Energy Management Strategy of Four-wheel Drive Hybrid Electric Vehicle Based on ECMS Algorithm

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Abstract

In order to improve the fuel economy of four-wheel drive hybrid electric vehicle, equivalent consumption minimum strategy of fuel control for four-wheel drive hybrid electric vehicle is proposed based on the Pontryagin's minimum principle. The vehicle dynamics model is constructed, and the instantaneous energy management optimization strategy based on equivalent consumption minimum strategy is designed. MATLAB/Simulink simulation platform is used to verify the proposed energy management strategy. The simulation results show that the proposed strategy can realize the energy optimization management of the whole vehicle. Compared with the dynamic programming energy management strategy, the average fuel economy of the strategy is higher by 6.23% under typical operating conditions.

Keywords: four-wheel drive hybrid vehicle, energy management strategy, equivalent consumption minimum strategy

Nomenclature

Abbreviation
ECMS Equivalent Consumption Minimum Strategy
HEV Hybrid Electric Vehicle

1. Introduction

While improving people's lives, vehicles also cause a great increase in traffic energy consumption and aggravation of environmental pollution. Low energy consumption and low emission become the main trend of vehicles industry development. Hybrid electric vehicles (HEV) are vehicles equipped with two or more power sources, for example, the most widely used vehicle today is a hybrid powered by an internal combustion engine and electric motor. It has the advantages of both conventional and purely electric vehicles. Through optimization and coordination of different energy sources, it can effectively reduce fuel consumption and exhaust emissions compared with the traditional vehicles. HEV energy management strategy is the basis of good performance of vehicles. As vehicles are random when driving on the road and drivers have different driving characteristics, so the HEV is a time-varying and complex nonlinear dynamics system. Scholars have conducted extensive and in-depth research on it, dynamic programming, fuzzy logic control, genetic algorithm, ECMS, model predictive control, rule-based control.

In the control method based on optimization, the theoretical global optimal solution can be obtained by the dynamic programming, but its program structure is complex, and the online optimization needs to combine with the model predictive algorithm to obtain the cycle conditions. The rule-based control method has been applied in industrialization, and it has good real-time performance and low development cost. However, this method does not have good adaptability of working conditions, and relies on expert experience. Fuzzy logic rule has good robustness and easily to realize nonlinear control, but it requires expert experience and great human influence. In order to solve the above problems, an energy management strategy based on ECMS algorithm optimization and penalty function parameters is proposed in this paper.

The paper is organized as follows. In Section 2, the model is constructed. In Section 3, we explain the ECMS algorithm used to solve the energy management problem. In Section 4, a comparative simulation analysis of the dynamic programming and equivalent fuel consumption minimization optimization energy management control strategy is presented, the results are presented and discussed. Finally, in Section 5, we state our conclusions.

2. Model construction

The structure diagram of the four-wheel drive hybrid vehicle is shown in figure 1, including the engine,
battery, gearbox, torque converter, motor and its controller.

2.1 Engine model

The maximum power of the engine is matched at the top speed. The maximum power is

\[
P_{em} = \frac{1}{\eta_i} \left( \frac{m_g g f u_m}{3600} + \frac{C_D A}{76140} u_m^3 \right) + (P_a)_m \tag{1}
\]

Where, \( P_{em} \) is the maximum power designed for the engine, \( u_m \) is the top speed, and \( (P_a)_m \) is the total power consumed by the on-board accessories.

The engine numerical model is constructed by the engine steady-state test data, and it mainly includes the fuel consumption numerical model, torque numerical model and efficiency numerical model. Engine thermal efficiency is an important index to evaluate the engine performance, with the following formula

\[
\eta_e = \frac{3.6}{b_c E} \times 10^6 \tag{2}
\]

Where, \( \eta_e \) is the engine efficiency under standard atmospheric pressure, \( b_c \) is the effective fuel consumption rate of the engine, \( E \) is the calorific value constant of the gasoline mass.

