh
P_3^{max}	5 kW	η_c	0.85
P_4^{max}	5 kW	η_d	1.0

series: $Y(k) = Fx(k) + \Phi U(k)$, and the objective functions can be given by

$$\begin{aligned} J(k) &= (Y(k) - R(k))^T (Y(k) - R(k)) \\ &= (Fx(k) - R(k))^T (Fx(k) - R(k)) \\ &\quad + 2(Fx(k) - R(k))^T \Phi U(k) + U(k)^T \Phi^T \Phi U(k), \end{aligned}$$

where the first term at the right side is independent on $U(k)$. Consequently, optimizing $J(k)$ can be transformed as following:

$$\begin{aligned} &\min J(k) = \min (Y(k) - R(k))^T (Y(k) - R(k)) \\ \Rightarrow\ &\min \left[2(Fx(k) - R(k))^T \Phi U(k) + U(k)^T \Phi^T \Phi U(k)\right] \\ \Rightarrow\ &\min \left(U(k)^T EU(k) + 2HU(k)\right). \end{aligned} \tag{11}$$

iii. Optimization: find optimal $U(k)$, such that the objective function given by (11) is minimized, and constraints (10) are satisfied:

$$\min \quad \left(U(k)^T EU(k) + 2HU(k)\right), \text{ s.t.: } \bar{M}U(k) \leq \bar{\gamma}.$$

iv. Calculate the receding horizontal control:

$$u(k) = [I_{3\times3}, 0, \cdots, 0]\, U(k).$$

v. Set $k = k + 1$, and update system states, inputs and outputs with the control $u(k)$ and state-space equations (4). Repeat steps i-v until k reaches its predefined value.

Remark 1. MPC differentiates from open loop optimal strategy in that it adopts receding horizontal control in Step iii. At every sampling time, MPC calculates predictive control vector for next N_c times, but only implements the first $u(k+1|u)$ in $U(k)$; at the next sampling time, it re-calculates predictive controls of next N_c times. This feedback scheme (receding horizontal control) is capable of addressing disturbances. As a comparison, in open loop optimal strategy, controls in all future times are calculated by optimization algorithm, and $U(k)$ is directly used instead of receding horizontal control in Step iii.

4. SIMULATION RESULTS FOR A SPECIFIC SITE

In this section, simulation examples of the PDB hybrid system under different situations are presented. Data concerning the daily load demand and PV array in a Zimbabwean site are listed in Table 1 and 2. To test the robustness of the closed-loop system, it is assumed that actual load demands are 20% larger than expected, while PV provides 20% less power than expected. Values of system parameters are listed in Table 3, and values of control parameters are listed in Table 4. Initial values of $P_i(k) (i = 1, 2, 3, 4)$ are set to zeros. Initial values of state of charge is set to $x_m(1) = B_C^{min}$. "Interior Point" (Sousa et al. (2011)) is used as the numerical approach to solve optimization problem in MPC at each sampling time. Time spans of simulation cases are assigned to 4 days (96 hours).

Fig. 2 and 3 depict the situation in summer. It can be seen from the figures that, when PV power (P_{pv}) is sufficient,

Table 4. Values of control parameters

Notations	Values	Notations	Values
c_1	1	N_p	24
c_2	0.2	N_c	24
c_3	0.8		

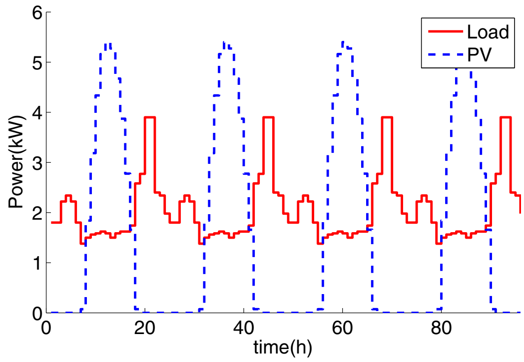

Fig. 2. Load demand and PV power in summer

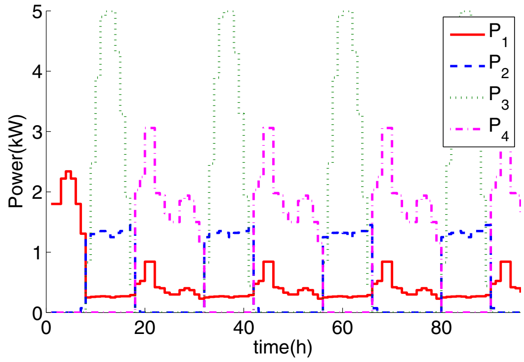

Fig. 3. Energy flows of the closed-loop system (summer)

