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Methodology for optimal sizing of hybrid power system using particle swarm optimization and dynamic programming

Rui Xiong[a,b,]*, Hongwen He[a,b], Fengchun Sun[a,b]

[a]*National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, Beijing, 100081, China;*
[b] *Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing Institute of Technology, Beijing, 100081, China.*

Abstract

A methodology for optimal sizing of hybrid battery-ultracapacitor power system (HPS) is presented. The purpose of the proposed methodology is to locate the optimal voltage level for HPS used in a plug-in hybrid electric vehicle (PHEV). A combined optimization framework for a HPS is proposed and the optimization problem is solved in a bi-level manner. The framework contains two nested optimization loops. The outer loop evaluates the selected parameters through particle swarm optimization (PSO) algorithm, while the inner loop generates the optimal control strategy and calculates the costs through dynamic programming (DP) algorithm. The Chinese Typical City Bus Drive Cycle (CTCBDC) has been used to verify and evaluate the performance of the proposed methodology. The optimization result shows that higher voltage degree usually means better performance and the battery tends to provide a constant power for the HPS. It is noted that the constant power closes to the high efficiency district of the battery and DC/DC convertor. After that the optimal result is further analyzed under various optimization goals and battery charge/discharge current constrains.

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Keywords: particle swarm optimization; dynamic programming; combined optimization; HPS; plug-in hybrid electric vehicle.

1. Introduction

Under the worldwide demand for reduction in greenhouse gas emissions and PM2.5 productions, advanced battery systems powered electric vehicles (EVs) have earn widespread respect and recognition. Though the operation performance of EVs has improved a lot, the energy storage technology has become the technical bottleneck for the wide application of the EVs. The challenges come from many aspects, such as high energy/power density requirement [1–3], fast charging property [4–6], high cost, etc.

The proper combination of ultracapacitor and the battery has become an efficient way to satisfy the vehicles' power and energy requirement [7,8]. The proper component sizing and control strategy can effectively promote working performance of hybrid power system (HPS).

The optimal control strategy design and optimal system parameter design is a coupled problem. Ref.[9] concluded and discussed four combined optimization methods including the sequential, iterative, bi-level, and simultaneous methods and the bi-level method was widely used [10]. Ref.[11] proposed an integrated

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* Corresponding author. Tel.: +86-010-6891-4070; fax: +86-010-6894-0589.
E-mail address: rxiong@bit.edu.cn.

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optimization method for the optimal sizing and control strategy design of a HPS. Ref.[12] proposed a combined optimization method to design the size of the engine, motor and battery for a hybrid electric vehicle.

In this paper, a combined optimization framework is proposed for locating the optimal voltage level for HPS with a bi-level manner. The frame consists of two nested optimization loops. The outer loop evaluates the selected parameters by Particle Swarm Optimization (PSO), while the inner loop generates the optimal control strategy and calculates the costs by dynamic programming (DP) algorithm under the Chinese Typical City Bus Drive Cycle (CTCBDC).

This paper is organized as follows: In Section 2, the HPS configuration and operation process is illustrated. The optimization framework and system models including battery pack, ultracapacitor and DC/DC convertor are introduced in section 3. The simulation results are given in section 4. Finally, conclusions are presented in Section 5.

2. Configuration and operation process

2.1 The topology structure of the hybrid power system.

The structure of HPS is presented in Fig. 1. The HPS is made up of batteries and ultracapacitor. The batteries are connected with a DC/DC converter in series before connected in parallel with the ultracapacitors. The hybrid energy from the battery pack and ultracapacitor pack inputs into the motor through motor controller according to power requirement.

2.2 The operation process

We assume that the power management strategy of target plug-in hybrid electric vehicle (PHEV) is a kind of Charge-Depleting/Charge-Sustaining (CD/CS) strategy. This strategy will operate the PHEV as a pure electric vehicle first. When the batteries' State of Charge (SoC) is depleted to a given value, the CD/CS strategy will sustains the SoC around this value. In this article, we will only consider the pure electric working performance of PHEV when we try to optimize the HPS. The main parameters of the vehicle are given in table 1.

