

Energy Management Strategy Development for Fuel Cell Hybrid Loaders

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Abstract. The application of fuel cell powered loaders will be an attractive option in the future. Compared with passenger cars and commercial vehicles, the operating conditions of loaders are complex and varying as the poor working environment, which pose a great challenge to the energy management problem of fuel cell hybrid loaders (FCHLs). This paper presents four energy management strategies (EMSs) based on dynamic programming, Pontryagin's minimum principle, equivalent consumption minimization strategy, and model predictive control for FCHL comprising fuel cell and supercapacitors. The basic principles of the proposed approaches are described. Hydrogen consumption, fuel cell durability, and SoC maintenance were considered in the cost functions. Simulations are performed in the MATLAB environment under representative cycles of a wheel loader. Simulation results demonstrate the feasibility and effectiveness of the proposed EMSs.

1. Introduction

Loaders are significant and indispensable in construction. Loaders usually have low efficiency, high fuel consumption, and bad emissions. Energy usage and emissions have attracted great attention. In recent years, a number of construction machinery manufacturers and research institutes have introduced some hybrid loaders, which have acceptable energy saving effect [1]. Fuel cells are efficient, clean, and green power source with high conversion efficiency and no emissions. The application of fuel cell in loaders has attracted increasing interest. In 2000, Wagner Company and INCO Company developed a fuel cell underground loader (FCUL) based on EST-6 electric underground loader [2]. In 2004, Fuelcell Propulsion Institute and Vehicle Projects LLC started to develop fuel cell mining vehicles, Caterpillar introduced a FCUL based on R1300 underground loader [3,4]. Studies show that FCUL reduced the total mining cost, and had obvious advantages over batteries powered underground loaders [5]. The application of fuel cell hybrid loaders (FCHLs) will be an attractive option in the future.

For various FCVs, the vehicular performances are closely related to energy management. Via appropriate energy management strategies (EMSs), the fuel cell hybrid system can improve fuel cell performance and durability, system efficiency, and energy utilisation [6]. Generally, the EMSs of FCVs can be basically divided into rule based EMSs and optimal EMSs. The former usually includes certainty rule based algorithms and fuzzy logic algorithms [7,8]. The latter is based on optimal control theories, such as dynamic programming (DP) [9], Pontryagin's minimum principle (PMP) [10–12],



equivalent consumption minimization strategy (ECMS), and model predictive control (MPC) [13]. DP requires complete knowledge of the future driving conditions, it has theoretically optimum. However, the calculation of DP will be tremendous with the growth of the control horizon. Therefore, DP is often realized offline and employed as benchmark. PMP is effective in generating near-optimal results that are close to those of DP. ECMS is an instantaneous algorithm, it considers the system fuel consumption rate, and the charge and discharge power of the auxiliary power source, then obtains the system equivalent fuel consumption. It needs to be pointed out that PMP and ECMS based strategies require at least one parameter to be tuned to obtain the optimal results over a specific driving cycles. MPC can repeatedly optimize decisions on-line over short and receding future time horizons to coordinate the control system, which can achieve good control through rolling optimization [14].

The energy management of FCHL is quite difficult and challenging. In this study, we will develop EMSs for FCHL powered by a fuel cell supercapacitor hybrid system. The paper is organized as follows: In Section 2, the system description of FCHL is introduced, and a system model is established. Four EMSs are proposed in Section 3. In Section 4, simulation results are presented and discussed. Finally, the conclusions are summarized in Section 5.

2. System Description and System Model

2.1. System description

In this study, wheel loaders are utilized to explore the energy management problem of FCHL. The electrical structure of the FCHL essentially involves a fuel cell stack (FCS), a supercapacitor pack, and electrical motors powered powertrain. The system topology of FCHL is shown in figure 1.

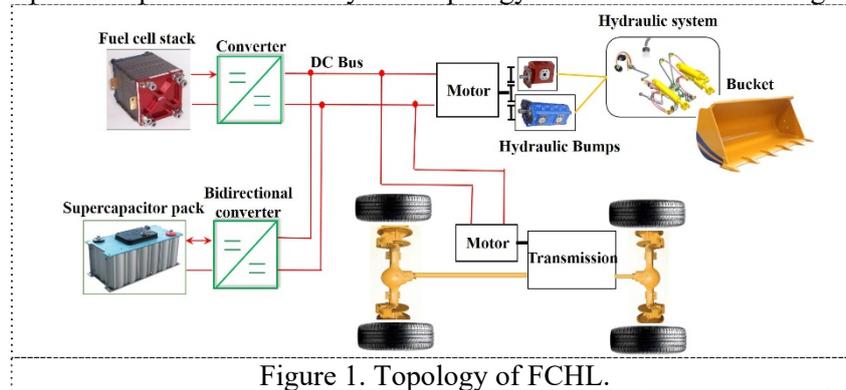


Figure 1. Topology of FCHL.

