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RESEARCH ARTICLE

# Study on the Design and Speed Ratio Control Strategy of Continuously Variable Transmission for Electric Vehicle

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**ABSTRACT** In order to develop continuously variable transmission (CVT) suited for electric vehicle (EV), a comparative analysis of the transmission used on EV is introduced in this paper. To solve the problems of traditional CVT used for EV, a newly designed electric CVT (ECVT) is proposed. The final drive ratio, speed ratio range of variator and hydraulic system of ECVT are redesigned for improving the transmission efficiency. Considering that the permanent magnet synchronization traction motor (PMSTM) of EV has an ideal driving characteristic (Constant torque at low speed, constant power at high speed) and wider high efficiency area compared with gasoline engine, the speed ratio control strategy of ECVT is studied again for improving the vehicle driving range and better meeting the requirements of driver. Finally, a simulation test system is fabricated for evaluating the battery energy consumption of an EV equipped with ECVT and single-speed transmission (SST) under constant speed and road drive cycle. The simulation results show that the ECVT proposed can extend the endurance mileage of EV at the speed of 20 to 90km/h, and improve the acceleration performance from 0 to 50km/h. The EV equipped with ECVT showed more advantages compared with SST in urban conditions.

**INDEX TERMS** Continuously variable transmission, electric vehicle, speed ratio control strategy, vehicle performance.

## NOMENCLATURE

| | |
|---|---|
| $a_{\text{ve}}$ | Vehicle acceleration. |
| $eff_{\text{vr}}$ | Efficiency of CVT. |
| $eff_{\text{tm}}$ | Efficiency of PMSTM. |
| $h_{\text{ap}}$ | Percentage of accelerator pedal (%). |
| $h_{\text{tv}}$ | Percentage of throttle (%). |
| $i_{\text{fd}}$ | Speed ratio of final drive. |
| $i_{\text{vr}}$ | Speed ratio of CVT. |
| $m$ | Vehicle mass (kg). |
| $n_{\text{en}}$ | Engine speed (rpm). |
| $n_{\text{tm}}$ | PMSTM speed (rpm). |
| $P_f$ | Power of rolling resistance (kW). |
| $P\text{w}$ | Power of wind resistance (kW). |
| $P\text{i}$ | Power of slope resistance (kW). |
| $P_{\text{tm}}$ | PMSTM output power (kW). |
| $P_{\text{tms}}$ | Demand Power from PMSTM (kW). |
| $r_{\text{wh}}$ | Wheel radius (m). |
| $T_{\text{en}}$ | Engine output torque (Nm). |
| $T_{\text{tm}}$ | PMSTM output torque (Nm). |
| $T_{\text{tms}}$ | Demand torque from PMSTM (Nm). |
| $u_{\text{ve}}$ | Vehicle speed (km/h). |
| $\delta$ | Rotational inertia coefficient. |

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## I. INTRODUCTION

With the promulgation of more stringent emission regulations in various countries and the continuous progress of electrical motors and battery industries, more and more vehicle manufacturers have formulated their route schemes in the electrification of vehicles, including both all-electric and hybrid solutions. Hybrid electric vehicles have been widely popularized since their charging time is relatively short and could also meet the phased energy-saving requirements, such as Toyota's hybrid system (THS) [1], [2] for Prius, Honda's Intelligent Multi-Mode Drive (IMMD) [3] for ACCORD and CRV, Hyundai's parallel hybrid system [4], [5] for Sonata, and General Motor' two-mode hybrid transmission [6], [7] for Chevrolet volt. However, with the rapid development of electric drive technologies, mainstream companies of automobile industry are shifting most of their production capacity to EV. PMSTM being widely employed as powertrains of EV, have superior performance in both low-speed constant torque and high-speed constant power regions. In another word, the powertrain of EV has less dependence on the transmission than the traditional internal combustion engine. At present, most mainstream EV adopt the SST technology as a balance between the cost and performance. However, the SST unable to meet more complex needs such as PMSTM working at the optimal point, a reduction of noise caused by higher rotational speed, and better dynamic performance in acceleration. Thus, in order to meet the above demands, numerous researches are now focusing on the application of multi-speed transmission (MST) in EV.

Except for SST, current transmission systems used on EV can be mainly classified into three types viz. two-speed transmission (TST), MST and CVT, according to their number of transmission gears. Since the PMSTM usually has quite good driving characteristics, most the state-of-the-art researches are now focusing on the TST. For example, in [8], [9], [10], and [11], a comparison study between the TST and SST on the driving range under various driving cycles is conducted, of which an investigation on the improvement of climbing performance is conducted in [8] and [9]. In [12], [13], and [14], the shift process control of TST is investigated, whereas it shows that the smoothness of the shift process and the transmission of torque at high speeds are difficult to guarantee in real applications. A further comparative study on the performance improvement of MST against SST and TST is conducted in [15], [16], and [17], which manifests that the MST has a superior performance on the driving range under various driving cycles. In [18] and [19], a shifting controller for MST and a dynamic model of MST for analyzing the dynamic process of shifting are proposed, respectively. In [15] and [20], it is found that the size of PMSTM can be reduced via. the application of MST while the acceleration performance of vehicle remains unchanged.

Other than the MST, the application of CVT has also been widely reported recently [15], [21], and it shows better performance than the conventional SST in driving range and can also achieve a lower comprehensive cost. Further, a comparative study in [22] and [23] manifests that the EV equipped with traditional CVT cannot improve the driving range due to its lower efficiency compared with the vehicle with SST, unless the efficiency of traditional CVT is improved. In [24], a toroidal continuously variable transmission (TCVT) is proposed, which has a higher efficiency than SST in low-speed high-torque region and can achieve higher speed in low torque region. Thus, compared with the conventional SST, the TCVT can achieve a higher driving mileage and average speed in driving cycles such as NEDC and HWFET. In [25], an electric CVT shifting by electrical motor is proposed and used in EV, which shows better performance at acceleration process than the conventional TST. This type of CVT cooperating with a speed ratio braking control strategy is also studied in [26], and it can be found that the energy recovery rate during regenerative braking has been improved compared with TST.

From the above analysis, it is obvious that multi-speed transmission techniques can be effective in the improvement of acceleration performance, driving mileage, and also can reduce the overall size of PMSTM. It also can be concluded from [1], [2], [3], and [27] that a combination of multi-speed transmission and high-voltage drive motor can be a quite

**TABLE 1. Comparison of different technical solutions.**

| Item | SST | TST | MST | Traditional CVT | Proposed ECVT |
|---|---|---|---|---|---|
| Cost | low | middle | high | high | middle |
| Power interruption | without | strong | slight | without | without |
| Transmission efficiency | high | middle | middle | low | middle |
| Dynamic performance | general | better | much better | much better | much better |
| Economic performance | general | better | much better | depend on efficiency | much better |

