An energy management for series hybrid electric vehicle using improved dynamic programming

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Abstract. With the increasing numbers of hybrid electric vehicle (HEV), management for two energy sources, engine and battery, is more and more important to achieve the minimum fuel consumption. This paper introduces several working modes of series hybrid electric vehicle (SHEV) firstly and then describes the mathematical model of main relative components in SHEV. On the foundation of this model, dynamic programming is applied to distribute energy of engine and battery on the platform of matlab and acquires less fuel consumption compared with traditional control strategy. Besides, control rule recovering energy in brake profiles is added into dynamic programming, so shorter computing time is realized by improved dynamic programming and optimization on algorithm.

1. Introduction

Hybrid electric vehicle (HEV) has the advantages of less fuel consumption and longer endurance distance compared with traditional car and electric vehicle respectively, so research on HEV is of great value. This paper researches on the series hybrid electric vehicle (SHEV) and it has two energy sources, engine and battery, which can provide power together. Therefore, the distribution of two energy sources is the most important task in the field of SHEV.

At present, the main control strategies of energy management are rule-based control strategies [1-5], instantaneous optimization [6] and global optimization [7-13]. Rule-based control strategies are mainly divided into two, ON-OFF control strategy and ‘power follow’ strategy. Because of the feature that engine doesn’t have mechanical connection with transmission system in SHEV, the core ideas of its are on the premise of satisfying the power demand of vehicle and then formulating corresponding rules to control the engine or the battery group running in the individual effective zone, which can achieve better fuel economy, but it is not the globally optimum. Equivalent consumption minimization strategy [6] belongs to instantaneous optimization and it computes the present energy distribution by the present required power and drive order. Although it can be applied in real-time control, it still isn’t the globally optimum and depends on the calculation speed of controller. However, global optimization solves this problem. When the drive profile is acquired in advance, the globally optimum fuel consumption can be calculated. So global optimization is usually used in bus. The common global optimization includes dynamic programming [7-12], linear programming [13] and so on. Apart from those methods, predictive control [14-16], fuzzy control [17] are also applied in energy management of SHEV.

Although dynamic programming can get the globally optimum fuel consumption, it costs too much time to calculate so that it can not achieve real-time control. Reference [7] has presented a improved
algorithm to reduce the computing time and this paper adds the control rule that battery recovers energy in brake profiles into algorithm to reduce the computing time further.

This paper is organized as follows. Section 2 presents the five working modes of SHEV. The mathematical model of main relative components in SHEV is discussed in section 3. Section 4 describes the theory of dynamic programming and improved algorithm. Section 5 presents the result and analysis. Finally, conclusion is presented in section 6.

2. The working mode of SHEV

The structure of SHEV is presented in figure 1. From it, there is no direct mechanical connection between engine and transmission system, so engine can be controlled in fuel effective zone by controlling the speed of engine when outputting the required power (This paper mainly discusses the energy distribution and the method controlling speed is ignored, but the minimum fuel consumption at different power is presented in figure 2.).

So the five working modes of SHEV is as follows. Pure electricity driving, engine and battery driving together, separate engine driving with no charging, separate engine driving and charging, regenerative braking.

3. The mathematical model of SHEV

According to energy conservation law, an equation should be obeyed:

\[ P_{gen}(t) + P_{bat}(t) = \frac{P_{req}(t)}{\eta_t} + P_{el}(t) \] (1)

where \( P_{gen}(t) \) is the output power of generator at time \( t \), \( P_{bat}(t) \) is the output power of battery, \( P_{req}(t) \) is the required power of vehicle, \( \eta_t \) is the efficiency of transmission system, \( P_{el}(t) \) is the power consumption of electric load (such as air conditioner, lump, etc.) which is set to a fixed value in this paper. The profile in this paper is known, so \( P_{req}(t) \) is known at all the time.

So equation (1) has only two unknown variables, \( P_{gen}(t) \) and \( P_{bat}(t) \). While one is ensured, another is also ensured. Therefore, energy management problem can be changed to seek \( P_{gen}(t) \) at the particular profile.

