Research on real-time simulation modeling of hybrid electric vehicle power system

Zheng Miao\(^1\) and Ying Zhang\(^1\)
\(^1\)Army Armored Force Academy Non-commissioned Officer School, Jilin Changchun, 130117, China

Corresponding author and e-mail: Ying Zhang, 35346532@qq.com

Abstract. This article conducts simulation research on the power plant of hybrid electric vehicles. Through the strategy and logic control of the power system, the stable operation of the engine in the economic area is realized. The engine model can express the relationship between performance and operating point more clearly, and can better meet the real-time response requirements of the system. This paper establishes Simulink-Amesim joint simulation model and conducts simulation analysis. The results show that the curve of engine torque changing with speed basically conforms to the engine principle.

1. Introduction
Hybrid electric vehicles are currently the key development direction of many vehicle manufacturers. One of the technical difficulties is that there are many non-linear links in the power of hybrid electric vehicles, and the interaction between various components is complicated. It will take a lot of time and material resources if you compare design schemes and test the actual effects of various control strategies through the establishment of prototypes and a large number of experiments. Therefore, in terms of comparing the performance of hybrid electric vehicles with different structures [1] and comparing the control strategies of hybrid electric vehicles with the same structure, more system modeling and simulation methods are required to be used. By establishing its simulation mathematical model and performing simulation analysis on its actual working state, it not only flexibly adjusts the design scheme, optimizes the design parameters, but also reduces the research funding and shortens the development cycle.

This article will discuss the problems related to the real-time simulation model of the dynamic system, alleviate the contradiction between the simulation accuracy and the simulation speed from the perspective of the simulation algorithm, and carry out related experiments and model verification.

2. Modeling and causality
The three basic activities of system simulation, namely system modeling, simulation modeling and simulation experiment, are unified through the three elements of system simulation, namely system, model, and simulation computer (including hardware and software). The relationship between them is as follows: Shown in Figure 1.
Causality is a problem that must be considered when establishing the mathematical model and simulation model of a complex system. It not only determines the expression of the mathematical model, but also determines the final solution order of the models in the simulation model.

2.1. Mathematical model and causality
Taking Newton’s second law as an example, there can be two different expressions, Equations 1 and 2. Equation 1 is the differential causality, which means that the differential of speed is used to calculate the force; Equation 2 is the integral causality, which means the integral of force Calculate the size of the speed.

\[ F = m \frac{dv}{dt} \quad (1) \]

\[ v = \frac{1}{m} \int F dt + C \quad (2) \]

Backward simulation is essentially a differential causality modeling method, and the two-forward simulation method is an integral causality modeling method.

2.2. Simulation model and causality
In the current popular graphical modeling software, the simulation model of the system uses graphical software almost without exception, and Matlab/Simulink software is mostly used as the modeling and simulation technology platform. Simulink is a module-oriented modeling software that can directly build models on the platform [2, 3], but when using this type of software to modularize components, causality needs to be carefully considered, otherwise it will cause algebraic loops.

2.3. Algebraic loop
Since Simulink is a module-oriented software, when using it to build simulation models, Algebraic Loop is a frequent problem. The algebraic loop is caused by direct feedthrough modules such as Sum, Gain, etc. connected end to end, and its essence is implicit algebraic constraint equations. Simulink generally needs to be solved by an iterative method, which will not only greatly reduce the speed of simulation, but even cause the simulation program to fall into an endless loop, and simulation models with algebraic loops cannot be used for real-time simulation.

In order to establish a real-time simulation model, it is necessary to eliminate the algebraic loop in the model. In order to eliminate the algebraic loop, this article summarizes the following methods:
(1) Add nondire-feedthrough modules such as Memory and Unit delay to the path where the algebraic loop exists, so as to convert the original algebraic equations into recurrence relations with initial values, but this sometimes changes the original there is an internal relationship with the model.

(2) The formation of algebraic loops is often caused by modularization during component modeling. By reorganizing the components in the system, or considering the factors that have been ignored during modeling, and taking the state quantity as the output as much as possible, the formation of algebraic loops can be effectively avoided.

3. The basic idea of power system simulation model
The simulation process used in this paper is shown in Figure 2, in which the driving energy flows from each power source to the transmission system and wheels, and is transformed into the actual vehicle speed through the vehicle dynamics model. At each moment in the simulation process, compare the given vehicle speed (the cyclic test standard) with the actual vehicle speed to find the difference, which is converted into the accelerator pedal command $\alpha$ or brake pedal of the vehicle through the driver model Command $\beta$, which is input to the powertrain control unit together with feedback parameters such as battery charge power SOC. After control logic calculations, it sends a "throttle" command signal to the engine and the motor. The engine is the throttle opening $\alpha_e$, and the motor is the torque command. $T_m$, controls the shifting of the transmission system, and then calculates the change value of the battery SOC at the same time, and finally calculates the actual vehicle speed $u$ according to the vehicle dynamics. The vehicle speed is fed back to the driver model and HCU.