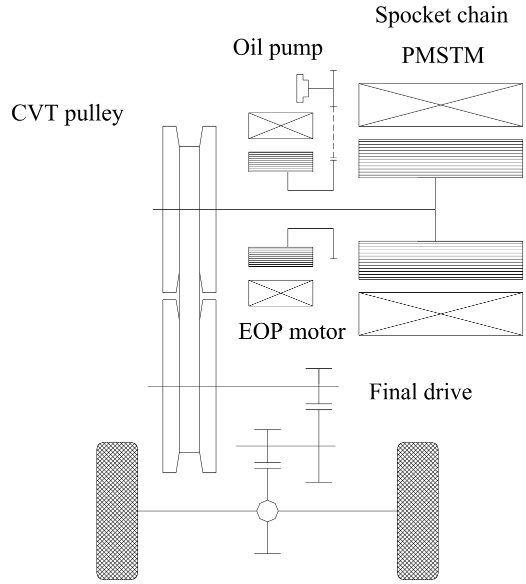


**FIGURE 1. Schematic diagram of ECVT powertrain.**

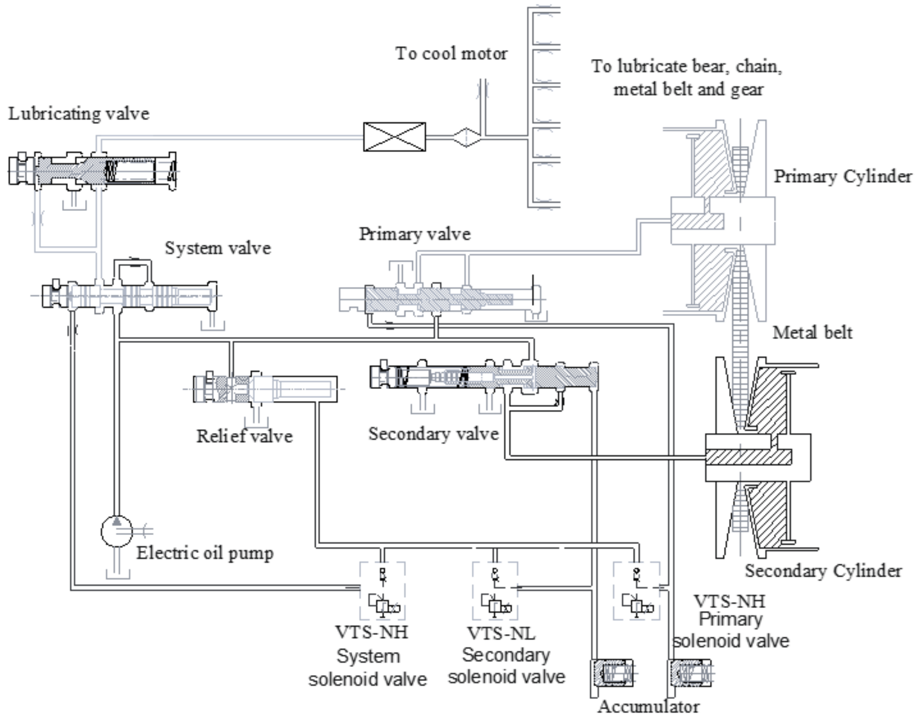


**FIGURE 2.** Schematic diagram of ECVT hydraulic system.

competitive solution for improving the powertrain performance and reducing the overall size of motor system.

Although much more research work has been carried out about TST, MST and CVT as summarized by [28], there is no mass production of TST and MST on EV. There are not only technical problems, but also cost and other reasons. For two-speed dual clutch transmission (DCT) or automatic transmission (AT), it is difficult to shift by slipping clutch when the PMSTM speed more than 3000 rpm, and this will interrupt power transmission. This is a big disadvantage in terms of comfort, compared with SST for passenger cars. Multi-speed DCT and AT still have the problem of power interruption on gear shifting when PMSTM speed is high, and the cost increased with the gear numbers. CVT as a continuously variable transmission device, can deliver power continuously in the process of shifting in principle. But the low transmission efficiency is the main drawback. This even drawn opposite conclusions like literature [21] and [22]. By optimizing the structure, hydraulic system and clamping force control strategy of CVT, the transmission efficiency can be significantly improved, while quantitatively indicating whether CVT can save energy.

In this paper, an ECVT scheme based on the optimization of both speed ratio control and ratio range of variator is proposed, which aims to improve the overall efficiency of powertrain by taking into account factors such as electric oil pump (EOP) and CVT experimental test [29], [30], [31]. Table 1 summarizes the advantages and defects of mainstream technical solutions and the proposed ECVT from different dimensions. The proposed ECVT has better performance and lower cost compared with traditional CVT. The economic and dynamic performance of EV with ECVT is finally verified by a proposed simulation test system. ECVT has better economic performance at 20 to 90 km/h and shows a 21% decrease of time in the acceleration process from 0 to 50km/h. The road cycle simulation results also show the advantage of ECVT at urban drive area.

## II. ELECTRIC CVT

### A. STRUCTURE OF ECVT

ECVT is designed by modifying traditional CVT. The drive, neutral and reverse (DNR) clutch and hydraulic torque converter of traditional CVT are removed for the PMSTM has the ability of forward and reverse rotation and output large torque at low speed. Because the PMSTM of EV can work at zero speed, the mechanical oil pump driven by engine on traditional CVT is replaced by an EOP to provide sufficient hydraulic flowrate for each actuator at vehicle launch. In order to save the cost of the hydraulic control block, the hydraulic schematic diagram of ECVT has been redesigned, the clutch and torque converter control circuit and relevant valves on traditional hydraulic block are removed. The PMSTM connected with the input shaft of ECVT through splines. Fig. 1 is the schematic diagram of ECVT powertrain with PMSTM.

### B. HYDRAULIC SYSTEM OF ECVT

Fig. 2 is the schematic diagram of the hydraulic system of ECVT. The power source of the hydraulic system is provided by an EOP. The system, primary and secondary pressure are

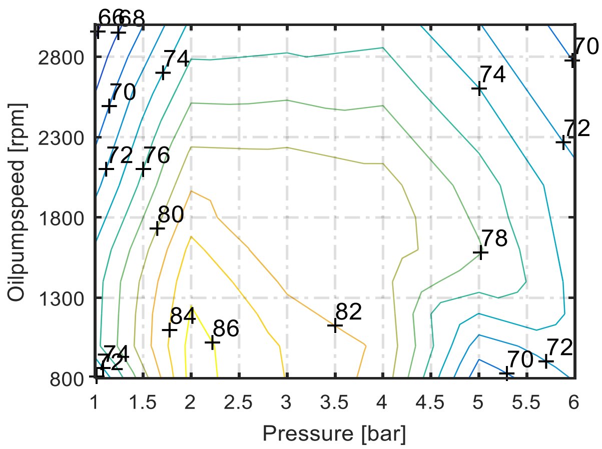


**FIGURE 3.** Efficiency map of the EOP oil pump.

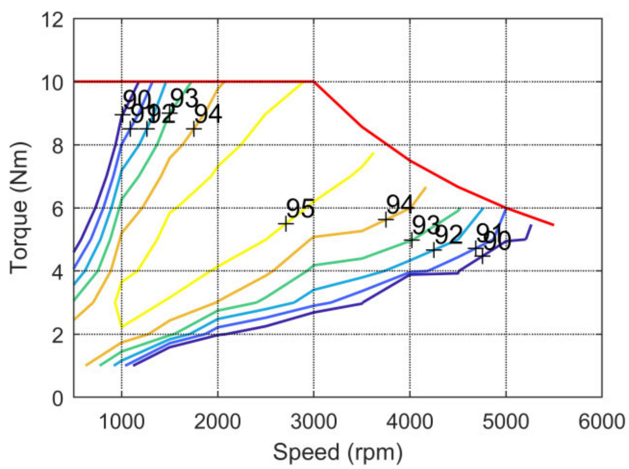


**FIGURE 4.** Efficiency map of the EOP motor.

controlled by three solenoid valves respectively to realize the ECVT function of shifting and transmitting torque. To avoid the pressure fluctuations of the primary and secondary cylinder, an accumulator is added to the corresponding solenoid valve control oil circuit. The flowrate provided by the EOP is divided into three parts: one part is supplied to the input of each solenoid valve control circuit through pressure relief valve; one part is supplied to the primary and secondary cylinder through the primary and secondary valve; the other part is supplied to the lubrication and cooling circuit through the overflow valve to cool and lubricate the metal belt, bearing, oil pump motor and gear.

