A Heuristic Rule-based Control Strategy Using for Series Hybrid Tracked Vehicles

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Abstract. A heuristic rule-based energy management for a series hybrid electric tracked vehicle is proposed and verified in this paper. Based on the results of equivalent consumption minimization strategy (ECMS), the new control strategy extracts the optimized control rules and considers the fuel consumption and battery manners together by adjusting the control mechanism. The series hybrid electric tracked vehicle model and the driving cycle are built in MATLAB/Simulink. The simulation results show that the proposed strategy have a better fuel economy and battery manner than traditional rule-based strategies. Compared with the equivalent consumption minimization strategy, the new method also shows the easiness and convenience, but a nearly close fuel consumption and battery manner. This heuristic strategy can show us its advantages and serve some experiences when designing the control strategies in practical application.

1. Introduction

Nowadays, the short of fossil energy is one of the biggest developing problems spreading the countries all over the world. The combustion of fossil fuel even causes worse air pollution, which affects people's lives recent years. To solve all these issues, many countries introduce relevant policies to limit the use of internal combustion engines (ICE). Some automakers even plan to stop producing diesel locomotives in the near future. The government has got a very aggressive plan for promoting electric vehicles and hybrid vehicles. And for now, hybrid electric vehicles (HEV) play an important role in today’s automobile industry, which have all advantages in the fuel density and the facility for ICE, and the cleaner discharge for electric automobiles. Hybrid electric vehicles have two power sources at least. Hybrid system containing an ICE and a battery is the most traditional form for HEVs. There are three main configurations of HEVs: series, parallel and series-parallel. In series hybrid electric vehicles (SHEV), only the drive motor can serve the traction to the wheels. An ICE, as the primary source of the tracked vehicle, mechanically drives a generator, which can convert the mechanical energy to electrical energy. To earn a better fuel consumption performance and a higher efficiency, energy management strategy is of great importance.

Two decades ago, thermostat control strategy (TCS) had first been proposed by Anderson C and Pettit E [1]. The strategy is based on the principle of load-leveling, which operates the ICE working at a constant load and satisfies the load power by the battery. The other traditional energy management
strategy, power following control strategy (PFCS), was papered by Cuddy M R and Wipke K B in 1997 [2]. PFCS makes the ICE power follow the load power, which is a principle of load following. The equivalent consumption minimization strategy (ECMS) is a kind of optimization-based control strategies, which is conducted by Park J and Park J H in reference [3]. They found ECMS had a better fuel consumption performance compared to rule-based strategy, while it has a more complex application for online using. Both of TCS and PFCS are based on the mechanism of state-changing. Concerning the defaults of TCS and PFCS, Shabbir W [4] extracted the ideas of ECMS and introduced a new rule-based energy management strategy called exclusive operation strategy (XOS). Compared with the state-changing mechanism, threshold-changing mechanism was introduced to improve the conditions of charge sustaining. To continue the heuristic exploring of rule-based strategy, Shabbir W and Evangelou S A introduced an optimal primary source strategy (OPSS), which is an improvement of XOS by combining the two fundamental mechanisms of threshold-changing and load-leveling [5].

The new strategy was finally proved that it had a better fuel consumption performance than any other existing rule-based control strategy, and at the same time, maintains the battery capacity. In SHEVs, generator, battery and driver motors were connected and linked by direct current (DC) bus. Can Luo [6] combined PFCS and DC-link control strategy to manage the energy of SHEV, the results were found that the fuel economy was improved.

The rest parts of the article are organized as follows: Section 2 shows a model of series hybrid electric tracked vehicle and the fundamental relationship of the model. Section 3 presents the PFCS, ECMS and introduces the new heuristic strategy OPSS. In Section 4, the simulation on the SHEV model is conducted and the results are analysed. Section 5 summarizes the conclusions of this article in the end.

2. Model of Powertrain System
Primary source (PS), secondary source (SS) and propulsion load (PL) are the three components of a SHEVs construction. The PS consists of an ICE, a generator and a rectifier. The SS consists of a battery and a DC-DC converter. The PL is composed of motors and a bidirectional inverter. It is easy to see that PL power demand is provided by both the PS and SS. Energy management strategy mainly solves the distribution problem between the PS and SS. The relationship between the two power sources can be expressed as follows:

\[ P_{PS} + P_{SS} = P_{PL} \]  \hspace{2cm} (1)

\( P_{PS} \) represents the power of PS, \( P_{SS} \) represents the power of SS and \( P_{PL} \) represents the power of PL. The basic connection and vehicle model are shown in figure 1.

