Multi-working points Power follower based energy management strategy for series hybrid electric vehicle

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Abstract. The series hybrid electric vehicle is powered by an internal combustion engine-regenerator and the battery, and the two kinds of source have different operational characteristics. Energy management strategy will effect fuel consumption, SOC maintenance, and the driving performance. So, it is very important to do Energy distribution well. In this study, a Multi-working points Power follower based energy management strategy was erected, PPU will supply the low-frequency and base power while BMS will supply the high-frequency and peak power, and both of PPU and BMS work in their efficient operating regions. A typical driving cycle was employed to test the effectiveness of the proposed strategy, and the simulation results show that the strategy can effectively split the power between PPU and BMS, and help the vehicle follow the Driving cycle well.

1. Introduction
With the increasing demand for hybrid electric vehicle performance, such as fuel consumption, emission performance, and driving performance, energy management strategy gets more and more attention.

During the past decade, a large variety of studies have been published about the energy management strategy (EMS) for HEV, and the strategies can be commonly classified to two major types: rule-based (RB) and optimization-based (OB). RB-EMSs, such as deterministic and fuzzy-logic, split the power demand according to the vehicle’s current state (the vehicle velocity and the battery state of charge (SOC)) and the input variable (the power demand required by the driver) through predefined scheme without prior knowledge of the trip. OB-EMSs, such as offline (dynamic programming (DP) and genetic algorithm (GA)) and online (equivalent consumption minimization strategy (ECMS) and model predictive control (MPC)) optimization[1-7], should know the vehicle’s current and future state. So, OB-EMSs should identify and predict the driving condition firstly, but the driving condition keep changing strongly in reality, especially for off-road vehicles, and the calculation intensity will be greatly increased. The optimization results are often converted to rule-based strategies to get good real-time control performance Considering the feasibility of real-time implementation and robustness, Multi-working points power follower based (RB) energy management strategy is presented to effectively distribute demanded power between PPU and BMS.

2. Vehicle dynamic
Before describing the energy management, the power demanded for driving the vehicle should be getting from the vehicle dynamics firstly. For a given driving cycle, the vehicle speed v is known a priori as a function of time t, and then the power demand from the driving cycle can be determined as follows
\[ P_d = F_i v \]  

(1)

Where \( P_d \) is the power demanded, \( F_i \) is the tractive force, \( v \) is vehicle speed.

Keeping the vehicle speed demanded by the actual driving cycle, \( F_i \) should overcome the resistive forces acting on the vehicle, including the rolling resistance, the aero-dynamic resistance, as well as the vehicle acceleration demanded by the driving cycle, and can be expressed as

\[ F_i = m g f + \frac{C_D A v^2}{21.15} + m \frac{d v}{d t} \]  

(2)

Where \( P_d \) is the power demanded, \( F_i \) is the tractive force, \( v \) is vehicle speed.

Keeping the vehicle speed demanded by the actual driving cycle, \( F_i \) should overcome the resistive forces, where \( f \) is the rolling resistance coefficient, \( m \) is the vehicle mass, \( g \) is the gravitational acceleration, \( A \) is the effective frontal area of the vehicle, \( C_D \) is the effective aero-dynamic drag coefficient, \( v \) is the vehicle speed. The vehicle parameters are shown in table 1.

| Vehicle mass (kg) | Frontal area of the vehicle (m^2) | Tire radius (m) | Aero-dynamic drag coefficient |
|-----------------|----------------------------------|----------------|-------------------------------|
| 8500            | 5.16                             | 0.507          | 0.65                          |

### 3. Energy management

The series hybrid electric vehicle is powered by: an internal combustion engine-regenerator (the primary power unit-PPU) and the battery. Energy management has several control objectives, such as a minimization of the fuel consumption, and SOC maintenance, and enhances the driving performance. Low-pass filter is used to decompose the high- and low-frequency components in the power demand of the electric vehicle. Thus, the base power can be supplied by the PPU (with slow dynamics), whereas the dynamic power can be compensated by the battery management system (BMS with faster dynamics).