![Figure 2. Simulation flow chart of powertrain system.](image)

The cycle test standard in Figure 2 is a predetermined test driving specification (speed-time function) . For different vehicle types and road conditions. According to the vehicle speed requirements at each moment, the specific operation mode is selected through the logic operation of the control strategy, thereby determining the operating conditions of the engine and the motor, and the change value of the battery charging and discharging power and SOC, so as to optimize the control strategy and develop the control unit provides theoretical guidance.

4. Engine model
The engine is one of the power sources of a hybrid electric vehicle, and its output torque is transmitted to the drive wheels through the drive train to generate traction, driving the vehicle forward. Therefore, the basis of the entire power train is whether establishment of the engine model correctly or not.

For hybrid power systems, control the engine speed and torque as much as possible to make it work in a high-efficiency area. Therefore, the operating point of the engine is adjusted by controlling the external control variable—throttle opening. Some internal control parameters of the engine, such as
the ignition advance angle, exhaust gas recirculation and air-fuel ratio, will be used as pre-calibrated control variables. It is not considered in the modeling [4]. The steady-state output torque and universal characteristic curves of the engine are shown in Figure 3 and Figure 4 respectively. Among them, if each corresponding power in the engine supply characteristic field is maintained at the lowest fuel consumption speed, the relationship between the engine throttle opening and the speed is the most economical speed adjustment characteristic. If the engine can work at the speed that emits the maximum power under each throttle, then the relationship between the throttle opening and the speed is the best dynamic speed regulation characteristic. In the simulation of this article, through the control of the vehicle power transmission system control strategy and control logic, the stable operation of the engine is realized in the most economical region. The engine model must be able to express the relationship between performance and operating point more clearly, and can better meet the real-time response requirements of the system. For this reason, on the basis of the bench test, this paper adopts the polynomial fitting method and combined with the dynamic equations to establish a quasi-linear empirical model of the engine, and approximate the dynamic characteristics with the steady-state characteristics.

4.1. Mathematical model of engine

4.1.1. Torque mathematical model. The torque balance equation of the engine is

$$J_e \frac{d\omega}{dt} = T_e - T_{el}(t)$$

(3)

$$n_e = \frac{30}{\pi \omega}$$

(4)

Where: $J_e$ is the moment of inertia of the engine, kg⋅m$^2$; 
$\omega$ is the angular velocity of the crankshaft, rad/s; 
$n_e$ is the engine speed, r/min; 
$T_e$ and $T_{el}(t)$ is the effective driving torque and external load torque, Nm.

4.1.2. Data processing method. In the process of data processing and model establishment, the corresponding engine switch and torque process program codes were written.

When all operating conditions meet the following conditions, the engine runs (engine_on=1):

1. $T>0$ OR $n>n_{ndel}$;
2. $n>n_{neidle}$ OR $e_{idle}=1$;
3. $n>n_{nele}$ OR $SOC<SOC_{lo}$;
4. $SOC<SOC_{lo}$ OR $T>T_{eoff}=fe_{off} \cdot Temax$
L: Accelerator pedal opening signal  
L: Brake pedal opening signal  
N: Speed signal at the input of the transmission, rpm  
T: Torque output command for hybrid powertrain, Nm  
\( f_{\text{eff}} \): Proportional coefficient of engine cut-off torque limit \( (0 < f_{\text{eff}} < 1) \)  
\( T_{\text{off}} \): Engine cut-off torque limit, Nm  
\( n_{\text{ele}} \): Minimum engine speed limit under driving conditions, rpm  
\( n_{\text{del}} \): Minimum engine speed limit under braking conditions, rpm  
\( n_{\text{idle}} \): Engine idling speed, rpm

When the operating conditions do not meet one of the above conditions, the engine is stopped \((\text{engine}\_\text{on}=0)\). According to the control logic, the control algorithm block diagram of the subroutine is shown in Figure 5.

![Figure 5. Limiting the engine working range-engine switch control subroutine.](image)

At the same time, according to the control strategy, the engine torque output command subroutine function is proposed: collect SOC and n signals, and determine \( T_{\text{out}} \) and \( L_{\text{e}} \) through calculations according to \( \text{engine}\_\text{on} \) and \( T \) commands. The input and output signals of the subroutine are shown in Figure 6.

![Figure 6. Input and output signals of engine torque output subroutine.](image)
Le: Engine torque output command
Teout: The maximum output torque of the engine, Nm

4.2. The simulation model of the engine

5. Conclusions
The engine model realized by Simulink above is simulated based on the MATLAB/Advisor platform, and the simulation result is shown in Figure 8. The results show that the regular curve of engine torque with speed basically conforms to the engine principle. Similarly, the simulation theory can be used for real-time simulation of asynchronous motors, batteries, power transmission devices, power distribution devices, rear axle drives, wheels, and etc.
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