### C. ELECTRIC OIL PUMP

The maximum pressure of the hydraulic system is designed to be 6 MPa to ensure the demand of clamping variator and changing speed ratio under emergency conditions. According to the flowrate demand of shifting, cooling and lubricating, the maximum design flow is 20 L. Table 2 is the parameters of the designed EOP. The EOP is integrated in the ECVT, and the oil pump motor is connected with the oil pump through a sprocket chain.

**TABLE 2.** Parameters of the designed Eop.

| Description | Value/Unit |
|---|---|
| Displacement | 7.5 mL/rpm |
| Sprocket chain ratio | 1.08 |
| Maximum power | 2.5 kW |
| Maximum speed | 2500 rpm |
| Maximum pressure | 6 Mpa |

**TABLE 3.** Vehicle parameters.

| Description | Value/Unit |
|---|---|
| Vehicle mass | 1505 kg |
| Area | 2.13 $m^2$ |
| Wind coefficient | 0.2409 |
| Rolling coefficient | 0.0087 |
| Wheel radius | 0.3065 m |

**TABLE 4.** Vehicle performance parameters.

| Description | Value/Unit |
|---|---|
| Maximum speed | 155 km/h |
| Mileage | 450 km |
| Acceleration time (0-50km/h) | 3.8 s |
| Grade | 30% |

**TABLE 5.** Parameter of PMSTM.

| Description | Value/Unit |
|---|---|
| Rated power | 60kW |
| Maximum power | 120 kW |
| Rated torque | 143 Nm |
| Peak torque | 286 Nm |
| Rated speed | 4000 rpm |
| Peak speed | 12000 rpm |

The efficiency map of the EOP can be measured by experiments. Fig. 3 is the efficiency map of the oil pump, which is a combination of mechanical efficiency and volumetric efficiency. The rotor vane pump is used in the oil pump design. It can be seen from the figure that the high efficiency area of the oil pump is mainly concentrated at the range of 1.5 to 4 MPa and 800 to 2000 rpm, and the comprehensive efficiency is mostly higher than 80%.

Fig. 4 is the oil pump motor efficiency map of the EOP. In order to improve the overall efficiency of hydraulic system, the EOP motor is a permanent magnet synchronous motor, which has a high efficiency area, up to 95%.

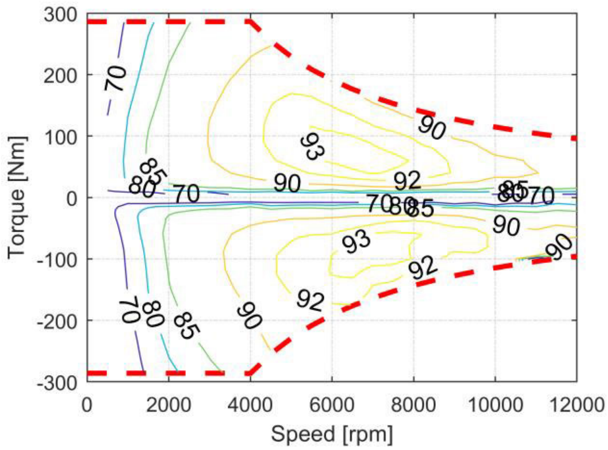


**FIGURE 5.** Comprehensive efficiency map of the PMSTM.

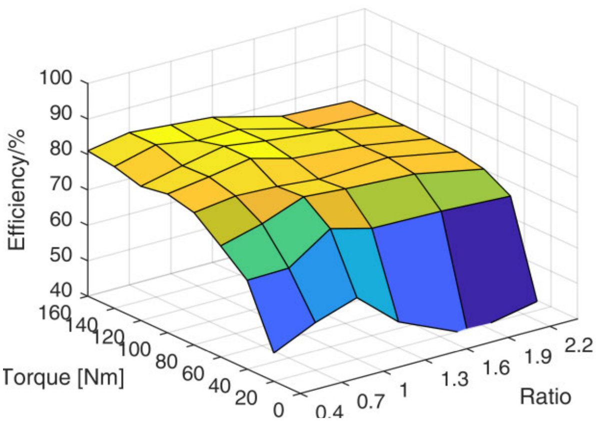


**FIGURE 6.** Efficiency map of the traditional CVT at 3000 rpm.

## III. SPEED RATIO DESIGNE

### A. VEHICLE PERFORMANCE TARGET

In order to design the speed ratio of ECVT, the performance parameters of an EV equipped with SST are taken as the design objective. The speed ratio of SST is 9. Table 3 and 4 are the parameter and performance objectives of the vehicle respectively. Table 5 is the PMSTM parameters of the EV, and Fig. 5 is the comprehensive efficiency map of the PMSTM and its controller of the designed vehicle.

### B. FINAL DRIVE SPEED RATIO

For PMSTM, the high-efficiency area is very wide, and the efficiency gradient is small in the high-efficiency area. Therefore, it is not necessary to change the speed ratio in a large range to adjust the working point of the PMSTM to reduce the energy consumption of the vehicle. Moreover, the characteristics of output maximum torque at low-speed indicate that it is not necessary to use a large speed ratio like the traditional CVT to meet the requirements of vehicle launching and climbing at low speed. So, the speed ratio range of ECVT can be adjusted. Fig. 6 shows the efficiency map

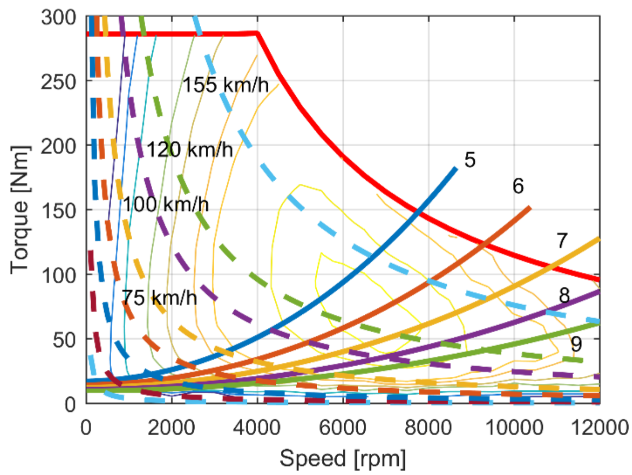


**FIGURE 7.** Vehicle resistance curve under different final drive ratios.

**TABLE 6.** Speed ratio of ECVT.

| Traditional CVT variator | ECVT variator | Final drive | Total speed ratio range |
|---|---|---|---|
| 0.4-2.3 | 0.6-1.8 | 6.12 | 3.67-11.02 |

of the traditional CVT under different torque and speed ratio at 3000 rpm. The efficiency at both ends of the speed ratio is lower than other, and it reaches the maximum near the speed ratio 1. Therefore, in order to improve the efficiency of EV powertrain, the speed ratio range of ECVT should be redesigned.

