Study on Control Strategy for Series-Parallel Hybrid Electric Vehicles

Lei Xu\textsuperscript{a}, Zhe Li\textsuperscript{*}, Hanwen Sun\textsuperscript{b}, Jie Fan\textsuperscript{c}, Qin Bai\textsuperscript{d}, Yang Ou\textsuperscript{e}, Peng Wang\textsuperscript{f}, Bo Deng\textsuperscript{g}

New Energy Vehicle Center, China Automotive Engineering Research Institute Co., Ltd., Chongqing, China

\textsuperscript{a}xulei@caeri.com.cn, \textsuperscript{b}sunhanwen@caeri.com.cn, \textsuperscript{c}384954890@qq.com.cn, \textsuperscript{d}baiqin@caeri.com.cn, \textsuperscript{e}ouyang@caeri.com.cn, \textsuperscript{f}wangpeng@caeri.com.cn, \textsuperscript{g}dengbo@caeri.com.cn

*Corresponding author: lizhe@caeri.com.cn

Abstract — This paper proposed a power allocation mechanism and mode switching strategy for the series-parallel hybrid electric vehicles. A test-data based simulation platform for series-parallel plug-in hybrid electric vehicles is established and developed for theoretical verification. The results indicate that the proposed control strategy realized a more reasonable power distribution in the combined power system under various working modes, which means a remarkable improvement in vehicle fuel economy.

1. INTRODUCTION

Vehicles equipped with hybrid driving system is known as a solution for the balance between the energy crisis and the mileage anxiety [1-3]. The series-parallel driving system, compared with the traditional ones, has a more controllable configuration, which demonstrates obvious economical potential and dynamical advantages in its application process. And it has brought significant attention in automotive industry and R&D institutions [4,5]. Due to the complex coupling characteristics of the propulsion system and the special arrangement of the energy source in series-parallel driving configuration, a well-developed energy allocation for gasoline and power battery, a state of art power management for internal-combustion engine and driving motor, as well as a sophisticated mode switching strategy are the three essential factors for the balancing of dynamic and economic in series-parallel driving system[6-8]. And also, the necessary conditions for promoting vehicle performance [9-12]. In this paper, a test-data based simulation platform for energy allocation and power management in series-parallel driving system is established and developed, meanwhile the corresponding mode switching strategy for plug-in electric vehicles with hybrid powertrain in one clutch is proposed accordingly. The results indicate that it can realize a reasonable power distribution in various working modes, which benefited the fuel economy in series-parallel driving system effectively and improved the comprehensive performance in vehicle consequently. This study provides a practical case on the control method of the power management for series-parallel plug-in hybrid vehicles.
2. THE SERIAL-PARALLEL HYBRID CONFIGURATION

The structural topology of plug-in hybrid vehicle is depicted in Figure 1. It can be seen from the hardware configuration of series-parallel driving system that, the hybrid propulsion powertrain consists of two major driving system—one 2.0 liter naturally aspirated internal-combustion engine (in which the max output power is 105kW at 6200rpm) and one permanent magnet synchronous driving motor (in which the max output power is 124kW), which convert energy from on-board gasoline tank and power battery respectively. The coupled longitudinal dynamics are assigned according to power management strategy and the switching between series mode and parallel mode is executed by means of clutch engagement.

In general, based on diverse drive’s operating input (pedal, power demand) and current state (speed, SOC, etc.) of hybrid vehicle, the working modes of series-parallel driving system can be separated and summarized as EV Drive, Hybrid Drive and Engine Drive. The EV Drive is pure electric working mode, which the driving force is offered by driving motor and the primary driving power is provided from power battery solely. At this moment, the hybrid vehicle can realize zero emissions in this mode. The Hybrid Drive is serial working mode. On one hand, the propulsion system is offered by driving motor as same as EV Drive. But there are some separations between the two mentioned modes. And the difference is that, on the other hand, the electric current supplied to the driving motor is joint energized by the power battery and the generator driven by internal-combustion engine, which means the power battery decreases the supply capacity in this mode. The Engine Drive is parallel working mode in series-parallel driving system. In this mode, as a result of clutch engagement, the speed of internal-combustion engine is coupled with wheel rotation because of direct connection. Besides, the hybrid vehicle is powered by the combined action of electro-mechanical driven force and thermo-mechanical driven force in series-parallel driving system, which are energized by electricity and fossil oil respectively at the same time.