![Figure 1. The diagram of series HEV powertrain.](image)

The ICE drives the generator to generate electricity supplying for the DC-link. Through the function of power electronics, the DC-link module combines the direct current acquired from the ICE and the battery to serve the electrical power to the permanent magnet synchronous generator when the propulsion load is large. Except for serving power to the motor, the engine can also charge the battery when the battery is running low. The vehicle can only be propelled by the electric power rather than the mechanical power from the engine. The parameters of HEV is specified in table 1.
Table 1. The parameters of the vehicle model.

| Name                  | Value |
|-----------------------|-------|
| Vehicle mass          | 1.5t  |
| Engine                | 1.06L |
| Peak power of PS      | 36kW  |
| Battery capacity      | 10A∙h |

3. Vehicle Control Strategy

3.1. Power Following Control Strategy (PFCS)

Power following control strategy is a very common rule-based control strategy used in many occasions. Its mechanism is that the engine power follows the load power demand. The battery plays the role of supplement. To display the control logic clearly, we use the method of block subdivision as figure 2[7].

![Figure 2: Diagram of PFCS rules.](image_url)

In which, \( P_{PS_{max}} \) and \( P_{SS_{max}} \) are the maximum power of the primary source and the secondary source, \( P_{min} \) is the minimum power of the propulsion load. The \( P_m(t) \) is called the following power, which is defined as:

\[
P_m(t) = P_{PL} + P_{ch}(0.5(SOC_u + SOC_l) - SOC(t))
\]

\( P_{ch} \) is called the charging factor and its range is 0-3 kW. The PFCS has two tunable parameters, \( P_{ch} \) and \( P_{min} \), which is more cumbersome than the other strategies.

3.2. Equivalent Consumption Minimization Strategy (ECMS)

The terminal goal of ECMS is considering the electrical consumption and minimizing the total equivalent fuel expenditure. The method is defined as the following equations:

\[
m_{eq} = \int_0^t m_{eq} dt
\]

\[
m_{eq} = m_{f_{uel}}(P_{PS}) - s_d \frac{P_{SS}}{Q_{LHV}} \quad P_{SS} \geq 0
\]

\[
m_{eq} = m_{f_{uel}}(P_{PS}) - s_c \frac{P_{SS}}{Q_{LHV}} \quad P_{SS} < 0
\]

In which, \( m_{f_{uel}} \) is the fuel consumption rate of the engine and the \( Q_{LHV} \) is called fuel lower heating value. \( s_d \) and \( s_c \) are the constant equivalent factors which calculate the battery power to the equivalent fuel consumption. If the SS is discharging, the total equivalent fuel consumption is larger. If the SS is charged, the total fuel mass can be seen stored. We can conclude that the equivalent fuel consumption is determined at every instant time if the PL and the share regulation is determined. It can be formulated by an optimization problem as follows:
\[ P_{opt} = \min \{ m_{eq}(P_{PL}, u) \} \quad \forall P_{PL} \in [0, P_{PLmax}], 0 \leq u \leq \frac{P_{PSmax}}{P_{PL}} \] (6)

At each set of factors \( s_d \) and \( s_c \), we can calculate an optimal factor \( u \) to determine the power share between the two power sources. In a steady cycle of the vehicle, an optimal control strategy map is derived after a sweep by conducting the equation 3-6. And then this routine is repeated at every set of factors \( s_d \) and \( s_c \) to find the optimal set of the factors which can come to an optimal fuel consumption. We choose two specific cycles applying on the SHEV to simulate the process of driving, which can be seen in figure 3. CYCLE-L and CYCLE-M present the low and medium speed cycle.

![Figure 3. CYCLE-L(left) and CYCLE-M(right) used in the model.](image)

The optimal control maps are displayed in figure 4. We can see that the ECMS strategy leads the maps to a direction as follows: the PS is expected to closed when the PL power is low; once the PS is turned on, it delivered a more power than the PL to charge the second source; when the PL is much more, the hybrid mode is operated as expected.

![Figure 4. The extracted power share factor and PS power for varying power requirement of CYCLE-L and CYCLE-M driving cycles with ECMS.](image)

We can obtain the optimal equivalent factor values by using the ECMS method, which is shown in table 2.

| Driving Cycle | \( s_d \) | \( s_c \) |
|---------------|--------|--------|
| CYCLE-L       | 2.96   | 2.80   |
| CYCLE-M       | 2.98   | 2.75   |

### 3.3. Optimal Primary Source Strategy (OPSS)

The new energy management strategy we focused in this article is called Optimal Primary Source Strategy (OPSS). This method uses a charge sustaining mechanism called threshold-changing to encourage the use of the SS when the SOC is high, and discourage it when the SOC is low. The assigned primary source power for various operating conditions is shown in figure 5 [5]. It can be seen that the OPSS operation is divided into four main stages: the first(low \( P_{PL} \) and medium or high SOC)
is SS-only; the second (medium $P_{PL}$ and low SOC) is PS-only; the third (medium $P_{PL}$ and medium SOC) is one hybrid mode in which the PS is operated at its optimal value $P_{PSopt}$; the fourth (high $P_{PL}$) is the other hybrid mode in which the primary source is delivering its maximum power. The load-leveling mechanism and the value of $P_{PSopt}$ is defined as:

$$P_{PSopt} = P_{PL} - P_{th} \times ((SOC - SOC_{initial})/SOC_{range}) \tag{7}$$

![Figure 5. The diagram of OPSS rules.](image)

$P_{th}$ is the only parameter in the OPSS strategy. This parameter can be tuned according to the comparison of the PS and SS efficiencies, which is described detailly in reference [5].

4. Simulation Results
Three methods proposed above were all set up to simulate in the MATLAB/Simulink environment. The cycle we used in this simulation is displayed in figure 6, which is a combination of the CYCLE-L and CYCLE-M mentioned above.

![Figure 6. The speed profile of the cycle we built.](image)

To verify the effectiveness of the third strategy OPSS, we contrasted SOC statement and fuel consumption of the three strategy. The initial SOC is determined by 70%. The results are displayed in figure 7 and table 3.

![Figure 7. The SOC profiles for PFCS, ECMS and OPSS when driving the cycle.](image)
Table 3. The contrast of the fuel economy.

|               | PFCS  | OPSS  | ECMS  |
|---------------|-------|-------|-------|
| Fuel [kg]     | 1.118 | 1.083 | 1.132 |
| $SO_C_{final}$ [%] | 54.37 | 64.71 | 71.03 |
| $m_{EFC}$ [kg] | 1.290 | 1.165 | 1.121 |
| $\Delta m_{EFC}$ [%] | +15.1% | +3.9% | +0 |

The results show that all three control methods can satisfy the PL power demand of the vehicle in the simulation. In figure 4, the SOC manner of OPSS is much more stable than that of PFCS. In detail, the equivalent fuel consumption of OPSS has a 11.2% improvement than that of PFCS, and the equivalent fuel consumption of the ECMS has a 15.1% improvement than that of PFCS. Although the fuel economy of OPSS is no better than the ECMS, but they are not much different as we can see. At the same time, the method OPSS is only a kind of rule-based control strategy and only have one parameter to tune, which shows a much more convenient and easier than the mechanism of the method ECMS.

5. Conclusion
This paper uses a heuristic rule-based energy management applying on a series hybrid electric tracked vehicle. The new method, we called OPSS in this paper, was applied on the tracked vehicle model and the simulation was conducted in the environment of MATLAB/Simulink. Through the comparison of three energy management strategies mentioned in paper, we found OPSS method is a kind of easy rule-based strategy, which has its great advantages. Through the simulation results in a specific driving cycle, we found the OPSS had a very good performance in fuel consumption compared with the PFCS. Although the fuel economy of OPSS is no better than ECMS, while it is much easier than the optimization-based strategy and more appropriate in practical application. At the same time, the battery manner is also been compared with each other. It shows that the battery manner of OPSS is much closer to ECMS than the method PFCS. These results enlighten us to choose a proper rule-based control strategy and use a heuristic method to adjust the strategy for practical application in engineering.

References
[1] Anderson C and Pettit E 1995 The effects of APU characteristics on the design of hybrid control strategies for hybrid electric vehicles (no.950493) SAE Technical Paper
[2] Cuddy M R and Wipke K B 1997 Analysis of the fuel economy benefit of drivetrain hybridization SAE transactions pp 475-485
[3] Park J and Park J H 2012 Development of equivalent fuel consumption minimization strategy for hybrid electric vehicles International Journal of Automotive Technology 13 835
[4] Shabbir W and Evangelou S A 2016 Exclusive operation strategy for the supervisory control of series hybrid electric vehicles IEEE Transactions on Control Systems Technology 24 2190
[5] Shabbir W and Evangelou S A 2019 Threshold-changing control strategy for series hybrid electric vehicles Appl. Energy 235 761
[6] Luo C, Shen, Z, Evangelou S, Xiong G and Wang F Y 2019 The combination of two control strategies for series hybrid electric vehicles IEEE/CAA Journal of Automatica Sinica 6 596
[7] Shabbir W 2015 Control strategies for series hybrid electric vehicles (Doctoral dissertation, Imperial College London)