In order to design the speed ratio range of ECVT, the final drive ratio should be determined first. It is expected that when the speed is 60 to 120 km/h, both the motor and ECVT will work at the high efficiency area to improve the powertrain efficiency. From Fig. 6 we can see that traditional CVT has maximum efficiency at speed ratio 1, and the final drive ratio is the total speed ratio of the powertrain. Under this speed ratio, the optimal efficiency of the powertrain can be guaranteed by ensuring that the PMSTM works in the high efficiency area as much as possible by adjusting appropriate final drive ratio.

Fig. 7 shows the mapping of driving resistance curve on PMSTM efficiency map under different final drive ratios, the slope resistance is not taken into account. The bold-solid line is the driving resistance curve when the final drive ratio is 5, 6, 7, 8 and 9 respectively with ECVT speed ratio at 1. The bold-dotted line is the iso-power curve with the same vehicle speed. The intersection of the bold-solid line and the bold-dotted line is the PMSTM working point under the balanced vehicle speed. It can be seen from the figure that the driving resistance curve with final drive ratio 6 passes through the center of the contour line of the highest efficiency area. The PMSTM can work at more higher efficiency point under this final drive ratio than others, so the final drive ratio is set at about 6. Considering the constraints of gear parameters, the final drive ratio is 6.12.

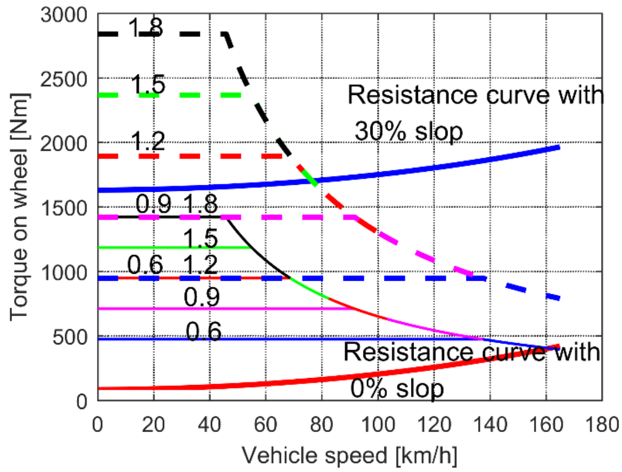


**FIGURE 8.** Driving torque at wheel with different ECVT speed ratio.

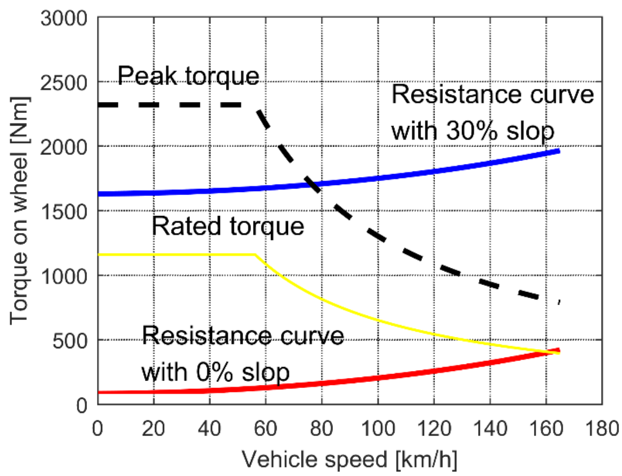


**FIGURE 9.** Driving torque at wheel of SST.

### C. SPEED RATIO RANGE OF ECVT

The original speed ratio range of variator of the traditional CVT is 0.4 to 2.3, it is close to an AT with 6 gears. Considering that the PMSTM has wide high efficiency area, there is no need to use such a large speed ratio range. A speed ratio range of 3 equivalent to the AT with 3 or 4 gears can meet the needs of optimizing the working point of the PMSTM. Fig. 6 shows that the CVT has higher efficiency near speed ratio 1 and lower efficiency near the end. Therefore, the range of the speed ratio of ECVT is selected as 0.6 to 1.8, and then the feasibility of the range is verified by the constraints of climbing slope and maximum speed. Table 6 is the designed speed ratio of ECVT.

### D. SPEED RATIO VERIFACATION

Fig. 8 and 9 respectively shows the drive torque curve and resistance curve at wheels of ECVT and SST. In Figure 8, the bold-dotted line is the driving torque curve of ECVT at different speed ratio with the peak torque of PMSTM, and the thin solid line is driving torque curve with the rated

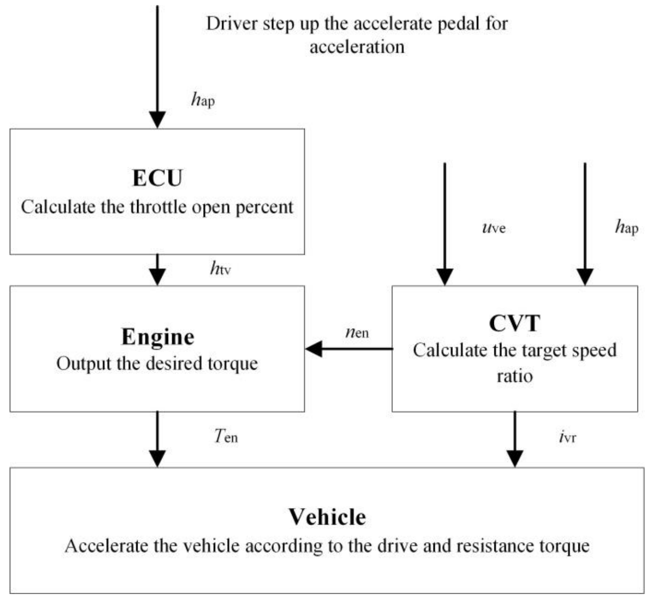


**FIGURE 10.** Control flow block of traditional Vehicle acceleration.

torque. The thick red and blue solid lines are the resistance curve with 0 and 30% slop respectively. It can be seen from the figure that the rated driving torque curve intersects the vehicle's resistance curve at around 160 km/h, so the designed ratio range of ECVT meets the requirements of maximum vehicle speed. When the speed ratio of ECVT is 1.8, the maximum driving torque curve corresponding to the peak torque is higher than the resistance curve with 30% slop, which indicates that the climbing performance of the vehicle is guaranteed. In summary, the designed ratio range of 0.6 to 1.8 can satisfy the performance requirements previously proposed. Comparing Fig. 8 and 9, we can see that the driving and climbing capability of EV with ECVT is better than that with SST. ECVT can improve the dynamic performance of EV.