3. THE POWER DISTRIBUTION MECHANISM

In EV mode, as mentioned before, the series-parallel driving system adopts the power battery as the sole energy source for the hybrid vehicle by means of electromagnetic driving power. And the output capability of power battery is the strongest among the three modes. As a result, on the basis of the max discharge capacity of power battery, the operating range of the driving motor is determined, and thereby proposing the speed boundary in upper and lower limitation of hybrid vehicle which the series-parallel driving system is in EV mode. For the Hybrid Drive mode and Engine Drive mode, both of them involve the energy distribution from the two power sources in series-parallel driving system, which are the electro-mechanical provided by power battery and the thermo-mechanical provided by fossil oil. The ignition initialization for internal-combustion engine has completed already in these two modes.

Figure 1. Serial-Parallel Hybrid System Configuration
The same point is that the internal-combustion engine works on the optimal consumption rate line for fuel in both modes. The difference is that in the Hybrid Drive mode, the speed of internal-combustion engine is decoupled from the wheel rotation, which widened the accepting speed interval and controlling range of the internal-combustion engine in the series-parallel driving system. However, in the Engine Drive mode, the output terminal of internal-combustion engine is mechanically connected to the wheel because of clutch engagement. It narrows the speed interval controlled by the internal-combustion engine, which decreases the output power of internal-combustion engine in Engine Drive mode. As a result, thanks to the intactness of battery output capability, the Hybrid Drive mode is not only adopted in the hybrid vehicles under high driven power demand at high speed, but also can be applied to the situation that the hybrid vehicles experience a low driven power demand at low speed when the SOC is insufficient. On the contrary, the Engine Drive mode merely meet the low power demand when vehicles at medium or high speed as a result of compromise on engine output interval and battery output capability.

Based on previous discussion, the power allocation of series-parallel driving system in each mode is determined by corresponding speed interval and power demand in plug-in hybrid vehicles. In addition, as another important indicator to character vehicle status, the SOC is adopted here to regulate the power allocation as well. Therefore, the specific power allocation protocols about EV Drive, Hybrid Drive as well as Engine Drive in different stages of SOC (Charge Depleting, CD stage in which the power battery is the major source for energy supply at this moment, and Charge Sustaining, CS stage in which the fossil oil is the major source for energy supply at this stage) are defined as follows,

1) If the plug-in hybrid vehicle is in CD stage of SOC, then in the EV Drive mode, the max output power provided from the series-parallel driving system is 41kW, corresponding to the highest speed of 100km/h. Moreover, if the plug-in hybrid vehicle is in CS stage of SOC, the max output power of EV Drive mode provided from the series-parallel driving system is declined to 20kW, and the corresponded vehicle speed is 70km/h.

2) In the Hybrid Drive mode, the engine speed is decoupled from the vehicle speed, which enables the engine, with multiple power requirements in Hybrid Drive mode, been controlled exactly under optimal economic point (which is 31.4kW at 2500rpm in this case). In the CD stage, the working area of the series-parallel driving system is 41~124kW. And when the required power is less than 70kW (which is maximum discharge power of the battery plus the output power of internal-combustion engine operated under optimal economic point), the engine is controlled under that point and the remaining power is replenished by power battery. Furthermore, when the required power is between 70kW and 124kW, the discharge power of battery is fixed at certain limit, and the remaining power is replenished by engine operating point adjustment. In addition, since the power from the battery during the CS stage cannot be adopted as much as possible as in the CD stage. The choice of discharge power and operating point for the battery and engine needs to consider the overall efficiency of the series-parallel driving system including the efficiency of mechanical-electrical conversion. As a result, if the required power is more than 20kW in EV Drive but less than 31.4kW which is engine output power under optimal economic point, the redundant power is charging back to power battery so that the engine speed is fixed to 2500rpm for the optimization of fuel economy.

3) The series-parallel driving system changes to Engine Drive mode during plug-in hybrid vehicles at high-speed cruising. The torque from internal-combustion engine is provided here for the running resistance balancing and acceleration driving force supplying occasionally. As a result, the engine operates at middle or low load areas in the CD stage. In addition, because the speed of engine and vehicle is coupled with each other at this time, the operating area of the engine is selected to be distributed along the BSFC (Brake Specific Fuel Consumption) line according to corresponded vehicle-engine speed. More specifically, when the required power is greater or equal to the output power from engine at BSFC line but less than or equal to the output power from engine at BSFC line plus 20kW (Output limit of power battery in Engine Drive mode), then the operating point of engine is controlled on the BSFC line, and the driving motor acts as a power supplement component in the series-parallel driving system at this time. Moreover, if the required power is less than the output power from engine
at BSFC line, then the operating point of engine is adjusted to low load area. Similarly, if the require power is greater than the reference point (BSFC+20kW as mentioned before), the discharge power of battery is fixed at certain limit, and the remaining power is replenished by engine operating point adjustment towards higher load areas. In the CD stage, because the power battery is fully charged, the engine is controlled off the BSFC line to reduce the load when the required power is small. When the demand power is large, the engine is operated on BSFC line, the rest driven power is supplemented by the battery discharge. However, as shown in Figure 2, the same process in CS stage is limited by the SOC, which manifested as the high required power can only be satisfied by the engine deviating from the BSFC line to the high load direction while the low required power be satisfied by the engine departing from the BSFC line to low load direction.