2.2 Battery model

This paper ignores the complex electrochemical reactions inside the battery, the equivalent internal resistance model is used to describe the performance of the battery, simplifies the battery pack to an ideal voltage source and resistance in series, which is shown in figure 2.

\[
R I^2 - V_o I + P_b = 0 \tag{3}
\]

By Kirchhoff's law

\[
R I^2 - V_o I + P_b = 0 \tag{3}
\]

\( R \) is the internal resistance of the battery, \( V_o \) is the open circuit voltage of the battery, \( P_b \) is the electric energy required by the motor and generator, namely the electric energy used by the battery, which is defined as follows

\[
P_b = \eta_m (\omega_m, \tau_m) + \eta_g (\omega_g, \tau_g) \tag{4}
\]

Motor efficiency \( \eta_m \) is a function of motor speed \( \omega_m \) and torque \( \tau_m \), and generator efficiency \( \eta_g \) is a function of generator speed \( \omega_g \) and torque \( \tau_g \). Solves the equation (3) and get

\[
I = \frac{V_o - \sqrt{V_o^2 - 4R_i P_b}}{2R_i} \tag{5}
\]

Differential equation of the charged state of a battery is

\[
\dot{\rho} = \frac{1}{2R_i C} \left( \sqrt{V_o^2 - 4R_i P_b} - V_o \right) \tag{6}
\]

Where, \( C \) is the maximum capacity of the battery.

2.3 Transmission model

The automatic transmission model is represented by the following formula

\[
\begin{align*}
T_i &= T_{in} - J_i \frac{d\omega_i}{dt} \\
T_o &= T_{in} i_i \eta_i \\
T_{out} &= T_o - J_o \frac{d\omega_o}{dt} \\
\omega_o &= \omega_i / i_i
\end{align*} \tag{7}
\]

\( T_i, T_o \) are the torque transmitted by the input/output shaft of the automatic transmission respectively, \( T_{in}, T_{out} \) are the input/output torque of the automatic transmission respectively, \( J_i, J_o \) are the moment inertia of clutch input and output respectively, \( i_i \) stands for automatic transmission \( i \) speed ratio, \( \eta_i \) represents the automatic transmission \( i \) efficiency, \( \omega_i, \omega_o \) are the input/output speed of the automatic transmission respectively.
2.4 Hydraulic torque converter model

Pump and turbine torque are functions of the engine and turbine speed.

\[
T_p = \begin{cases} 
  C_1 \omega_e^2 + C_2 \omega_e \omega_i + C_3 \omega_i^2 & 0 \leq \omega_i / \omega_e < \varphi_c \\
  C_4 \omega_e^2 + C_5 \omega_e \omega_i + C_6 \omega_i^2 & \varphi_c \leq \omega_i / \omega_e \leq 1 \\
  -C_4 \omega_e^2 - C_5 \omega_e \omega_i - C_6 \omega_i^2 & \omega_i / \omega_e > 1 
\end{cases}
\]

\[
T_i = \begin{cases} 
  C_7 \omega_e^2 + C_8 \omega_e \omega_i + C_9 \omega_i^2 & 0 \leq \omega_i / \omega_e < \varphi_c \\
  C_4 \omega_e^2 + C_5 \omega_e \omega_i + C_6 \omega_i^2 & \varphi_c \leq \omega_i / \omega_e \leq 1 \\
  -C_4 \omega_e^2 - C_5 \omega_e \omega_i - C_6 \omega_i^2 & \omega_i / \omega_e > 1 
\end{cases}
\]  

\[T_p, T_i \text{ are the pump and turbine torque of hydraulic}

\]

\[
\text{torque converter, } C_i \text{ is the empirical coefficient, } \varphi_c \text{ is}

\]

\[
\text{the torque coupling speed ratio and } \omega_i \text{ is the turbine}

\]

\[
\text{speed. If the hydraulic torque converter lock clutch is combined, then the hydraulic}

\]

\[
\text{torque converter is rigidly coupled, } T_p = T_i, \omega_c = \omega_i.