## IV. SPEED RATIO CONTROL STRATEGY

The accelerator pedal is the key for the driver to control the vehicle speed and acceleration. For a traditional passenger car, the output torque of engine is controlled by the distance of accelerator pedal. However, it is also affected by the engine speed. So, the output torque may not meet the needs of driver, if the gear setting is unreasonable. Fig. 10 is the block diagram of the acceleration control of a traditional CVT. For PMSTM, the output torque or power has the possibility to decouple with vehicle speed, so the speed ratio control strategy of ECVT need to be studied.

The balance equation of vehicle driving and resistance power can express as follow:

$$P_{\mathrm{tm}} = \frac{1}{\mathit{eff}_{\mathrm{vr}}}(P_{\mathrm{f}} + P_{\mathrm{w}} + P_{\mathrm{i}} + \frac{\delta m u_{\mathrm{ve}}}{3600} a_{\mathrm{ve}}) \tag{1}$$

It can be seen from the equation (1) that when the speed is $u_{\mathrm{ve}}$, the acceleration is only related to the output power of $P_{\mathrm{tm}}$, no matter what gear the transmission is if the influence of $\delta$

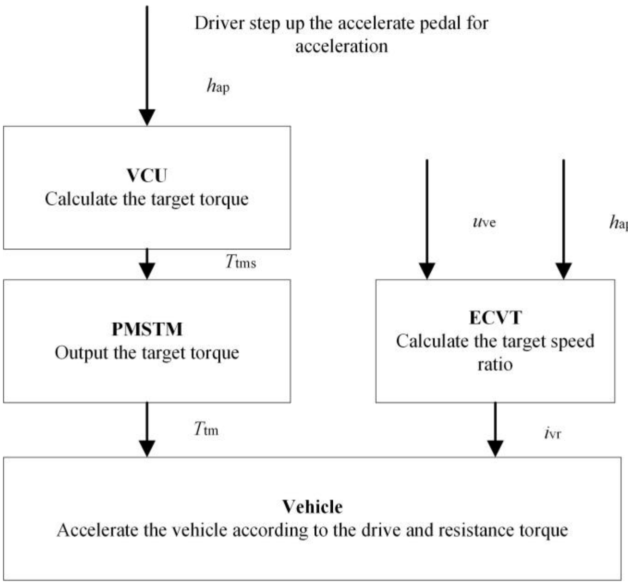


**FIGURE 11.** Control flow block of EV acceleration with APT.

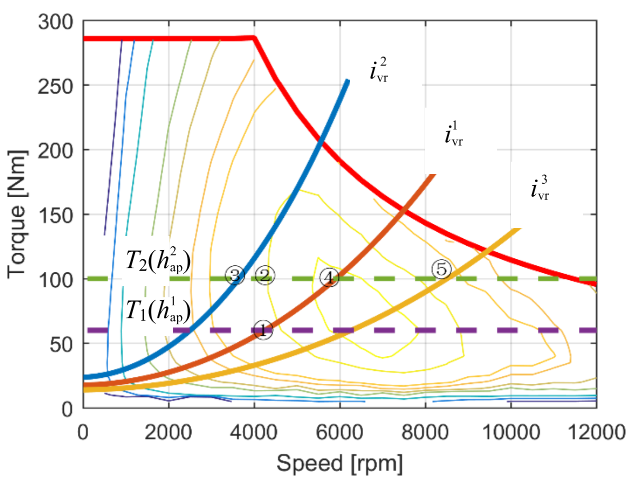


**FIGURE 12.** Speed ratio control diagram on APT control strategy.

and $eff_{\mathrm{vr}}$ is ignored. Therefore, if the output power of PMSTM keep constant, the acceleration will not affect by the speed ratio of ECVT, and the speed ratio control strategy can only consider how to optimize the working point of PMSTM. For EV, the signal of accelerator pedal can be translated directly as the power or torque demand for PMSTM instead of the throttle percentage of traditional fuel vehicle. So, the control strategies of speed ratio will be different from traditional vehicle. Depending on whether the accelerator pedal signal is translated into torque or power demand, there are two possible control methods for speed ratio.

### A. ACCELERATOR PEDAL – TORQUE CONTROL STRATEGY (APT)

When the accelerator pedal signal is translated into torque demand, the PMSTM output torque corresponds to the accelerator pedal. Fig. 11 is the control flow block of APT control

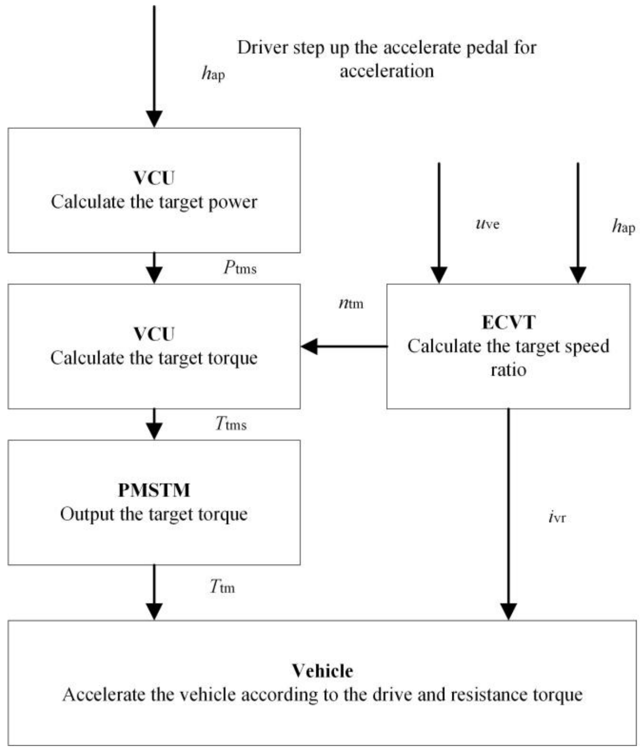


**FIGURE 13.** Control flow block of EV acceleration with APP.

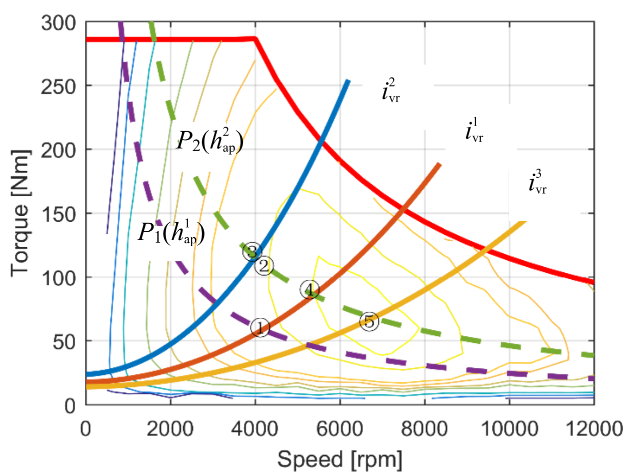


**FIGURE 14.** Speed ratio control diagram on APP control strategy.

strategy. The output power and torque are related as follows:

$$T_{\mathrm{tm}} = f(h_{\mathrm{ap}}) \tag{2}$$

$$P_{\mathrm{tm}} = \frac{i_{\mathrm{fd}} u_{\mathrm{ve}}}{3600 r_{\mathrm{wh}}} i_{\mathrm{vr}} T_{\mathrm{tm}} \tag{3}$$