![Figure 2. Operating points distribution for engine in different driving modes/stages](image)

Finally, the power distribution mechanism for the series-parallel driving system in EV Drive mode, Hybrid Drive mode as well as Engine Drive mode at CD and CS stages of SOC respectively are summarized and depicted in Figure 3.

![Figure 3. Power Distribution Mechanism](image)
4. Modeling and Strategy Verification

4.1 Modeling of Series-Parallel Driving System
A series-parallel driving system for plug-in hybrid vehicles is established and developed in Matlab/Simulink environment to verify the effectiveness of the proposed power distribution mechanism and mode switching strategy for the multi-dynamic propulsion system, as shown in Figure 4, which consists of driver model, vehicle dynamics model in longitudinal direction, powertrain model and controller model assembled. The powertrain model embodies main actuators on hardware configuration of the series-parallel driving system such as driving motor, generator, inter-combustion engine, power battery as well as clutch, etc. The controller model contains calculation modules for driving demand, braking demand, vehicle load, which provided as the control input for mode selection strategy. More specific, the driver model is providing the pedal input to the driving demand calculation module, is with another input, such as vehicle load and operating feedback signals for the other components in series-parallel driving system, is inputting and adopted to mode selection strategy, and the resulted mode switching is executing by clutch engagement.

![Figure 4. The Model of Serial-Parallel Driving System](image)

4.2 Modeling of Mode Switching Strategy
The aim of mode switching strategy proposal is to maximize the operation efficiency of the entire series-parallel driving system. Therefore, the power distribution and collocation reconfiguration between driving components in multi-dynamic propulsion system and energy sources, and the followed mode selecting regulation and switching implementation are completely based on that regulation. In general, the mode switching implementation mainly refers to the mode switching between EV Drive and the Hybrid Drive, the EV Drive and the Engine Drive, as well as the Hybrid Drive and the Engine Drive. However, even if the series driven is characterized as multiple engine operating point selectivity due to speed decoupling, it is worth noting that the required power is direct provided by internal-combustion engine can greatly reduce the consumption caused by secondary energy conversion compared to propelling mode under series driven. As a result, more efficiency considerations need to be taken into account for the mode selection between the Hybrid Drive and the Engine Drive.

The frameworks of the switching strategies and mode switching process for series-parallel driving system are depicted in Figure 5 and in Figure 6 respectively. Similarly, mode switching strategies are also proposed separately based on different capacity states of power battery, which is classified as CD stage and CS stage according to SOC. Moreover, each operating stage include three working modes as well: EV Drive, Hybrid Drive and Engine Drive. In the CD stage, the logical judgement diagram of mode switching strategy proposed is shown in Figure 5.
On the contrary, in the CS stage, because the capacity of the power battery is relatively low, the objective of the mode switching strategy proposed needs to balance the power required by the vehicle for driven resistance overcome and the charged power demanded by the power battery for electric quantity maintenance. At this point, the logical judgement diagram of mode switching strategy for the series-parallel driving system in CS stage is shown in Figure 6.

After the comparison between Figure 5 and Figure 6, it can be noticed that, the similarities between CD stage and CS stage are the main trigger factors affecting the mode selecting regulation and switching implementation in the proposed mode switching strategies, which likewise, are battery SOC, driver control input, vehicle status such as current speed along with current required power, and so on. The difference lies in the discharge capacity of the power battery under the state of low electric quantity yet. While in the CS stage, the operation range of the EV mode is reduced by the discharge limitation.
CS Mode

- Required power > the maximum output power from the battery?
  - Yes: EV Drive
  - No: Vehicle speed < the maximum speed in CS_EV Drive?
    - Yes: EV Drive
    - No: CS Engine

CS Engine

- CS Engine Initialized?
  - Yes: CS Engine Stop
  - No: Required power from the vehicle < current engine torque?
    - Yes: CS_Engine_Drive
    - No: Required power < the maximum discharge power from the battery?
      - Yes: CS Engine
      - No: Vehicle speed > the maximum vehicle speed in CS_EV?
        - Yes: CS_Hybrid Drive
        - No: CS Engine