Assuming the efficient of generator is \( \eta_{gen} \) (set to a fixed value here), seeking \( P_{gen}(t) \) is same as seeking \( P_{eng}(t) \).

\[ P_{eng}(t)\eta_{gen} = P_{gen}(t) \] (2)
where \( P_{\text{eng}}(t) \) is the output power of engine which is limited by inequality (3).

\[
P_{\text{eng min}} \leq P_{\text{eng}}(t) \leq P_{\text{eng max}}
\]

where \( P_{\text{eng min}} \) and \( P_{\text{eng max}} \) is the minimum and maximum output power of engine.

The goal of optimization is minimum fuel consumption, so the objective function is defined as,

\[
fuel(t) = \int_0^t f_{\text{min}}(P_{\text{eng}}(t))dt
\]

where \( fuel(t) \) is cumulative fuel consumption until time \( t \), \( f_{\text{min}} \) is the minimum fuel consumption function of engine power, which is showed in figure 2. Figure 2 is yielded by reading the minimum fuel consumption data per 5 kw from engine universal performance characteristics map and then fitting the curve.

The model of battery can be simply described as (ignore the loss of battery):

\[
P_{\text{bat}}(t) = UI(t)
\]

where \( U \) is the bus voltage, \( I(t) \) is the total current of battery at time \( t \) which is positive when discharging and negative when charging, \( SOC_0 \) is the initial \( SOC \), as well as, \( SOC(t) \) is the value of \( SOC \) at time \( t \) and \( Q_{\text{max}} \) is the maximum charge capacity of battery.

In order to ensure that the battery does not over charge and over discharge, and extend the life of the battery, \( SOC \) and \( I(t) \) are limited as

\[
SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}}
\]

\[
I_{\text{min}} \leq I(t) \leq I_{\text{max}}
\]

where \( SOC_{\text{min}} \) and \( SOC_{\text{max}} \) is the minimum and maximum \( SOC \) allowed, \( I_{\text{min}} \) is the minimum current which is negative and \( I_{\text{max}} \) is the maximum current which is positive.

At last, in order to reflect all the fuel is used to drive vehicle, \( SOC(T) \) which is the \( SOC \) at the end of profile is ruled to be same as the initial \( SOC_0 \).

\[
SOC(T) = SOC_0
\]

In summary, the energy management problem of SHEV is to seek \( P_{\text{eng}}(t) \) to make the objective function value minimum on the premise of satisfied \( P_{\text{req}}(t) \) and other constraint conditions.

4. Dynamic programming
Dynamic programming is a nonlinear programming method presented by Bellman in the 1950s. This method transforms a multiple-phases problem into a number of single-phase problems and solves optimization quickly through recurrence relation between each phase. So discrete optimization with constraints can be effectively solved by dynamic programming, hence we present the discretization model.

Equation constrains.

\[
P_{\text{gen}}(k) + P_{\text{bat}}(k) = P_{\text{req}}(k) + P_e(k)
\]

\[
P_{\text{eng}}(k)\eta_{\text{gen}} = P_{\text{gen}}(k)
\]

\[
P_{\text{bat}}(k) = UI(k)
\]

\[
SOC(k+1) - SOC(k) = \frac{I(k)\Delta t}{Q_{\text{max}}}
\]

\[
SOC(N) = SOC_0
\]
Inequality constrains.

\[ P_{\text{eng min}} \leq P_{\text{eng}}(k) \leq P_{\text{eng max}} \]  
\[ \text{SOC}_{\text{min}} \leq \text{SOC}(k) \leq \text{SOC}_{\text{max}} \]  
\[ I_{\text{min}} \leq I(k) \leq I_{\text{max}} \]  

The objective function.

\[ \text{fuel}(k) = \sum_{k=0}^{N-1} f_{\text{min}}(P_{\text{eng}}(k))\Delta t \]  

where \( k \in [0, 1, \ldots, N-1] \), \( N \) is the discrete number of profile.

After obtaining discretization model, set SOC to be system state variable and divide its feasible region into \( M \). Now, algorithm is explained as follows (For simplicity, set \( N=6, M=4 \)).