Fig. 12 is a schematic diagram of speed ratio control with APT control strategy. It is assumed that when the accelerator pedal is $h_{\mathrm{ap}}^1$, the vehicle works stably at point ① , the driving resistance of the vehicle with speed ratio $i_{\mathrm{vr}}^1$ is balanced with the driving toque $T_1$. When the driver adjusts the accelerator pedal to $h_{\mathrm{ap}}^2$, it means acceleration is required. In order to ensure that the acceleration requirements can be met quickly, the PMSTM working point can be directly adjusted from point ① to ②. The difference between points ② and ① is the torque will transmit to the wheel for acceleration. When the output torque is $T_2$, the PMSTM can work at points ②, ③, ④ and ⑤ with different speed ratio. When the PMSTM moving from point ② to point ④, if the speed ratio is not changed, the speed of the PMSTM can only be increased with the vehicle speed. When the working point of the PMSTM reaches point ④, the resistance torque and the output torque are balanced at the wheel, and the vehicle will no longer accelerate. If hope the PMSTM works at point ⑤, the speed ratio should be increased from $i_{\mathrm{vr}}^1$ to $i_{\mathrm{vr}}^3$, and finally the working point of the PMSTM will be stable at point ⑤. From the analysis above, we can know that when the PMSTM output torque $T_2$, there are many possible vehicle stable speeds, the acceleration performance is affected by the speed ratio control strategy. To better satisfy the requirements of driver, the speed ratio control strategy can be specified according to the change rate of accelerator pedal. When the change rate of accelerator pedal is fast, the PMSTM should output more power to satisfy the driver's demand for acceleration, so the speed ratio of ECVT should be controlled higher than stable state at the acceleration process, such as $i_{\mathrm{vr}}^3$. When the change rate of accelerator pedal is slow, the speed ratio can be controlled to $h_{\mathrm{vr}}^i$. When the change rate of accelerator pedal is zero, the speed ratio can be controlled at the balanced point, such as $i_{\mathrm{vr}}^1$. From the analysis above we can know that the APT control strategy can't fully and directly show the driver's intentions for acceleration, for the acceleration power will affect by the accelerator pedal but also the speed ratio. The method described next will solve this problem.

### B. ACCELERATOR PEDAL - POWER CONTROL STRATEGY (APP)

When the accelerator pedal signal is translated into power demand, the PMSTM output power corresponds to the accelerator pedal. Fig. 13 is the control flow block of APP control strategy. The output power and torque are related as follows:

$$P_{\mathrm{tm}} = f(h_{\mathrm{ap}}) \tag{4}$$

$$T_{\mathrm{tm}} = \frac{3600 r_{\mathrm{wh}}}{i_{\mathrm{fd}} u_{\mathrm{ve}}} \frac{P_{\mathrm{tm}}}{i_{\mathrm{vr}}} \tag{5}$$

According to the previous analysis, when the output power of PMSTM keep constant, the speed ratio change of ECVT will not affect the acceleration performance in theory. Therefore, the speed ratio control strategy is mainly considered in the aspect of optimizing the efficiency of powertrain. The target speed ratio and PMSTM working point can be obtained from solving the following optimization problem.

$$\max(\mathit{eff}_{\mathrm{tm}} * \mathit{eff}_{\mathrm{vr}}) = \max(\mathit{eff}_{\mathrm{tm}}(T_{\mathrm{tm}}, n_{\mathrm{tm}}), \mathit{eff}_{\mathrm{vr}}(T_{\mathrm{tm}}, n_{\mathrm{tm}}, i_{\mathrm{vr}}))$$

$$S.t. \begin{cases} P_{\mathrm{tm}} = \text{constant} \\ u_{\mathrm{ve}} = \text{constant} \\ P_{\mathrm{tm}} = \dfrac{T_{\mathrm{tm}} n_{\mathrm{tm}}}{9550} \\ u_{\mathrm{ve}} = \dfrac{0.377 n_{\mathrm{tm}} r_{\mathrm{wh}}}{i_{\mathrm{vr}} i_{\mathrm{fd}}} \\ 0.6 \le i_{\mathrm{vr}} \le 1.8 \end{cases} \tag{6}$$

Fig. 14 is a schematic diagram of speed ratio control with APP control strategy. It is assumed that when the accelerator pedal is $h_{\mathrm{ap}}^1$, the vehicle works stably at point ① , the resistance power of the vehicle with speed ratio $i_{\mathrm{vr}}^1$ is balanced with the driving power $P_1$. When the driver steps on the accelerator pedal to $h_{\mathrm{ap}}^2$, the acceleration power required is $P_2$. Because the response time of PMSTM output torque is faster than ECVT shifting, it can be assumed that the PMSTM working point can directly move from the point ① to ② in order to meet the power demand of $P_2$. The torque difference between point ① and ② multiplied by the ECVT speed ratio is the torque transmitted to wheel for acceleration. When the working point of the PMSTM moves on the iso-power line $P_2$ with the change of speed ratio, the acceleration performance will not be affected. If the PMSTM is expected to work at point ② all the time during acceleration, the speed ratio needs to be reduced from $i_{\mathrm{vr}}^1$ towards $i_{\mathrm{vr}}^2$ with the increase of vehicle speed. If hope the PMSTM to work at point ③, the speed ratio needs further reduce at $i_{\mathrm{vr}}^2$. If hope the PMSTM finally work at point ④, the speed ratio is no need to change, and the PMSTM working point moves from point ② to point ④ along iso-power line $P_2$ with the increase of vehicle speed. If hope the PMSTM work at point ⑤ finally, the speed ratio should be changed from $i_{\mathrm{vr}}^1$ to $i_{\mathrm{vr}}^3$. And the PMSTM working point will be changed from point ② towards point ⑤ along the iso-power line $P_2$. It is obvious from the figure that when working at point ⑤, the PMSTM efficiency is the highest. From the analysis above we can know that the APP control strategy can decouple the accelerating purpose with speed ratio control method. The speed ratio of ECVT can be controlled to optimizing the powertrain efficiency and directly satisfy the driver's demand for accelerating. It is better than the APT control strategy, and it will be used on the next offline evaluation.