We chose the CTCBDC as the simulation test driving cycle. The power requirement P_n from the CTCBDC can be got by the following equation (1):

$$P_n = \frac{u_a}{\eta}\left(\frac{Mgf}{3600} + \frac{Mgi}{3600} + \frac{C_D A}{76140}u_a^{\,2} + \frac{\delta M}{3600}\frac{du}{dt}\right) \tag{1}$$

where u_a denote the vehicle speed, i represents the grade of the road. Fig. 2(a) and Fig. 2(b) show the CTCBDC and the power requirement P_n.

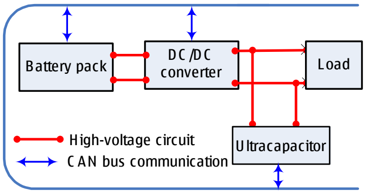

Fig. 1. The configuration of the hybrid power system

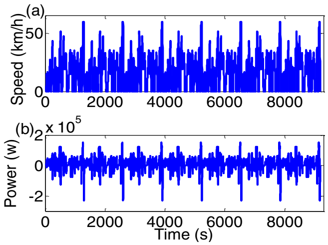

Fig.2 (a)Profiles of the cycles;(b)power requirement

3. Bi-level optimization method.

3.1 Models

To make sure the applicable and calculation accuracy of the system models in dynamic optimization process, simplified but sufficiently complex HPS and vehicle models are developed. The details of the sub-systems: battery packs, ultracapacitor pack and DC/DC converter are described below.

(1) Batteries model: The battery model is comprised of an open circuit voltage module, a resistance module and they are connected in series. Its operation behavior can be expressed by:

$$U_t = U_{ocv} - R_i i_L \tag{2}$$

where U_t denotes the batteries' terminal voltage, U_{OCV} denotes the open circuit voltage, R_i and i_L denote the resistance and load current respectively.

(2) Ultracapacitor model

The ultracapacitor model is combined by an ideal capacitor and resistance R_c. The operation process of the ultracapacitor can be expressed by the following equation:

$$U_{ct} = U_{co} - R_c i_c \tag{3}$$

where U_{ct} denotes the ultracapacitors' terminal voltage, U_{co} denotes the voltage and i_c denotes the load current of ultracapacitor.

(3) DC/DC model

We use the test data of DC/DC convertor to calculate the efficiency of the DC/DC convertor according to the output power and current as displayed in table 2.

Table 1. Basic parameters of the target vehicle

Name	Value	Unit
Vehicle mass M	16500	kg
Efficiency of the transmission system η_0	0.9	null
Rolling resistance coefficient f	0.011	null
Windward area Aar	6.6	m^2
Air resistance coefficient C_D	0.55	null
Gravitational acceleration g	9.81	m/s^2
Correction coefficient of rotating mass	δ	1.03

Table 2: Test efficiency of the DC/DC

	Power 10kW	Power 20 kW	Power 30 kW	Power 40 kW	Power 50 kW
Current 10 A	92	95	97	95	94
Current 50 A	91	93	96	93	92
Current 100 A	88	91	95	92	91
Current 150 A	82	89	92	91	90

3.2 Dynamic Optimization Problem

According to Bellman's optimization theory, a numerical-based DP method is applied in this paper to locate the optimal strategy in the inner loop [6,12]. The models of the battery or ultracapacitor can be generally displayed by the following equation:

$$x(k+1) = f(x(k), u(k)) \tag{4}$$

where x(k) represent the state vector of target system: for batteries, x(k) denotes the SoC and the diffusion voltage U_D; for ultracapacitors, x(k) denotes the state of voltage SoV. The control variable $u(k)$ denotes batteries output current. The detailed state equation evolved from Eq.(3) based on above models is displayed below:

$$SOC(k+1) = SOC(k) - i_L(k)\Delta t / Q \tag{5}$$

$$SOV(k+1) = \left(SOV(k) \times \mathrm{C} - i_c\right)/C \tag{6}$$

The target is to get the control input u(k) to minimize a target function that consists of the battery loss L_b, ultracapacitor loss L_c and DC/DC converter loss L_{dcdc}. The cost function to be minimized has the following form:

$$J = \sum_{k=0}^{N-1} \mathrm{L}(x(k), u(k) = \sum_{k=0}^{N-1} \left(L_b(k) + L_c(k) + L_{dcdc}(k)\right) \tag{7}$$