\]

2.5 Motor model

The ISG motor and the rear-drive motor are permanent magnet synchronous alternating current motors, and the dynamic torque can be expressed as the response of the second-order system.

\[
T_m = \begin{cases} 
  \frac{\omega_n^2}{s^2 + \frac{2 \xi_m \omega_n}{s} + \omega_n^2} \min(T_{m0}, T_{mn}) & T_{m0} > 0 \\
  \frac{\omega_n^2}{s^2 + \frac{2 \xi_m \omega_n}{s} + \omega_n^2} \max(T_{m0}, T_{mn}) & T_{m0} < 0 
\end{cases}
\]  

\[
\text{Where, } T_m \text{ is the output torque of the motor, } T_{m0} \text{ is the}

\]

\[
\text{target torque of the motor, and } T_{mn} \text{ is the}

\]

\[
\text{maximum torque of the motor. } \omega_n \text{ is the inherent}

\]

\[
\text{frequency of the motor, } \xi_m \text{ is the damping ratio of the}

\]

\[
\text{second-order system of the motor.}

\]

2.6 Vehicle dynamics model

When analyzing the vehicle model, this paper only analyzes the longitudinal forces of the vehicle, it does not involve the vehicle vibration and handling stability. The forces exerted on the vehicle during driving includes slope resistance, rolling friction resistance, inertia resistance and air resistance. And the dynamic equation of the vehicle is as follows

\[
F_i = mgf \cos \alpha + \frac{C_D A}{21.15} u^2 + \delta m \frac{du}{dt} + mg \sin \alpha
\]

\[
(11)
\]

\[
\text{Where, } F_i \text{ is the demand driving forces of the}

\]

\[
\text{whole vehicle, } m \text{ is the total mass of the vehicle, } f \text{ is}

\]

\[
\text{the rolling resistance coefficient, } \alpha \text{ is the road grade, } C_D \text{ is}

\]

\[
\text{the air resistance coefficient, } A \text{ is the road area, } \delta \text{ is}

\]

\[
\text{the rotation mass conversion coefficient of the vehicle, and } u \text{ is the vehicle speed.}

\]

3. Energy management based on ECMS algorithm

The equivalent fuel consumption minimization energy management strategy is a transient optimization strategy which does not depend on the information of cycle conditions or future path. That is, the sum of the actual fuel consumption of the engine and the equivalent fuel consumption of the motor at each time t are minimized. Since the pure equivalent fuel consumption minimization energy management strategy cannot effectively maintain the battery's SOC, the penalty function \( f_p \) is imported to control the range of SOC, and get

\[
\dot{m}_{eq} = \dot{m}_e + \dot{m}_m (f_p + s)
\]  

\[
(12)
\]

\[
\text{Where, } \dot{m}_{eq} \text{ is the equivalent fuel consumption rate,}

\]

\[
\dot{m}_e \text{ is the fuel consumption rate of the engine, which is}

\]

\[
\text{obtained by interpolation of the engine's steady-state model, } \dot{m}_m \text{ is}

\]

\[
\text{the equivalent fuel consumption rate of the motor, } s \text{ is the equivalent fuel}

\]

\[
\text{coefficient.}

\]

\[
f_p = \begin{cases} 
  k_p (x - x_{min}) & x < x_{min} \\
  0 & x_{min} < x < x_{max} \\
  k_p (x_{max} - x) & x > x_{max} 
\end{cases}
\]  

\[
(13)
\]

\[
k_p (x - x_{min}) \text{ is the penalty term of SOC below the}

\]

\[
\text{lower limit, and } k_p (x_{max} - x) \text{ is the penalty term of}

\]

\[
\text{SOC exceeding the upper limit.}

\]

\[
\text{The formula of } \dot{m}_m \text{ is}

\]

\[
\dot{m}_m = \frac{k P_m}{\eta_p Q_i (1 - k)} + \left(1 + \text{sgn}(P_m)\right) \dot{m}_{NOx} \lambda_{NOx}
\]  

\[
(14)
\]

\[
\text{Where, } k = \frac{1}{2} (1 + \text{sgn}(P_m)), \ P_m \text{ is the power of}

\]

\[
\text{the motor and } Q_i \text{ is the low heat constant value of}

\]

\[
gasoline, \ \dot{m}_{NOx} \text{ is the equivalent fuel consumption}

\]
associated with \(NO_x\) emissions, \(\lambda_{NO_x}\) is a weight factor depending on the \(NO_x\) emissions.