## V. PERFORMANCE EVALUATION

### A. PERFORMANCE EVALUATION OF CONSTANT VEHICLE SPEED

In order to verify the performance of the designed ECVT, the vehicle equipped with ECVT and SST is analyzed and evaluated. Fig. 15 is the proposed evaluating system. Simulation data are gathered by prototype experiment. Fig. 16 shows the efficiency map of the traditional CVT and improved ECVT, the redesigned ECVT is obviously superior to traditional CVT. Fig. 17 shows the energy consumption of vehicles equipped with ECVT and SST under different vehicle speeds. When the vehicle speed is lower than 20 km/h, the energy consumption of EV with ECVT is higher. This is mainly for

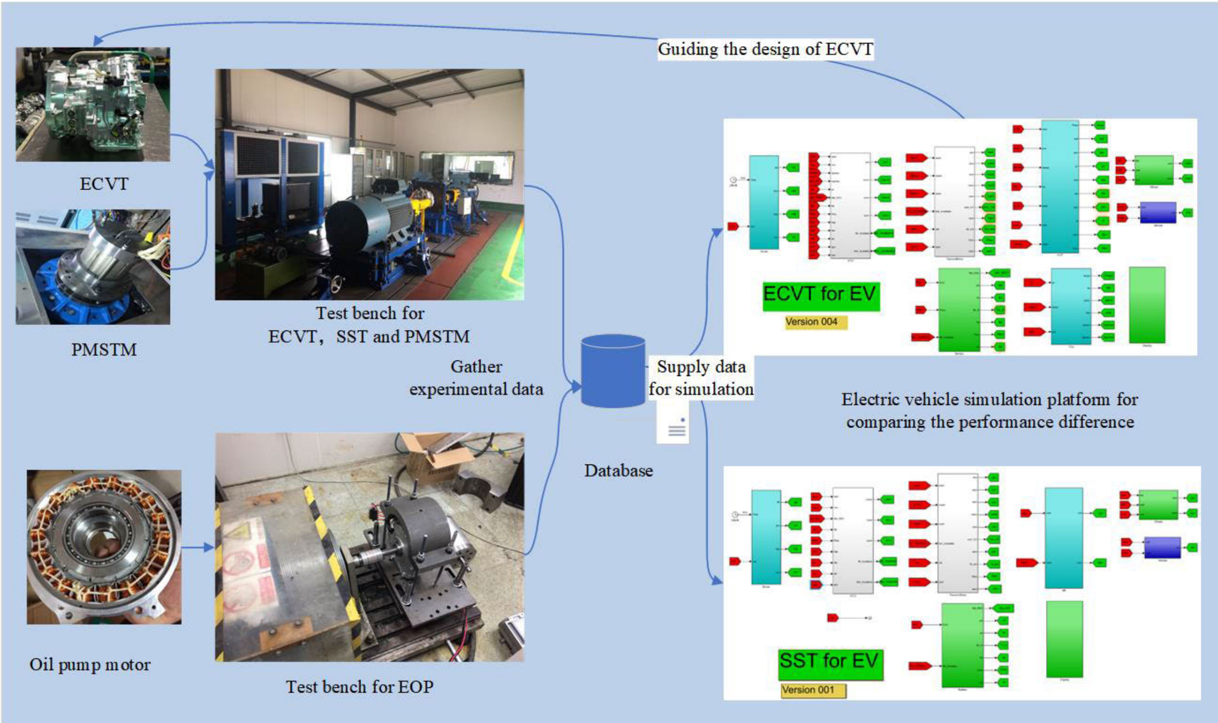


FIGURE 15. Performance evaluation and optimization for ECVT.

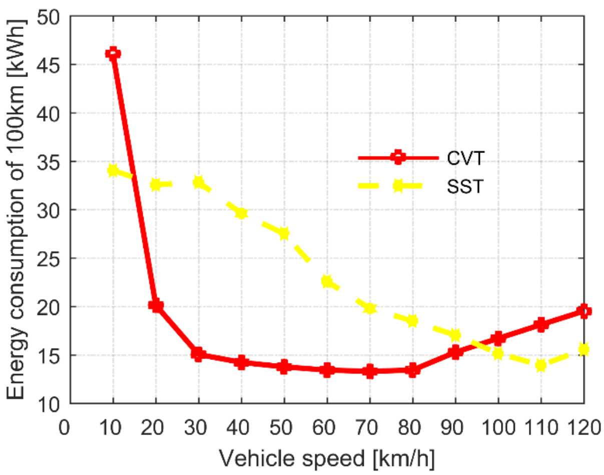


FIGURE 16. Comparison of power consumption with ECVT and SST.

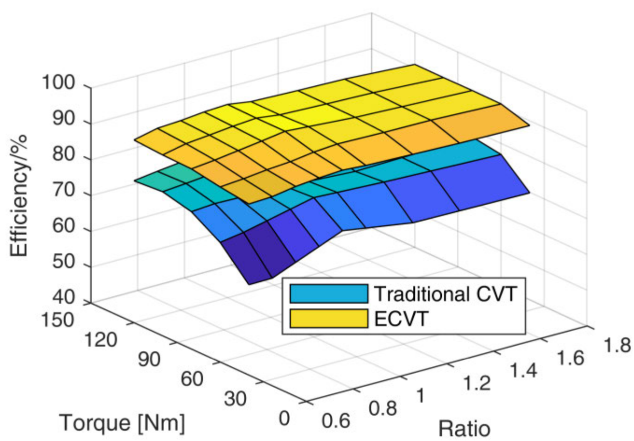


FIGURE 17. Efficiency map of traditional CVT and designed ECVT at 3000 rpm.

ECVT don't shifting below 20 km/h, the larger maximum total speed ratio of ECVT leads to the PMSTM work at lower torque area. Besides, the efficiency of ECVT under this circumstance is lower. When the vehicle speed is more than 20 km/h, ECVT starts to shifting and optimizes the PMSTM working point. However, the SST only has one fixed speed ratio, it can't decouple the vehicle speed with the PMSTM working point. This ultimately leads to the overall efficiency of the powertrain with SST is lower than ECVT. When the vehicle speed is higher than 90 km/h, the energy consumption with ECVT is higher. This is mainly because when the vehicle speed exceeds 90 km/h, the PMSTM working points with SST are already on the high speed and middle load areas in most cases, and the efficiency of PMSTM and SST are very high. ECVT don't have the advantage of further improve the efficiency of PMSTM by shifting, the efficiency difference between ECVT and SST finally leads to the vehicle with SST have better energy consumption performance. It can be seen from the comparison results that ECVT is more suitable for urban conditions.

### B. DYNAMIC PERFORMANCE

The vehicle performance simulation platform is established to compare the dynamic performance of the EV with different powertrain system. Fig. 18 is the test results of acceleration