\[ \text{Actual driving cycle} \rightarrow \text{Power demand} \rightarrow \text{Power split} \rightarrow \text{PPU} \rightarrow \text{BMS} \]

Figure 1. Energy management

The power demand and the power supplied should meet the following condition:

\[ P_d = P_{ppu} + P_{bms} \]  

(3)

#### 3.1. Primary power unit

PPU will supply the primary and low frequency power for the vehicle, and is composed of an internal combustion engine and an electric generator.
According to the engine efficiency map in figure 2, there are infinite numbers of combination between the engine torque and speed that can meet the PPU power requirement. However, a specific combination of the engine torque and speed will get the engine work more efficient, PPU work mode and work region are shown in table 1.

| PPU work mode                  | power coverage (kW) | Engine speed (rpm) |
|--------------------------------|---------------------|--------------------|
| Muti-working point Power follower | 0-60                | 1300               |
|                                  | 60-90               | 1500               |
|                                  | 90-120              | 1750               |
|                                  | 120-180             | 2000               |
|                                  | 180-220             | 2500               |
| Single working point Power follower | 0-220               | 2500               |

3.2. Battery management system
BMS will supply high-frequency and peak power for the vehicle. Considering the performance and lifetime the SOC of the battery should be maintained between 20% and 90%. The main battery parameters are shown in table 3.

| Table 3. Battery Parameters |
|------------------------------|
| rated voltage (V)           | 600                |
| Capacity(20°C/1C))          | 25                 |
| Maximum continuous discharge rate | 6C       |
| Maximum continuous charge rate | 3C      |
3.3. Driving cycles
As pointed above, the demanded power for a vehicle is based on the driving cycle that is known a priori. So, a typical driving cycle derived from the historic record was employed, shown in figure 3.

4. Simulation results
In order to verify the effectiveness of the proposed Energy management strategy, simulation model was build, and simulation was conducted with the driving cycle. The simulation results as shown in figure 3. – figure 5. and table 4.

![Figure 3. Driving cycle and the actual vehicle speed](image)

In figure 3. The simulation results show that, the actual vehicle speed can follow the target speed very well, with BMS provide high-frequency dynamic power, the hybrid electric vehicle driving performance can be promoted greatly compared with traditional vehicles.

As can be seen in figure 4, the transition between the operating points is decided based on the change in driver demand, a change in the vehicle operating conditions, and at every point the torque keep changing to follow the power demand on the whole driving cycle.
Figure 4. Engine speed and torque according to the driving cycle
From the simulation results in figure 5, it can be noted that voltage fluctuating range is smaller around rated voltage, as well as that maximum power rates do not exceed nominal values. Moreover, when the SOC is low, the BMS will draw steady-state power from the power bus while providing the dynamic power until SOC reaches the ideal level.

Table 4. Fuel economy with different PPU work mode

| PPU work mode   | Fuel consumption(L/100km) | Equivalent power consumption(L/100km) | Comprehensive fuel consumption(L/100km) |
|-----------------|--------------------------|---------------------------------------|----------------------------------------|
| Multi-working point Power follower | 33.7544                  | -1.3987                               | 32.36                                  |
| Single-working point Power follower | 37.9059                  | -1.3989                               | 36.51                                  |

From table 4 it can be seen that the Comprehensive fuel consumption of the two PPU work mode are 32.36 L/100km and 36.51L/100km, respectively. Compared with single-working point mode, multi-working point Power follower can save fuel 12.8%.

5. Conclusions

Vehicle dynamic model and Energy management strategy were established based on the MATLAB/SIMULINK toolbox. The simulation results show that the Energy management strategy can help the vehicle follow the Driving cycle well, and the PPU and BMS can supply the base power and dynamic power respectively accroding to the vehicle operating conditions.

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