Where N is the duration of the driving cycle and L is the instantaneous cost. The energy loss can be get from the equation (8). To make sure the safe and reasonable operation of the optimal process, the inequality constrains in Eq.(9) need to be applied.

$$\begin{cases} L_{\mathrm{b}}(k) = i_{\mathrm{L}}^2(k) R_i(k) \\ L_c(k) = i_c^2(k) R_c(k) \\ L_{\mathrm{dcdc}}(k) = P_{\mathrm{b}}(k)\left(1-\eta_{\mathrm{dcdc}}(k)\right)\eta_{\mathrm{dcdc}}{}^{\text{-S}}(k) \end{cases} \tag{8}$$

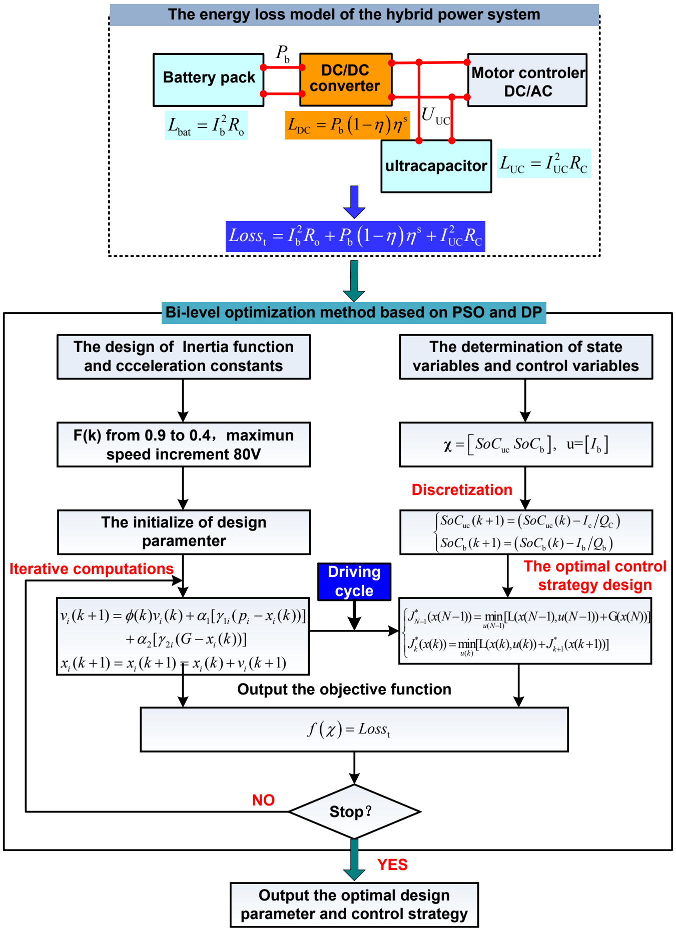

Fig. 3 The proposed flowchart of the optimization process

$$\begin{cases} \mathrm{SOC}_{\min} \le SOC(k) \le \mathrm{SOC}_{\max} \\ \mathrm{SOV}_{\min} \le SOV(k) \le \mathrm{SOV}_{\max} \\ i_{L\min}(k) \le i_L(k) \le i_{L\max}(k) \\ i_{\mathrm{c}\min}(k) \le i_c(k) \le i_{\mathrm{c}\max}(k) \\ U_{t\min} \le U_t(k) \le U_{t\max} \end{cases} \tag{9}$$