2.2. System model

A system level model is established for the FCHL. The vehicle dynamics is expressed as follows [15]:

$$F_d = m \cdot g \cdot (f \cdot \cos(\theta) + \sin(\theta)) + K_A \cdot S \cdot (v - v_w)^2 + \delta \cdot m \cdot \frac{dv}{dt} \quad (1)$$

where F_d denotes the vehicle driving force, m denotes the vehicle mass, g denotes the gravitational acceleration, f denotes the rolling resistance coefficient, θ denotes the road grade, K_A denotes the air resistance coefficient, S is the vehicle front area. v and v_w denote the vehicle speed and the wind speed, δ denotes the conversion factor of the rotating mass.

The demand power of FCHL consists of driving power of electrical motors. The vehicle demand power should be satisfied by FCS net power and supercapacitors output power.

$$P_{req} = P_{MHS} + P_{MD} = P_{FCS} + P_{SC} \quad (2)$$

where P_{req} , P_{FCS} , and P_{SC} denote vehicle demand power, FCS net power, and supercapacitors power, respectively. P_{MHS} and P_{MD} denotes the demand power of the two motors.

A static model is established for the electrical motors considering their working efficiency. A simplified model based on polarization curves is established for the FCS [16]. The FCS produces extra power for the auxiliary systems, and the demand power is also the FCS net power. A dynamic model

based on RC model was developed for the supercapacitors [17]. The state of charge (SoC) of supercapacitors is an important parameter in vehicle energy management problem, and it is defined as the amount of electrical energy left in the supercapacitors.

3. EMSs development

3.1. DP based strategy

DP is a numerical method solving multistage decision-making problems. The amount of calculation of DP based algorithms increases exponentially as the horizon extends. In this work, the DP benchmark will be implemented offline. Energy management of FCHL will be solved by finding an optimal trajectory of FCS net power. Therefore, the control variable of the optimal problem is set as the FCS net power, and supercapacitors SoC is set as the state variable.

Literatures have shown that the operating loads of loaders changes markedly and frequently, and has a highly repetitive mode [18]. The load dynamics has a negative effect on FCS durability. Restricting the load dynamics can prolong the FCS durability. Therefore, the objective of the optimal control problem is to minimize hydrogen consumption while considering the FCS durability. In addition, supercapacitors must work within appropriate bounds, avoiding overcharging or undercharging. Finally, objective of DP based EMS is shown below.

$$J(k) = \sum_{k=0}^{N-1} \left[\alpha_1(k) \cdot m_{H_2}(k) + \alpha_2(k) \cdot (SoC(k) - SoC_0)^2 + \alpha_3(k) \cdot I_{FCS}(k) \right] \quad (3)$$

where SoC_0 is a median SoC value. α_1 , α_2 , and α_3 are coefficient. I_{FCS} denotes the FCS current, k denotes the time step.

Some necessary constraints must be enforced. For the supercapacitors, the bounds on the SoC should be limited as constraints during working. FCS net power is limited to avoid startup problem, and its change rate should be limited for better performance. In addition, DP algorithm requires that the initial value of SoC is nearly the same as end value. Finally, the constraints are as follows.

$$\begin{cases} SoC_{\min} \leq SoC \leq SoC_{\max} \\ P_{FCS\min} \leq P_{FCS} \leq P_{FCS\max} \\ |\Delta P_{FCS}| \leq P_{FCS\text{Rate}} \\ SoC_{\text{Init}} \approx SoC_{\text{End}} \end{cases} \quad (4)$$

where SoC_{Init} and SoC_{End} denote initial value and end value of SoC, respectively. SoC_{\min} , SoC_{\max} , $P_{FCS\min}$, and $P_{FCS\max}$ are constant. ΔP_{FCS} denotes the change rate of FCS net power. $P_{FCS\text{Rate}}$ denotes the maximum power-changing rate of the FCS.

