Shift Schedule Optimization for AMT of EVs based on Motor Efficiency

HUA SUN, XIAOFENG YIN, XIAOHUA WU and WEI LI

ABSTRACT

Based on the analysis of the characteristics of vehicle and the motor, a new method for calculating the best efficiency shift schedule was proposed for electric vehicles (EVs) with 3-speed AMT. The proposed shift schedule was tested and compared with the best dynamic performance shift schedule through acceleration and ECE+EUDU driving cycle simulation using MATLAB/Simulink software. The simulation results demonstrate that the best efficiency shift schedule improves the economic performance by 6.91%, but reduces the dynamic performance by 7.43%, which is more suitable for economic driving style.

INTRODUCION

With the popularity of electric vehicles (EVs) and the development of automatic transmission technology, more and more EVs have been equipped with automatic transmissions, as it is vitally significant for reducing the demands on motor size and power by making full use of the advantages of both motor and automatic transmission.

Similarly to traditional vehicles, shift schedule is the critical technology of shift control strategy. The dynamic performance and economic performance are always considered in current studies on shift schedule, such as the dynamic shift schedule [1, 2], and the comprehensive shift schedule considering both dynamics and economy [3], while the influence of motor efficiency is less considered. In this paper, a method of calculating best efficiency shift schedule is formulated for EVs with a 3-speed Automated Manual Transmission (AMT).

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POWERTRAIN PARAMETERS MATCHING METHOD

Powertrain system of the investigated EV consists of a driving motor and an AMT, so it’s necessary to match the main parameters of the motor and the ratios of the transmission system before shift schedule optimization.

Motor Parameters

The main parameters of driving motor are rated speed, peak speed, rated power and peak power.

The demanded power $P_1$ for EVs running at the maximum speed is

$$P_1 = \frac{u_{amax}}{3600\eta_T} \left( mgf + \frac{C_D A u_{amax}^2}{21.15} \right)$$  \hspace{1cm} (1)

Where, $u_{amax}$ is the maximum speed (km/h), $m$ is the vehicle mass (kg), $f$ is the rolling resistance, $C_D$ is aerodynamic drag, $A$ is the frontal area (m$^2$), $\eta_T$ is the mechanical efficiency of the transmission system.

The demanded power $P_2$ for EVs corresponding to climbing the maximum ramp with $u_a$ is defined as

$$P_2 = \frac{u_a}{3600\eta_T} \left( m gf \cos \alpha_{max} + mg \sin \alpha_{max} + \frac{C_D A u_{amax}^3}{21.15} \right)$$  \hspace{1cm} (2)

Where, $u_a$ is the steady speed on the ramp (km/h), $\alpha_{max}$ is the maximum slope.

The demanded power $P_3$ for EVs speeding up on a level road is as

$$P_3 = \frac{1}{3600\eta_T} \left( \delta m u_{am}^2 + mgf u_{am} + \frac{C_D A u_{am}^3}{21.15 \times 2.5} \right)$$  \hspace{1cm} (3)

Where, $\delta$ is the equivalent coefficient of vehicle rotating mass, $u_m$ is the ending speed during acceleration (km/h), and 100 km/h is chosen in this paper, $t_m$ is the maximum acceleration time (s).

The rated power $P_e$ and the peak power $P_{max}$ of motor should satisfy

$$\begin{cases} P_e \geq P_1 \\ P_{max} \geq \max(P_2, P_3) \end{cases}$$  \hspace{1cm} (4)

After getting $P_e$ and $P_{max}$, the rated and peak speed of motor can be determined according to the characteristics of the driving motor, the maximum
and common vehicle speeds.

**AMT Gear Ratios**

Once the output characteristics of motor are constant, the ratios of transmission are compromised to achieve the performance indicators.

The minimum ratio $i_{\text{min}}$, which is the top gear ratio, should be able to ensure the vehicle reaching the top speed, and it is according to the top vehicle speed $n_{\text{max}}$ and the peak output speed of motor $u_{\text{amax}}$ as

$$i_{\text{min}} \leq \frac{0.377 n_{\text{max}} r}{u_{\text{amax}}} \quad (5)$$

The maximum ratio $i_{\text{max}}$ is determined through the maximum output torque of the motor $T_{\text{max}}$ and the maximum travel resistance $F_{\text{tmax}}$ on the ramp as

$$i_{\text{max}} \geq \frac{F_{\text{tmax}} r}{\eta T_{\text{max}}} \quad (6)$$

Based upon the characteristics of the motor and the vehicle performance indicators, a 3-speed AMT is used to keep the driving motor working in the high efficiency area as much as possible. Generally, the top gear is set to be the direct gear. The minimum gear is selected based on the maximum transmission ratio, and the middle gear is determined according to both the gear number and geometric progression.

**SHIFT SCHEDULE CALCULATING METHODS**

Generally, there are three types of shift schedules: single-parameter shift schedule, two-parameter shift schedule and three-parameter shift schedule. In this paper, a best dynamic performance shift schedule and a best efficiency shift schedule based on vehicle speed and the throttle are calculated. The best dynamic performance shift schedule is used for comparison purpose.
Best Dynamic Performance Shift Schedule

Graphical method and analytical method are two often used methods for developing dynamic shift schedules. In order to get the best dynamic performance, the intersection point of adjacent gear acceleration curves at the same throttle condition is usually chosen as the shift point, as point A in Figure 1. If there is no intersection point, the end point of acceleration curve of the lower gear at the same throttle condition will be chosen as the shift point, as point B in Figure 2.