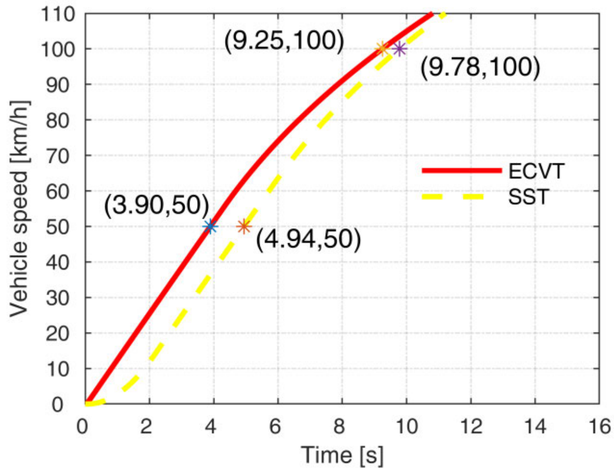


**FIGURE 18.** Comparison of full pedal accelerating with ECVT and SST.

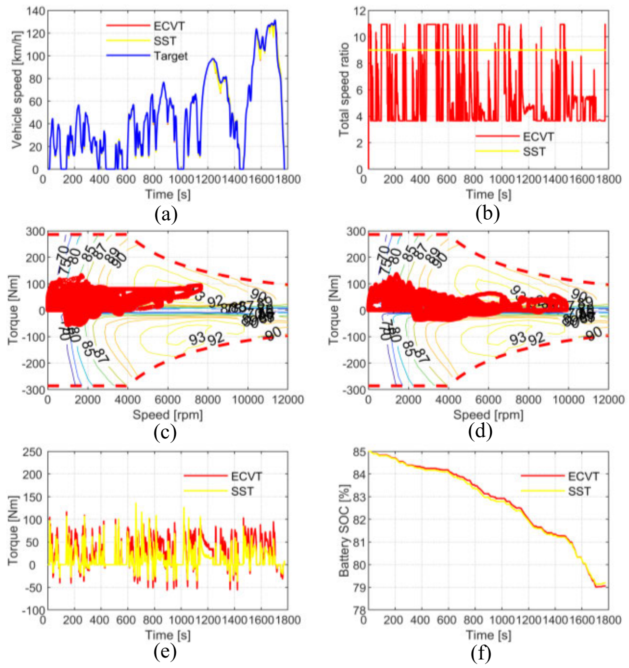


**FIGURE 19.** Simulation results of WLTC with ECVT and SST. (a) is the vehicle speed. (b) is the transmission speed ratio. (c) and (d) are the distribution of PMSTM working point with ECVT and SST respectively. (e) is the PMSTM output torque. (f) is the battery state of charge.

process with full accelerator pedal. The EV equipped with ECVT reaches 50 km/h at 3.90 s, while the SST reaches the same speed at 4.94 s. The ECVT improves the performance about 21% than SST. The EV equipped with ECVT reaches 100 km/h at 9.25 s, which is 0.53 s faster than with SST. On the process of accelerating from 0 to 50 km/h, the total speed ratio of ECVT is larger than that of SST, the PMSTM can reach the maximum power output point faster. Therefore, the acceleration time of ECVT is shorter than SST. When accelerating from 50 to 100 km/h, whether ECVT or SST, the PMSTM of each one worked at the maximum power point. Because the efficiency of ECVT is lower than SST, the actual

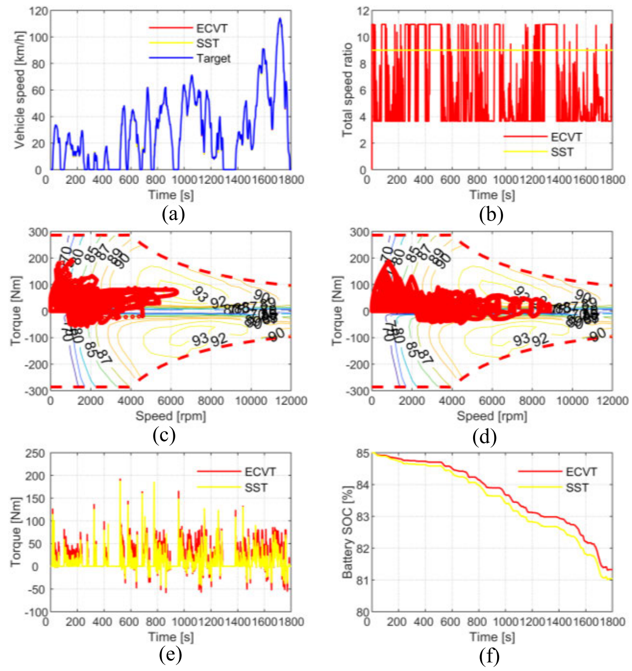


**FIGURE 20.** Simulation results of CLTC-P with ECVT and SST. (a) is the vehicle speed. (b) is the transmission speed ratio. (c) and (d) are the distribution of PMSTM working point with ECVT and SST respectively. (e) is the PMSTM output torque. (f) is the battery state of charge.

output power of ECVT to the wheel is smaller than SST, and this resulting in the acceleration time of ECVT is 0.51 s slower than SST from 50 to 100 km/h. From the comparison we can see that ECVT has better dynamic performance on urban conditions.

### *C. DRIVE CYCLE TEST*

In order to further compare the performance of EV equipped with ECVT and SST, two typical road cycles for passenger car, the world light vehicle test cycle (WLTC) and china light-duty vehicle test cycle for passenger car (CLTC-P), are adopted. Fig. 19 and 20 are the simulation result of WLTC and CLTC-P respectively. The ECVT can shift speed ratio to optimize the PMSTM working point and decouple the PMSTM and vehicle speed, so the PMSTM work point speed with ECVT is lower than SST and closer to the highest efficiency area under two cycle simulation. It can be seen from Fig. 19(f), the batter SOC of ECVT is higher than SST before 1500 s, and finally lower than SST at the end. This is mainly for the vehicle speed is higher than 90km/h after 1500 s at most case, and the energy consumption of ECVT is higher. The energy consumption with ECVT is 2.3% higher than SST under WLTC finally. Fig. 20(f) shows that the batter SOC of ECVT is higher than SST from start to end, and ECVT can save about 7.3% power consumption. This is mainly because the required average power under CLTC-P is smaller than WLTC, giving ECVT more opportunities to optimize the PMSTM operating point, and there are also fewer vehicle speeds exceeding 90km/h.

## VI. CONCLUSION

Based on the analysis of traditional CVT and transmission requirements of EV, an ECVT is proposed. The hydraulic system and EOP of ECVT are designed and developed to satisfy the requirements of powertrain. The speed ratio of ECVT variator and final reduction are redesigned to improve its transmission efficiency. To increase the powertrain efficiency with ECVT and PMSTM, the speed ratio control strategy of APT and APP are also been proposed and studied. The theory analysis show that APP control strategy can decouple the accelerating purpose with optimizing PMSTM working point, and achieving the dynamic and economic performance optimally at the same time.

To compare the performance of the EV equipped with the designed ECVT and SST, a performance evaluation platform is established. The results of constant vehicle speed test show that the power consumption of EV equipped with ECVT is lower than with SST at the speed from 20 to 90 km/h. Which shows the advantage of ECVT in optimizing the PMSTM working point through shifting to improve the overall transmission efficiency. The full force acceleration test of 0 to 50 km/h also shows the advantage of ECVT 21% improvement than SST. The road cycle tests of WLTC and CLTC-P show that the battery SOC of EV equipped with ECVT decreases less in urban conditions, which reflects the advantage of ECVT driving in urban areas.

Future research work includes how to match ECVT to develop low-speed PMSTM, and design the high efficiency area of PMSTM coincide with ECVT. Besides, developing high-voltage powered PMSTM with ECVT for high technology powertrain is another research direction. The high-voltage technology can reduce the material consumption of PMSTM while keeping the maximum power unchanged by improving the base speed, thereby reducing the cost of the overall powertrain.

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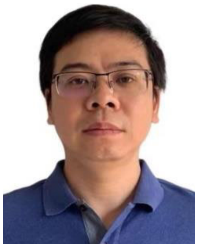

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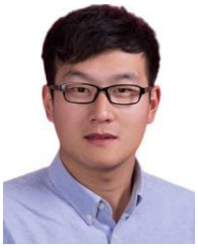

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