3.3 PSO Problem

The PSO process can be realized by the following equation:

$$x_i(k+1) = x_i(k+1) = x_i(k) + v_i(k+1) \tag{10}$$

$$\begin{aligned} v_i(k+1) = \phi(k)v_i(k) + \alpha_1[\gamma_{1i}(p_i - x_i(k))] \\ +\alpha_2[\gamma_{2i}(G - x_i(k))] \end{aligned} \tag{11}$$

where *i* denotes particle index, $x_i(k)$ is the position of the particle. In this paper, the position stand for the voltage of the battery pack and the feasible region is set to be [200,600], v_i is the velocity of the particle and the next time position $x_i(k+1)$of the particle can be got from equation (10); $\boldsymbol{\Phi}(k)$ is the inertia function and will change from 0.9 to 0.4 (it will be decreased to 0.4 when the generation is more than 50), $\boldsymbol{\alpha}_{1,2}$ is the acceleration constants for each particle, G is best position found by swarm (global best), p is the best position found by itself (personal best), $\boldsymbol{\gamma}_{1,2}$ is the random numbers on the interval [0,1] applied to each particle. This article selects 16 particles to search the best voltage degree for the battery pack.

3.4 Combined optimization framework

The flow chart of the optimization process used in this paper is shown in Fig.3. The framework includes two parts: the energy loss model of the HPS and the optimization process. Considering the uncertainty of the system parameter and to make sure the fair evaluation of different design parameters, we applying DP to find the optimal control strategy and calculates the costs instead of rule based method. When select the optimal design parameter we apply the PSO algorithm which is a simple and high efficiency intelligent optimal method. Then the bi-level optimization can adopted. It consists of two nested optimization loops. The outer loop evaluates the selected parameters by PSO algorithm while the inner loop generates the optimal control strategy and calculates the costs by DP algorithm.

4. Simulation results

Fig.4 shows the global best energy loss performance of each generation. From the calculation results we can get that the particles finally get the global best point where the rated voltage degree is 547.6V. This result indicates that higher battery voltage usually means better performances. This is because higher battery voltage can reduce the output current of battery system when the output power is given and the energy loss is proportionate to the square of the current. Fig.5 shows the output current of battery, ultracapacitor and the power requirement. From this figure we can get that in the optimal condition, the battery tend to provide the power according to the high efficiency area of the DC/DC convertor, while the ultracapacity prefer to compensate the remained power requirement, which can be seen more clearly in the Fig.6. This lead to the severe fluctuation of the energy loss for the ultracapacity compared with the battery and the DC/DC convertor as displayed in Fig.7. From Fig.7 we can also get that the energy loss of the battery and the DC/DC is relatively stable compared with the ultracapacitor. The main reason for this is that the efficiency of ultracapacitor is higher than that of the series combination of DC/DC convertor and battery due to its small resistance. From the above discussion, we can get that to minimum the energy loss of the system, the battery prefer to output the power at high efficiency point, where the output current is low. To further verify the conclusion, we change the target function in the formula (7) into the following format:

$$J=\sum_{k=0}^{N-1} \mathrm{L}(x(k),u(k))=\sum_{k=0}^{N-1}\left(\frac{|i_L|}{Z}\right) \qquad (12)$$

where Z denote the capacity of the battery (77 Ah). In this condition, the energy loss only problem becomes a C-rate only problem, whose purpose is to minimize the charging/discharging rate in the whole process. Fig.8 shows the comparison of the energy loss only and C-rate only problem. The output current of the battery and the ultracapacitor show a similar trend in the whole period, which verified the former conclusion: to minimum the energy loss of the system the battery prefer to output power in the high efficiency region of the DC/DC convertor where the output power is low.

For further analysis of control regulations from DP algorithm, we change the current constrain in the equation (9) and the simulation results is displayed in the Fig.9. From Fig.9 we can get that in the 3C condition, the battery and ultracapacitor tend to output large current when the power requirement is high, and under the 1.5C constrain the battery tend to charge the ultracapacitor when the power requirement is low. This simulation result shows that to apply the HPS properly in the electric vehicle, we should find out the control strategy, which can make fully use of the ultracapacitor to reduce the battery output current. This may not increase the energy loss and can protect the battery at the same time.