The constraint condition is

\[
\begin{aligned}
P_{e, req} & = P_m^+ P_m^- \\
S_m & \leq S \leq S_m^+ \\
P_{m, min} & \leq P_m \leq P_{m, max} \\
P_{e, min} & \leq P_e \leq P_{e, max}
\end{aligned}
\]  

(15)

Where, \(P_{req}\) is the required power, \(P_e\) is the engine power, \(P_{e, min}\), \(P_{e, max}\) are the minimum and maximum power of the engine respectively, \(P_{m, min}\), \(P_{m, max}\) are the minimum and maximum power of the motor respectively, \(S\) is the battery state of charge, \(S_{min}\), \(S_{max}\) are the upper and lower limits of battery capacity.

To obtain optimal control variables \(P_b\), the following performance indicator is defined as follows

\[
J = \int_{t_0}^{t_f} L(x(t), u(t), t) \, dt
\]  

(16)

The Hamiltonian equation is defined as follows

\[
H(x, u, p, t) = L(x(t), u(t)) + pf(x(t), u(t))
\]  

(17)

The state equation and the common state equation are as follows

\[
\dot{x} = \frac{\partial H}{\partial p} = f(x(t), u(t))
\]  

(18)

\[
\dot{p} = -\frac{\partial H}{\partial x} = -p \frac{\partial f}{\partial x}
\]  

(19)

The optimal control variable \(P_b\) at each step is satisfied

\[
H(SOC^+, P_b^+, p^+, t) \leq H(SOC^+, P_b, p^+, t)
\]  

(20)

And satisfies

\[
SOC(t_0) = SOC(t_f)
\]  

(21)

The minimum principle solution flow chart is shown in figure 3.

4. Verification by simulation analysis

To verify the effectiveness of the proposed energy management strategy, this paper adopts the new European driving cycle. When the initial value of SOC is 0.7, dynamic programming energy management strategy and equivalent fuel consumption minimization optimization energy management control strategy are compared.

As can be seen from figure 4, for the selected typical working conditions, the fuel consumption of the
dynamic programming method is 3.05L, and the fuel consumption of 100km is 5.35L. The fuel consumption of the energy management strategy adopted in this paper is 2.78 L, the fuel consumption of 100km is 4.86 L, the fuel consumption is declined by 6.23%.

The engine starts frequently with the dynamic programming energy management strategy, high speed after starting, and the time is short. The equivalent fuel consumption energy management control strategy adjusts the start and stop time of the engine, driven by the battery first. It can control the range of the battery’s SOC well, keep it in an efficient zone. The power distribution of hybrid electric vehicles can be adjusted according to the driving conditions. When the SOC is low, starts the engine to drive the vehicle, avoids starting the engine at low drive power demand, so it reduces the fuel consumption.

![Figure 5 Change of battery SOC](image)

5. Conclusion

For energy management strategy optimization is one of the core technologies of four-wheel drive hybrid vehicles, ECMS algorithm is applied in this paper, and this method is combined with the optimization strategy of Pontryagin’s minimum principle, and an energy management strategy optimization of four-wheel drive hybrid vehicles based on ECMS algorithm is proposed. The mathematical model is constructed, SOC is the state variable and the battery’s power is the control variable. The simulation results show that, compared to the energy management strategy based on dynamic programming, better fuel economy is gained by the proposed control strategy. The battery SOC changes more smoothly and is better maintained in the efficient zone with the penalty function. The power distribution between ISG motor and engine is better coordinated. It reduces the overall fuel consumption of the vehicle effectively, and achieves optimal energy management of hybrid electric vehicles, which provides a design idea for real-time energy management and control of hybrid electric vehicles. Compared with the dynamic programming energy management strategy, the average fuel economy of the strategy is higher by 6.23% under typical operating conditions.

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Reference