CS Hybrid Drive

- CS Engine Start
  - Yes: CS Engine Ramp up
  - No: Required torque from the vehicle < current engine torque?
    - Yes: CS Engine Drive
    - No: Vehicle speed > the maximum vehicle speed in CS_EV?
      - Yes: CS_Hybrid Drive
      - No: Clutch engagement initializing, at this moment, the torque/speed of the clutch follows the engine
        - Yes: Clutch engagement completed
        - No: Requested torque > the torque of CS_Engine_Drive?
          - Yes: Clutch off initializing, at this moment, even the torque/speed of the driven disc still follows the master clutch, but there is no engagement between them.
          - No: CD_Engine Ramp down

4.3 Simulate Verification

The New European Driving Cycle (NEDC), the Urban Dynamometer Driving Schedule (UDDS), and the Highway Fuel Economy Test (HWFET) are adopted here to verify the effects of proposed mode switching strategy, simulate results are shown in Figures 7~9 respectively.

Figure 6. Mode Switching Process in CS Stage
The simulate result of the vehicle speed for the series-parallel driving system under the NEDC is shown in Figure 7(a). It can be seen that the target vehicle speed is completely followed the reference one, which indicated that the accuracy of the proposed simulation platform is confirmed.

The variations of required power with time at different operation conditions under the NEDC are depicted in Figure 7(b). The operating modes of the series-parallel driving system are represented by different colors, which was divided into three cases:

1) When the battery SOC is relatively high and the required power of vehicle is relatively small, the vehicle basically operates in the pure electric mode, which is equivalent to EV Drive in the series-parallel driving system.

2) As the battery SOC decreases under the time course of NEDC, the battery discharge power can no longer meet the power demand of the vehicle. Thus, the vehicle operates in series mode, which is the Hybrid Drive in series-parallel driving system. At this moment, the internal-combustion engine speed is decoupled from the wheel rotation because of clutch disengagement. The driving motor, acts as the only driving device in the hybrid propulsion system equally to EV Drive, is joint energized by the power battery and the generator driven by internal-combustion engine.

3) While the required power from the vehicle is relatively large, and the battery SOC is relatively high at the same time. The vehicle operates in parallel mode, which is the Engine Drive in series-parallel driving system. At this moment, the internal-combustion engine and the driving motor are jointly driven the vehicle, and the internal-combustion engine speed is coupled with the wheel rotation because of clutch engagement.

Besides, according to Figure 7(c), the steady-state operating point of engine is basically controlled near the BSFC line in the two modes that the internal-combustion engine needs to start, which means an efficiency enhancement of the electro-mechanical and the thermo-mechanical driven force transferring, that improves the comprehensive performance of entire series-parallel driving system and is benefited to the fuel economy of the plug-in hybrid vehicle.
The power distribution of the series-parallel driving system under the UDDS is shown in Figure 8. It is noted that although the variation of the power demand for the plug-in hybrid vehicle under the UDDS operating condition is much more complicated than that under the NEDC, the pure electric mode, which is the EV Drive in the series-parallel driving system, is still dominated in the whole time course and overall operating range of UDDS. In general speaking, when the required power from vehicle is gradually increasing, the series-parallel driving system switches to Hybrid Drive mode or Engine Drive mode, which is equivalent to series mode or parallel mode in the plug-in hybrid vehicle. At these moments, the steady-state operating point of engine is changed along the BSFC line. More specifically, in the time range of 200s~300s, the series-parallel driving system switches to the Engine Drive mode based on Figure 8(b), which exists two cases at this situation according to Figure 8(c):

1. As the output power of internal-combustion engine along with BSFC line is greater than the current power demand from the vehicle, the excess energy generated by the series-parallel driving system is recharging back to the power battery, which leads to the rise of battery SOC in the time range of 210s~320s.