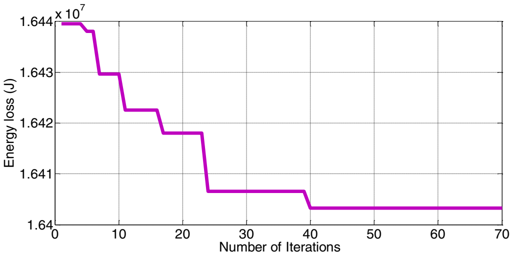

Fig. 4.Calculation result of the PSO-DP optimal sizing method

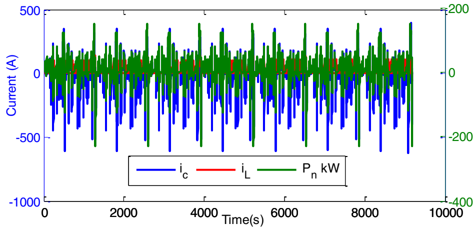

Fig. 5.The output current of the battery and the ultracapacitor (from 0 to 9198 seconds)

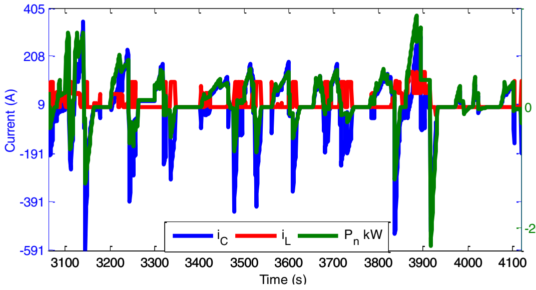

Fig. 6.The output current of the battery and the ultracapacitor (from 3063 to 4119 seconds)

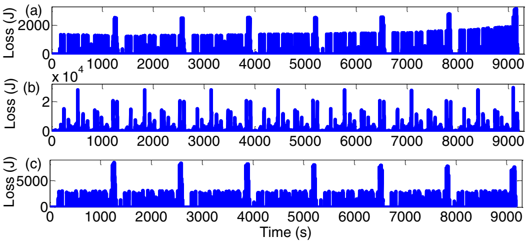

Fig. 7.（a）battery, (b) ultracapacitor, (c) DC/DC convertor

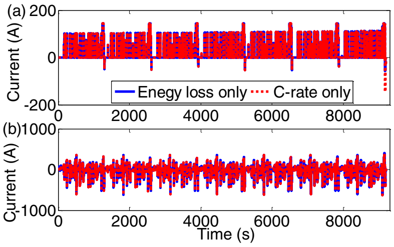

Fig. 8.Comparison of energy loss only and C-rate only: （a）battery, (b) ultracapacitor

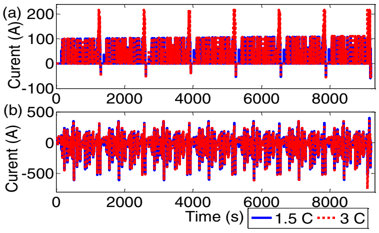

Fig. 9.The comparison different current constrain: （a） battery, (b) ultracapacitor

5. Conclusions

Base on the proposed optimization framework and simplified model, the rated voltage level was optimazed (547.6 V), which indicates that the higher battery voltage usually means better performances. The battery tends to provide the power in a stable quantity according to the high efficiency area of the DC/DC converter, while the ultracapacity prefer to compansate the remained power requirement. From the comparision of the different C-rate constrain, we can get that when applying the HPS in the electric vehicle, we should find out the control strategy, which can make fully use of the ultracapacitor to reduce the big output current from the battery, which may not increase the energy loss and can protect the battery.

6. Copyright

Acknowledgements

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Biography

Dr. Rui Xiong is an Associate Professor of Beijing Institute of Technology, where he received his M.Sc. degree in vehicle Engineering and Ph.D. degree in mechanical Engineering in 2010 and 2014, respectively. His research interests include system identification, state estimation, optimal control, and their applications in batteries and electric vehicles.