Best Efficiency Shift Schedule

Motor efficiency is the ratio of motor output power to its input power, and it reflects the amount of internal power loss. Since the economic performance of a motor mainly depends on its operating efficiency, the best efficiency shift schedule is to keep motor working in the high-efficiency area as much as possible. When the speed is low, the motor efficiency corresponding to low gear is higher than that of high gear at the same throttle positions. With the speed increasing, the motor efficiency corresponding to high gear becomes higher than that of low gear then. If the same motor efficiency of adjacent gears at the throttle positions is served as the shift points, the driving motor will work in the high-efficiency area. Consequently, the method to determine the best efficiency shift schedule is as follows: Fitting the motor efficiency curves of each gear at different throttle conditions; getting the intersection points of adjacent gear efficiency curves at every throttle condition based on all the combinations of throttle conditions and adjacent gears. The main calculating program is shown in Figure 3.

If there is no speed difference between the upshift speed and the downshift speed, AMT will shift frequently and gears may be worn. To overcome this shortcoming, a divergent downshift schedule with forced low gear is designed [4].
CALCULATION EXAMPLE

Powertrain Parameters

Based on the vehicle parameters and required performance indicators, the matching results of powertrain system are listed in Table I.

Shift Schedules

With the powertrain parameters, the best dynamic performance shift schedule and the best efficiency shift schedule are calculated using the proposed methods. The best dynamic performance shift schedule and the best efficiency shift schedule are shown in Figure 4 and Figure 5 respectively.

TABLE I. PARAMETERS AND MATCHING RESULTS.

<table>
<thead>
<tr>
<th>Parameters and matching results</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle mass $m$</td>
<td>1750kg</td>
</tr>
<tr>
<td>Tire radius $r$</td>
<td>0.316m</td>
</tr>
<tr>
<td>Rolling resistance $f$</td>
<td>0.015</td>
</tr>
<tr>
<td>Aerodynamic drag $C_D$</td>
<td>0.32</td>
</tr>
<tr>
<td>Frontal area $A$</td>
<td>2m$^2$</td>
</tr>
<tr>
<td>The top speed $u_{\text{max}}$</td>
<td>135km/h</td>
</tr>
<tr>
<td>Acceleration time of 0-100km/h $t$</td>
<td>13.5s</td>
</tr>
<tr>
<td>Motor rated/peak power(kW)</td>
<td>42/85</td>
</tr>
<tr>
<td>Motor rated/peak speed(r/min)</td>
<td>3000/6100</td>
</tr>
<tr>
<td>Motor rated/peak torque(N·m)</td>
<td>134/270</td>
</tr>
<tr>
<td>AMT 1st gear ratio $i_1$</td>
<td>1.75</td>
</tr>
<tr>
<td>AMT 2nd gear ratio $i_2$</td>
<td>1.32</td>
</tr>
<tr>
<td>AMT 3rd gear ratio $i_3$</td>
<td>1</td>
</tr>
<tr>
<td>The gear ratio of final drive $i_0$</td>
<td>5.1</td>
</tr>
</tbody>
</table>
SIMULATION RESULTS

To evaluate these shift schedules an EV powertrain model is constructed using the MATLAB/Simulink software. The model contains the modules of an ECE+EUDC driving cycle, a driving motor, an AMT, the vehicle longitudinal dynamics and shift logic [4].

For comparison of the dynamic performance, acceleration tests from 0-100 km/h were performed using the best dynamic performance shift schedule and the best efficiency shift schedule respectively. As shown in Figure 6, the acceleration time of the best efficiency shift schedule is 13.45 s, and that of the best dynamic performance shift schedule is 12.52 s.

To evaluate the economic performance, the energy consumption corresponding to the best dynamic performance shift schedule and the best efficiency shift schedule under an ECE+EUDC (Economic Commission for Europe and the Extra Urban Driving Cycle) driving cycle simulation were calculated respectively. In the simulation, the test vehicle was controlled to follow the speed specified by the driving cycle shown as Figure 7.
The simulation results are presented in Table II. The energy consumption corresponding to the best efficiency shift schedule is 6.33 kW·h, which is less than that to the best dynamic performance shift schedule. The results demonstrate that the working points of motor have been optimized to relatively high-efficiency area, which improves the average operating efficiency of the powertrain.

<table>
<thead>
<tr>
<th>Shift schedules</th>
<th>Energy consumption (kW·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best dynamic performance shift schedule</td>
<td>6.80</td>
</tr>
<tr>
<td>Best efficiency shift schedule</td>
<td>6.33</td>
</tr>
</tbody>
</table>

CONCLUSION

Based on the analysis of the driving motor characteristics of EVs, a new calculating method for a 2-parameter shift schedule based on the motor efficiency was put forward. The best efficiency shift schedule for a 3-speed EV was calculated using the proposed method. And the best dynamic performance shift schedule was also calculated for comparison purpose.

The shift schedules calculated above were applied to the powertrain model in the Simulink environment of MATLAB. The results of acceleration and an ECE+EUDC driving cycle simulation demonstrate that the best efficiency shift schedule can significantly improve the economic performance of vehicle by 6.91%, at the expense of dynamic performance reduction by 7.43%. The best efficiency shift schedule is more suitable for economic driving style.

ACKNOWLEDGEMENTS

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