2. While the battery SOC of the plug-in hybrid vehicle is relatively low (down to the 27%), since the battery discharge power is restricted at this time, the operating point of internal-combustion engine is adjusted off the BSFC line toward higher load direction to meet the power demand from the vehicle.
The power distribution of the series-parallel driving system under the HWFET is shown in Figure 9. It is noted that the power demand from the vehicle under the HWFET is relatively low due to high speed operating condition and infrequent critical maneuvers, which means a relatively stable operating condition for the multi-dynamic propulsion system in HWFET. Moreover, according to Figure 9(b), the vehicle realizes the control logic and the state-flow of the power distribution mechanism and the mode switching strategy previously defined, which manifests as the EV Drive is triggered and the vehicle subsequently switches to pure electric mode when the battery SOC rises to 35%. On the contrary, while the battery SOC is as low as 28%, the Hybrid Drive is triggered and the vehicle subsequently switches to series driving mode. In that case, the whole series-parallel driving system is energized by the generator driven by internal-combustion engine, the output power here is partly offered to the driving motor for the vehicle running resistance balancing. The rest of it is provided to power battery for recharging. Besides, as to the running range of internal-combustion engine during HWFET, the steady-state operating point is distributed near the BSFC line according to Figure 9(c), which benefited the comprehensive fuel economy for the entire the multi-dynamic propulsion system.

5. CONCLUSIONS
Due to the dynamical coupling and structural complexity, the hybrid vehicles with series-parallel driving system possesses multiple working modes to adapt to different driving conditions. Since the power allocation mechanism and the chosen for mode switching are the two of the feasible and vital factors for the checking and balancing between the economics and the performance of the entire propulsion system. For the improvement of the series-parallel driving system in the purpose of multi-objective, a power distribution-based mode switching strategy is put forward by this paper. The effectiveness of proposed theory and mechanism is subsequently verified on a test-data based simulation platform for series-parallel plug-in hybrid vehicles under various driving cycle. The results indicated that with an optimal power allocation mechanism and a more reasonable trigger strategy for mode switching in the multi-dynamic propulsion system are realized, the optimization goals to the comprehensive performance enhancement in the series-parallel driving system and the fuel economy improvement for the plug-in hybrid vehicles are achieved.

ACKNOWLEDGMENT
The authors acknowledge the Project “Development and application of key technologies for performance evaluation of high performance pure electric 4WD SUV” (No. cstc2018jszx-cyztzxX0005) for financial support.

REFERENCES
[1] Yongtao Y. Optimization of Design and Control for Power-split Hybrid Electric Vehicle[D]. Changchun: Jilin University doctoral thesis, 2010.
[2] Wang D, Song C X, Song S X. Parameter Matching and Performance Simulation for a Distributed Power Extended-Range Electric Vehicle[C]//Applied Mechanics and Materials. Trans Tech Publications, 2014, 496: 1360-1364.

[3] Tian S, Wang Y, Wu L. Parameters Matching and Effects of Different Powertrain on Vehicle: Performance for Pure Electric City Bus[R]. SAE Technical Paper, 2015.

[4] Liu M, Zhao Z, Yang X, et al. Study on New Concept Powertrain for Range-Extended Electric Vehicles[C]//Proceedings of the FISITA 2012 World Automotive Congress. Springer, Berlin, Heidelberg, 2013: 687-695.

[5] Li Z, Zheng L, Gao W, et al. Electromechanical coupling mechanism and control strategy for in-wheel-motor-driven electric vehicles[J]. IEEE Transactions on Industrial Electronics, 2018, 66(6): 4524-4533.

[6] Lei Y. Matching Analysis of Power System of Extended-Range Electric Vehicle[C]//8th International Conference on Social Network, Communication and Education (SNCE 2018). Atlantis Press, 2018.

[7] Li Z, Zheng L, Ren Y, et al. Multi-objective optimization of active suspension system in electric vehicle with In-Wheel-Motor against the negative electromechanical coupling effects[J]. Mechanical Systems and Signal Processing, 2019, 116: 545-565.

[8] Gao W, Zou Y, Sun F. Optimal component sizing for a parallel hybrid bus based on dynamic programming[C]//2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific). IEEE, 2014: 1-5.

[9] Zhang N N, Zhang Z, Feng D J, et al. The Energy Management Control Strategy of Hybrid Electrical Vehicle Based on Efficiency Optimal[C]//Advanced Materials Research. Trans Tech Publications, 2013, 645: 422-425.

[10] Nema P, Nema R K, Rangnekar S. A current and future state of art development of hybrid energy system using wind and PV-solar: A review[J]. Renewable and Sustainable Energy Reviews, 2009, 13(8): 2096-2103.

[11] Jun Y, Xianglin G A O Y Y S Z, Ping S U N. PRESENT STUDY SITUATION AND DEVELOPING TREND OF CONTROL STRATEGIES FOR HYBRID ELECTRIC VEHICLE [J][J]. Chinese Journal of Mechanical Engineering, 2006, 11.

[12] Chen H, Zuo C, Cheng X. A Study of Parameter Matching and Experiment of Powertrain for an Extended-Range Electric Vehicle[R]. SAE Technical Paper, 2012.