3.2. ECMS based strategy

ECMS takes the minimum fuel consumption as the objective. It can convert the power of the auxiliary power source to equivalent hydrogen consumption in FCV. An equivalent factor is introduced, converting the consumed or stored electric energy into the hydrogen consumption. The hydrogen consumed by the FCS adds the equivalent hydrogen consumption of electric motors, can be used as an instantaneous cost function, which can be expressed by formula (5).

$$J = \min \left\{ m_{H_2} + \beta \cdot \frac{P_{SC}}{Q_{H_2}} \right\} \quad (5)$$

where Q_{H_2} denotes the calorific value of hydrogen, β is the equivalent factor.

ECMS will select the optimal control variable minimising the cost function at each time step, and allocates the output power of the FCS and supercapacitors. Some necessary constraints must be met, as shown in formula (4) excepting the last equation.

3.3. PMP based strategy

PMP can instantaneously provide the necessary conditions for optimal control problems. In PMP framework, not only the hydrogen consumption, FCS durability and batteries durability can be contained in cost functions to achieve specific objectives. Restricting the load dynamics is positive for prolonging the FCS durability, a limitation on the current change rate and heavy current of the FCS is introduced [15]. Finally, PMP based EMS for the FCHL is proposed, which minimizes the hydrogen consumption, restricts the current change rate and heavy current of the FCS, and maintains SoC within allowable bounds. Hamiltonian function of the PMP based strategy is defined as follow.

$$H = \dot{m}_{H_2} + \lambda \cdot \dot{SoC} + \gamma_1 \cdot (SoC - SoC_0)^2 + \gamma_2 \cdot (I_{FCS} - I_{FCSlast})^2 + \gamma_3 \cdot I_{FCS} \quad (6)$$

where λ is a co-state variable. γ_1 , γ_2 , and γ_3 are coefficient. $I_{FCSlast}$ denotes the FCS current at the last time step.

3.4. MPC based strategy

With prediction of the future process output, MPC can make the control more accurate and optimized. An accurate prediction model can effectively improve the predictive control effect of MPC. Markov chain and neural networks have been applied to establish the prediction model. In this paper, MPC is employed for FCHL with the same objective as that of PMP. A predictive model based on Levenberg-Marquardt neural network is introduced. The input of neural network is historical demand power, and the output is the predicted sequences. Figure2 shows the structure of the proposed MPC.

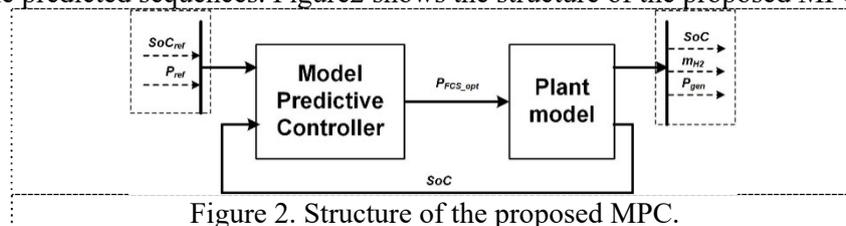


Figure 2. Structure of the proposed MPC.

where SoC_{ref} denotes the SoC reference, P_{ref} denotes the required power of excavator, P_{gen} denotes the generated power of the hybrid system, and m_{H_2} denotes the FCS hydrogen consumption.

4. Simulations and discussions

The proposed EMSs are performed in MATLAB environment. The operating load of a wheel loader under representative cycles is used as shown in figure 3. The FCHL is equipped with an 80 kW fuel cell module and a supercapacitor pack of four 48 V 63 F modules.

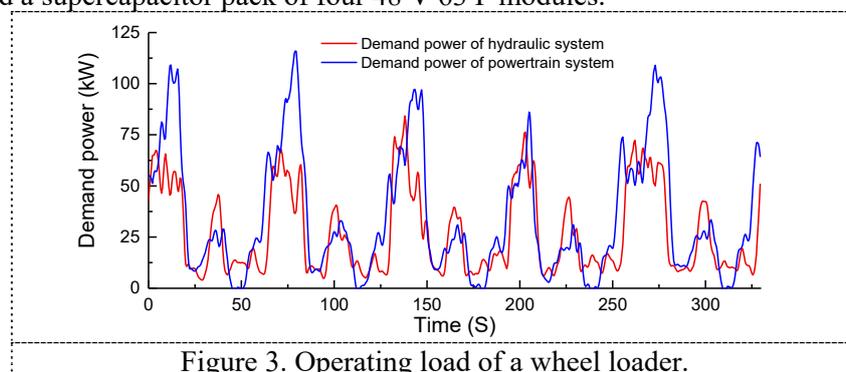


Figure 3. Operating load of a wheel loader.

Figure 4 and 5 show the simulation results of the FCS net power and supercapacitor SoC. As can be observed from figure 4 and 5, the implemented hybrid system can meet the load variations of FCHL. Figure 4 shows the simulation results of the FCS net power. The trajectories of the FCS net power vary similarly under different EMSs. DP can get the global optimal power trajectory, however, it doesn't limit the power changing rate in cost function, so the power trajectory has dramatic

fluctuations. The trajectories of the FCS net power under PMP and ECMS are quite smooth. PMP limits the power changing rate, so it has small fluctuations and has a positive effect on prolonging the FCS durability. ECMS could obtain a satisfactory control effect only when appropriate control parameters are selected. The trajectories of the FCS net power under MPC is not satisfactory. That is because MPC has some predictive errors during complex operating load conditions.

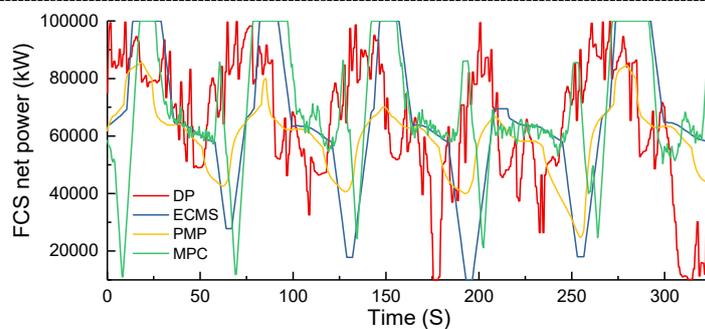


Figure 4. PFCS net power.

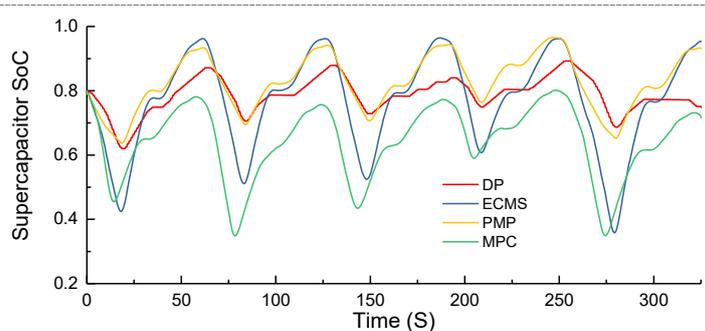


Figure 5. Supercapacitor SoC.

As can be seen in figure 5, the trajectories of the supercapacitor SoC under the four EMSs change with the demand power, and the SoC variations were similar. DP and PMP based EMS have smaller and more concentrated change range. That is because they limit the supercapacitor SoC in cost function. ECMS based EMS has the maximum change range, because it has no limitation. MPC has a lower change range, which may be that the prediction is limited and the prediction has some errors. The hydrogen consumption under DP, ECMS, PMP, and MPC based EMS is 414.28 g, 411.83 g, 395.31 g, and 434.41 g respectively. DP and ECMS have good fuel economy. That is because DP can obtain the global optimal objective, ECMS can obtain low hydrogen consumption. It should be pointed out that PMP gets the optimal hydrogen consumption. It may be that PMP limit the power changing rate, the trajectories of the FCS net power are smooth. MPC has the most hydrogen consumption, due to the predictive errors during rolling optimization process.

5. Conclusions

This paper has presented the energy management problem of FCHL comprising FCS and supercapacitors. The topology of a FCHL was presented. Then, a system model was established. Four EMSs based on DP, ECMS, PMP, and MPC were proposed for FCHL. To obtain better performance, new cost functions were introduced, considering hydrogen consumption, FCS durability, and supercapacitors SoC. Simulations were performed on representative driving cycles of a wheel loader. The superiority of the proposed EMSs was demonstrated.

Acknowledgments

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