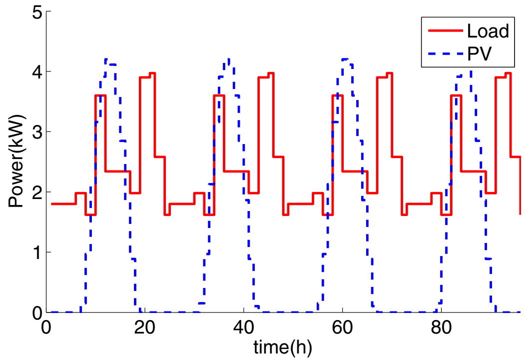

Fig. 4. Load demand and PV power in winter

P_2 is used as a priority to satisfy load demands, and the surplus PV power P_3 is utilized for charging the battery. If there is insufficient PV power, the battery discharges to satisfy load demands. In summer, it seems that the PV and battery together is always sufficient to satisfy the load demand. The diesel generator is operated to cover the disturbances in load demands. The diesel generator is also used for avoiding excessive usage of the battery, since the cost of using battery is penalized.

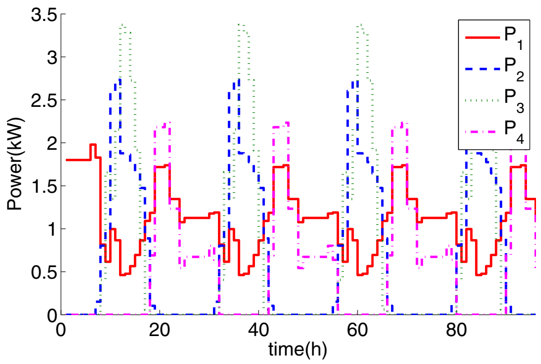

Fig. 5. Energy flows of the closed-loop system (winter)

Table 5. Diesel energy consumptions (kWh) of PDB hybrid system with different strategies

	MPC	intuitive	optimal
Summer	46.33	57.53	66.26
Winter	108.89	122.44	125.00

Simulation results of the closed-loop system in winter are presented in Fig. 4 and 5. As can be seen from the figures, PV power in winter is not so sufficient as that in summer. Consequently, although P_2 is still used as a priority to satisfy load demands, the battery charges less than it does in summer. At sampling times when PV power is insufficient, the battery provides less discharging power, and the imbalance has to be covered by the diesel generator. Another reason why charging and discharging power are much less than those in summer is that the use of battery is penalized by the cost function.

To demonstrate the superiority of the closed-loop system with MPC, we compare its energy consumption with those of an open loop intuitive control system (please see Section 2.1) and an open loop optimal control system (please see Remark 1). The comparison is listed in Table 5. As can be seen, performances of the closed-loop MPC system are superior. The reason is that, by using MPC, the system includes (1) a predictive strategy to prepare for future demands, and (2) a feedback scheme to address disturbances. The intuitive system are better than the open loop optimal control system in saving diesel energy consumption, because it is capable to respond to disturbances in each sampling time. Comparatively, performances of the open loop optimal control system are the worst, since optimization with one-time prediction would be deteriorated by possible disturbances, and imbalances of energy supply can only be covered by the diesel generator.

5. CONCLUSION

In this paper, the model predictive control approach is applied to a photovoltaic-diesel-battery hybrid system to optimally dispatch uses of its components. Based on the previous proposed hybrid system model, a cost function is constructed to penalize the use of diesel generator and battery while encourage the use of PV array. Constraints are established according to practical limitations of the hybrid system, and they are transformed into a compact form for MIMO MPC design. The control algorithm for the hybrid PDB system is derived within the framework of MPC for MIMO linear systems. Simulation results demonstrate that performances of the closed-loop system are satisfactory.

Some future works of this research might include: 1) MPC design for the PDB hybrid power system with more detailed mathematical modeling; 2) strict analysis on performances of the closed-loop system; and 3) practical experiments of hybrid power system.

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