**Figure 3.** Dynamic programming map where \( N=6, M=4 \).

As showed in figure 3, SOC at same row is same and the same column represents same time. Each line between present time and next time represents a transfer state. When this state satisfies the constraints, node at the end of this line is a feasible node for node at the beginning of this line. Then search the minimum fuel consumption node following the feasible node and present corresponding \( P_{\text{eng}}(k) \).

Reference [7] reduces the node calculation by inequality constraint (16). As showed in figure 4, for node \( \text{SOC}(i,k-1) \), its feasible nodes are between \( \text{SOC}(p,k) \) and \( \text{SOC}(q,k) \). So there is no need to compute other nodes in the same column so that calculation time is reduced. This paper adds a control rule recovering energy in brake profiles to reduce calculation time further.

When driving in brake profiles, the value of \( P_{\text{req}}(k) \) is negative and \( P_{\text{gen}}(k) \) is set to be positive, so the symbol of \( P_{\text{bat}}(k) \) only depends on whether \( P_{\text{req}}(k)+P_{\text{el}}(k)-P_{\text{gen}}(k) \) is positive or not. Because the absolute value of \( P_{\text{el}}(k) \) is smaller than the absolute value of \( P_{\text{req}}(k) \) at most of time, \( P_{\text{bat}}(k) \) is negative that means battery will be charged when braking. Therefore the feasible nodes of node \( \text{SOC}(i,k-1) \) are between \( \text{SOC}(i,k) \) and \( \text{SOC}(q,k) \) that means \( \text{SOC}(p,k) \) to \( \text{SOC}(i,k) \) are not computed any more. The cross in figure 4 represents that battery will not discharge and current is not positive in brake profiles, so the computing time of brake profiles will decease in half.
In order to improve computing time, algorithm is optimized by release and displacement. Several 3D array is changed into 2D array that can reduce memory occupation and computing time.

5. results and analysis
The main vehicle parameters and algorithm parameters are presented in table 1.

| Parameter name                  | Parameter value |
|---------------------------------|-----------------|
| Curb weight                     | 12900kg         |
| Maximum power of engine         | 147kw           |
| Maximum charge capacity of battery | 10Ah           |
| Rated voltage of battery        | 240V            |
| $SOC_0$                         | 0.6             |
| $SOC_{min}$                     | 0.5             |
| $SOC_{max}$                     | 0.7             |
| M                               | 1000            |
| N                               | 195             |

Vehicle researched in this paper is city bus, so Urban Driving Cycle (UDC) is chosen and its required speed and power are presented in figure 5. Figure 6 and figure 7 present power distribution and the value of SOC of ON-OFF control strategy and ‘power follow’ strategy respectively. Figure 8 presents power distribution and the value of SOC of improved dynamic programming. Focused on fuel consumption, $SOC(T)$ is 0.62, 0.72 and 0.6 respectively and fuel consumption per 100 kilometers is 30.74L/100km, 42.89L/100km and 28.34L/km (The first two results are equivalent fuel consumption per 100 kilometers owing to difference of initial SOC and final SOC). Conclusion is that dynamic programming reduces fuel consumption and maintains SOC on the premise of satisfying $P_{req}(t)$, but decrement is not great. The main reasons are discrete step and profile. Smaller discrete step can obtain a better result and result of dynamic programming will be better in longer and more complex profile.

Figure 5. Requires speed and power of UDC.  
Figure 6. Power distribution and SOC of ON-OFF control strategy.

From figure 6 and 8, we can see that battery can satisfy required power before 50 seconds, but the output power of engine in dynamic programming has a large value and battery is charged which reflects dynamic programming can achieve global optimization rather than instantaneous optimization.

Comparing figure 7 with 8, we can see that because power provided by engine can satisfy the demand of vehicle in most of time and battery is always in charging state, SOC of ‘power follow’ strategy increases greatly in UDC profile. However, dynamic programming can achieve equality of initial SOC and final SOC easily.
6. Conclusions
This Paper simulates the SHEV at UDC profile using dynamic programming and proves it obtains less fuel consumption than ON-OFF control strategy and ‘power follow’ strategy. Though adding control rule into algorithm and optimizing algorithm, computing speed is improved.
Future work is to research on method for less fuel consumption.

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