Research on Control Strategy of Series Hybrid Electric Vehicles

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Abstract: The paper presents the analysis of two basic control strategies, the series thermostat control strategy and the series power follower control strategy, used for series hybrid electric vehicles. One of these control strategies, the series thermostat control strategy, is programmed and installed in an electronic control unit to manage the power flow of a two-seat series hybrid electric vehicle designed and fabricated at Mechatronics Department, Nha Trang University, Vietnam. The main vehicle components are composed of an 110cc gasoline internal combustion engine, a 12V three-phase alternator and two 350W in-wheel brushless DC motors powered by batteries. The experiment was also conducted to get some performance parameters of our series hybrid electric vehicle.

Keywords: Control Strategy, Series Hybrid Electric Vehicles, Series Thermostat Control Strategy, Series Power Follower Control Strategy.

Introduction:
Nowadays, the global climate change and reduction of fossil fuel capacity have required the improvements of emissions and fuel consumption. Due to the inherent advantages of increased fuel economy, reduced harmful emissions and improved vehicle performance, hybrid electric vehicles (HEVs) powered by internal combustion engine (ICE) and batteries, are being given more and more attention. Comparing with two other basic kinds of hybrid electric vehicles, parallel hybrid electric vehicles and series-parallel hybrid electric vehicles, the series hybrid electric vehicles (SHEVs) have excellent transient performance and simple architecture, so it is a good choice for urban transportation means. The main objective of power management in SHEVs is to satisfy power requirement with the cooperation of batteries and ICE-generator set to get minimization of the corresponding fuel consumption and emissions. In reality, the improvements in fuel economy and emissions of SHEVs mainly depend on the control strategy. In general, power control strategies of SHEVs can be roughly grouped into two kinds. The first kind is rule-based algorithm, such as energy follow and thermostatic [4]. In energy follow strategy, the engine is always on, and it changes the energy output based on the energy requirement. The thermostatic control strategy obtains electric power through generator and engine, and it turns the engine on and off based on battery state of charge (SOC) [1]. This kind of control strategy works fast and reliable, but often produces results far away from an optimal control [3]. The second approach is real-time optimization such as Support Vector Machine (SVM). In SVM, the authors define 3 different SHEV operation modes and a cost function. After the SVM training process, they generate a classifier to determine which operation mode should be chosen during driving cycles based on the road situation data, the SOC data and vehicle speed data. The approach does not need models of SHEV devices, costs less computationally and is more efficient. These distinguished advantages make the approach more practicable in real-time operation [2]. In this paper, a two-seat series hybrid electric vehicle designed and fabricated at Mechatronics Department, Nha Trang University has been chosen for the hybrid configuration. The paper is organized as follows. In Section 2, the series hybrid electric vehicle configuration is reviewed. Section 3 describes the thermostat and power follower control strategies. The SHEV model is presented in Section 4. Section 5 adds some conclusions and future work.

2. Shev Configuration

Fig. 1: SHEV configuration
The configuration of a SHEV is shown in Fig. 1. The SHEV typically consists of an ICE mechanically linked with an electric generator to make an ICE-generator set. The electric motor plays the role of providing all the propulsion power. An energy storage system (ESS) or battery pack charged from the ICE-generator set will supply electric energy for a traction motor via a Switch controlled by an electronic control unit (ECU).

The demand power $P_d$ is calculated based on the vehicle characteristics and speed, the driver demand and the road situations. Assuming that, the motor input direction is defined as positive axis, its sign can be a positive, zero or negative depending on its current stage such as driving the wheels, stopping or regenerating power when braking. In order to maximize the fuel efficiency, minimize the emissions and satisfy the demand power $P_d$, the ECU has to determine the split of ICE-generator set power $P_g$ and battery power $P_b$. Similarly, the generator output direction and battery output direction are also defined as the positive axes of $P_g$ and $P_b$, respectively. In SHEV, $P_g$ is always nonnegative and $P_b$ can be positive, zero or negative. The basic equation is presented as follows: [2]

$$ P_d = P_g + P_b \quad (1) $$

In a SHEV, because of no mechanical connection between the ICE and drive wheels, the ICE is possible to be operated very close to maximum efficiency. At the same time, there are some energy conversion progresses existing in a series HEV. The mechanical energy of ICE is converted into electrical energy via the electric generator and the conversion of electrical energy into mechanical energy via the electric motor.

3. Shev Control Strategy

3.1 Series Thermostat Control Strategy

The series thermostat control strategy employs the ICE-generator set to generate electrical energy for charging ESS pack used by the vehicle. The series thermostat control strategy uses the ICE-generator set as follows: [1]

- The fuel converter turns on if the SOC is below the low limit, SOC$_L$.
- The fuel converter remains on until the SOC reaches the high limit, SOC$_U$, if its previous state $S_{ICE}(t-1)$ was on. After reaching the high limit, it turns off.
- The fuel converter operates at the most efficient speed and torque level as previously determined by the control file.

![Algorithm Flow of Series Thermostat Control Strategy](image)

![Power Follower Control Strategy](image)
3.2 Series power follower control strategy

In the Power Follower Control Strategy, the engine-generator set provides the main power for the SHEV. The ECU will control the output power of the engine-generator set to follow the vehicle’s driving power requirement. The engine-generator set has to run at almost all the working time of SHEV. However, if low driving power is required and the SOC is higher than \( SOC_u \), the engine-generator set is stopped working. Figure 3 shows the Power Follower Control Strategy.

The built-in series controls strategy offers flexibility in ICE operation [1]:
- The ICE may be turned off if the ESS pack SOC gets too high.
- The ICE may be turned on again if the power required by the driver gets high enough.
- The ICE may be turned on again if the SOC gets too low.

When the ICE is on, its power output tends to follow the required power, accounting for losses in the generator so that the generator power output matches the vehicle’s driving power requirement. However, the ICE output power may be adjusted by SOC, tending to bring the SOC back to the center of its operating range.
- The ICE output power may be kept above some minimum value.
- The ICE output power may be kept below some maximum value (which is enforced unless the SOC gets too low). The ICE output power may be allowed to change no faster than a prescribed rate.

4. Shev Model

The SHEV model shown in Fig.4 is designed and fabricated at Mechatronics Department, Nha Trang University. It consists of an 110cc gasoline internal combustion engine, a (12V: 1.5kW) three-phase alternator and two (48V: 350W) in-wheel brushless DC motors powered by battery set. The battery set includes four 12V batteries in series with the total capacity of 40Ah.

Because the alternator has lower output voltage (12V) than the motor operating voltage (48V) and the battery set, so the transformer was used to amplify the alternator voltage from 12V to 48V before.
charging for the batteries. The ECU using ATmega32 microcontroller was employed to acquire the pedal position, SOC. These signals were processed to control the motor speed and turn on/off ICE for battery charging. 

In order to test the performance parameters, the series thermostat control strategy was programmed and installed in the controller. Unfortunately, due to the lack of chassis dynamometer, some of basic performance parameters were measured and listed in the following table.

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Max. vehicle steady state speed</td>
<td>km/h</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>Total running hours in charge depleting mode</td>
<td>hour</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>Total running distance in charge depleting mode</td>
<td>km</td>
<td>94</td>
</tr>
<tr>
<td>4</td>
<td>Max. grade, speed of 25 km/h, people weight of 130kg</td>
<td>-</td>
<td>8%</td>
</tr>
<tr>
<td>5</td>
<td>Acceleration time from (0-35) km/h</td>
<td>s</td>
<td>9</td>
</tr>
</tbody>
</table>

5. Conclusion and future work
The research focuses on the descriptions of control strategies of SHEV, the series thermostat control strategy and the series power follower control strategy. Their algorithm flows were built and one of them, the algorithm flow of series thermostat control strategy, was programmed and installed into the ECU to manage the power flow of our two-seat SHEV model. The experiment was also conducted to test some performance parameters of SHEV model.

Future work that could build off of this research would include gathering all performance, fuel consumption, and emissions data for some full driving cycles such as FTP, UDDS, etc. Additionally, other control strategies with their different parameter values will be installed and tested on a chassis dynamometer to find the best optimal value of control strategy parameters.

References: