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CONTROL STRATEGIES FOR DUAL-MOTOR POWERTRAIN SYSTEM CONSIDERING ENERGY EFFICIENCY

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ABSTRACT

Powertrain control strategy is a key technology that determines the energy consumption of dual-motor electric vehicles. However, existing control strategies cannot meet the requirements of a new dual-motor powertrain configuration with a two-speed gearbox for one of the motors, which is likely to be the mainstream powertrain configuration of commercial vehicles in the future. In this paper, two control methods including dynamic programming and an offline global optimization method are conducted to optimize torque distribution strategy and gear shifting law. The performance of the proposed methods is reflected through simulations based on MATLAB/Simulink, the results show that the proposed methods present considerable promotion on energy consumption compared with that of the fixed proportional control method.

Keywords: dynamic programming, energy consumption, torque distribution, gear shifting law, dual-motor electric vehicle

NOMENCLATURE

Symbols

η	The powertrain system efficiency
$\eta_i (i=1,2)$	The efficiency of motor i
$n_i (i=1,2)$	The rotation speed of motor i
n_d	The rotation speed of output shaft
T_d	The output torque on the output shaft
$T_i (i=1,2)$	The output torque of motor i
α	The ratio of regenerative energy
$\eta_{ir} (i=1,2)$	The regenerative efficiency of motor i

1. INTRODUCTION

Two exceptional characteristics of dual-motor powertrain includes avoiding power interruption during the multi-mode switching process, and energy efficiency improvements by the implementation of regenerative braking procedures[1]. A two-speed gearbox can raise the performance of electric vehicles, as well as take better advantage of the speed range of driving motors[2]. Therefore, a two-motor two-speed gearbox powertrain has an enormous potential for energy savings. While satisfying the conditions of vehicle dynamic performance, reasonable torque distribution and gear shifting law based on the efficiency data of each motor are effective solutions to reduce energy consumption. Therefore, it’s significant to discuss the control strategy for the two-motor two-speed gearbox powertrain configuration.

Researchers have proposed strategies and gear shifting laws for dual-motor two-speed gearbox powertrain systems aiming at reducing energy consumption. Li Congbo et al. developed an efficient gear shifting strategy and the lowest energy consumption torque and speed distribution strategy based on motor efficiency maps[3]. Mousavi et al. proposed a two-speed shifting system with no power interruption, and used Pontryagin’s minimum principle to optimize the control strategy[4]. Accordingly, the existing control strategy is just suitable for the configuration where motor torques are coupled before transmission, whereas the gearbox herein is located before torque coupling, which determines that the torque distribution strategy and the gear shifting law should be considered at the same time. In addition, the maximum speed limits the application of powertrain control strategies in some certain working conditions.

Thus, the control strategy for the new powertrain system remains unsolved.

In summary, we propose two powertrain control methods using dynamic programming and an offline global optimization method for the new dual-motor two-speed gearbox powertrain system, and compare the results with that of the fixed proportional control method. In dynamic programming method, we define the torque value of motor 1 as the state variable, and the change of torque for motor 1 and the gear state as the control variables. The strategies are applied to a vehicle kinematic model established on MATLAB/Simulink to verify the feasibility and energy efficiency of the control strategies.

2. POWERTRAIN CONFIGURATION

The dual-motor powertrain system used in this paper consists of motor 1, motor 2, a two-speed gearbox and a set of planetary gears, and provides driving forces to the rear wheels, as shown in Figure 1.

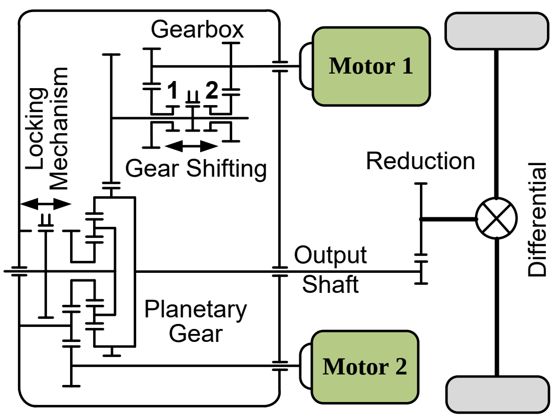

Fig 1 Dual-Motor Powertrain System

The planet carrier is fixed to the powertrain case by locking mechanism, and motor 2 is coupled to the sun gear to load torque on the ring gear via the planetary gears. The reduction ratio of motor 2 to the output shaft of the powertrain is fixed, that is, the transmission ratio of the planetary gear. Motor 1 loads torque on the ring gear via a two-speed gearbox. There are three ways in which the powertrain provides driving force: single motor (motor 1 or motor 2) driving mode and dual-motor driving mode.

In order to meet the dynamic performance requirement of the maximum speed of 100km/h, it is necessary to check the maximum rotation speed of the two motors. The maximum rotation speed of motor 2 corresponds to the vehicle speed of 90.2km/h, and motor 1 corresponds to 101.6km/h. Therefore, in high speed (90-100 km/h) working conditions, the single motor (motor 1) driving mode is employed.

3. DYNAMIC PROGRAMMING METHOD

The torque distribution and gear shifting problem can be described as an optimal problem of multi-stage decision process, which can be solved by dynamic programming method[5]. We define the typical test cycle, such as Chinese World Transient Vehicle Cycle (C-WTVC), as the steps, the torque of motor 1 as state, the change of motor1 torque and the gear state as the control variables. The problem can be described as formula 1-3.

$$\min_{1\le k\le N}\sum_{k=1}^{N} f(x(k),u(k),k)$$
$$s.t. \qquad (1)$$
$$\begin{cases} x(k+1)=x(k)+u(k) \\ x(0)=0 \\ x(N)\in[T_{1\min},T_{1\max}] \\ x(k)\in[T_{1\min}(k),T_{1\max}(k)] \\ u(k)\in[T_{1\min}(k),T_{1\max}(k)] \end{cases}$$

where

$$f(x(k),u(k),k)=P_1(k)+P_2(k) \qquad (2)$$

where

$$P_i(k)=\begin{cases} \dfrac{T_i\cdot n_i}{\eta_1}(T_i\ge 0) \\ T_i\cdot n_i\cdot\eta_{ir}\cdot\alpha(T_i<0) \end{cases} \quad (i=1,2) \qquad (3)$$

We define the ratio of regenerative energy as 0.5, which means that 50% of braking torque is supplied by motors and is used to generate electricity to the battery. The regenerative efficiency is 0.8 time of driving efficiency considering energy conversion consumption. The efficiency of motors can be acquired from motor efficiency maps. The maximum and minimum torque of motors at particular rotation speed can be found based on the external characteristic curve of motor efficiency maps.

4. OFFLINE GLOBAL OPTIMIZATION METHOD

4.1 Offline calculation of optimal energy efficient datasheet

Motor 1 and motor 2 can be torque-coupled at ring gear at any working point in the range of 0-90km/h. For each gear position, we set 100 rpm as an interval that rotation speed of motor 1 varies each time, and 10 Nm as an interval that powertrain output shaft demanded torque changes each time. So a complete powertrain system working point matrix is established.

For each working point, targeting the optimal energy efficiency of the powertrain system, we let the output torque of motor 1 continuously change at an interval of 1 Nm. Then the corresponding output torque of motor 2 is calculated, thereby the powertrain system efficiency according to efficiency maps of respective motors.

Optimization model based on energy economy is described as formula 4.

$$\lim \eta = \frac{T_d n_d}{P_1 + P_2} \tag{4}$$

So far, optimal energy efficiency torque distribution tables and powertrain efficiency tables under two gears are obtained by offline global optimization method respectively, as can be shown in Figure 2 and Figure 3.

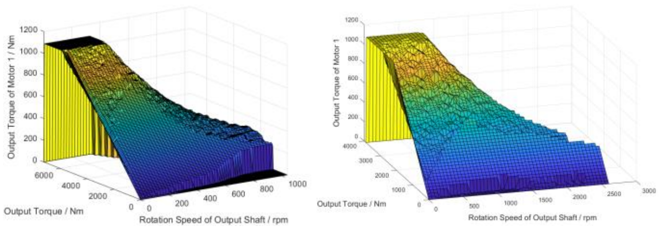

Fig 2 Optimal Torque Distribution

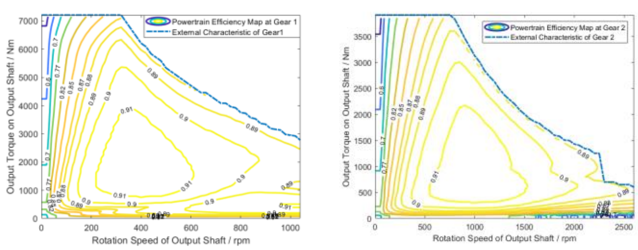

Fig 3 Powertrain Efficiency Tables

4.2 Efficient gear shifting law

For all the working points (0-100km/h), since the gearbox is located between motor 1 and planetary gear, it's necessary to determine the gears at each working point. Firstly, according to the external characteristic range of powertrain system for two gears, all the working points are divided into four zones: dual-motor low speed and large torque zone, dual-motor high-speed zone, dual-motor gear shifting zone, single motor high-speed zone (90-100km/h), as is shown in Figure 4. On working points in the range of 90-100km/h, motor 1 works alone and only 2nd gear can reach the speed requirement. It is easy to derive from the external characteristics that in dual-motor low-speed and large-torque zone, the 1st gear is needed; in dual-motor high-speed zone, the 2nd gear is required; in dual-motor gear shifting zone, either the 1st and 2nd gear can meet the driving needs of the vehicle, and the efficient gear shifting law is established here.

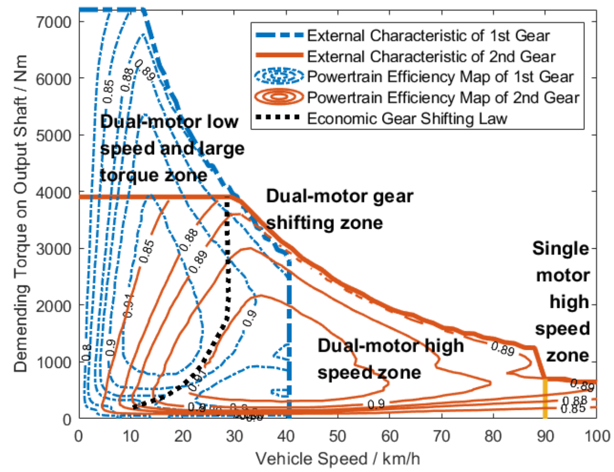

Fig 4 Efficient Gear Shifting Law

According to the powertrain system efficiency tables of the two gears obtained above, select a more efficient gear at any working point in dual-motor gear shifting zone. The boundary of two gears is the dividing line with the same efficiency, that is, the efficient gear shifting law. The structure of method is shown in Figure 5.

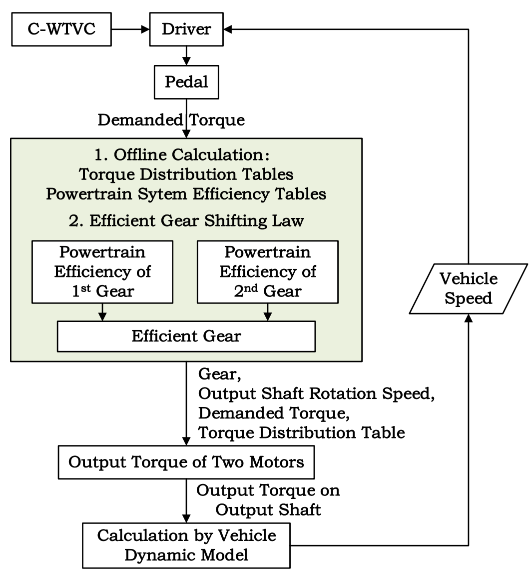

Fig 5 Stucture Of Offline Global Optimization Method

5. SIMULATION RESULTS AND DISCUSSION

For offline global optimization method, we built a kinematics model in MATLAB/Simulink of the vehicle as the simulation platform. Proportional-Integral Controller (PI) is adopted in driver model. The test cycle C-WTVC and the velocity of vehicle can be illustrated in Figure 6.

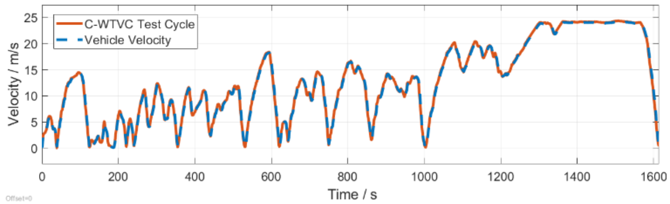

Fig 6 C-WTVC Test Cycle

The results of dynamic programming method indicating power of powertrain and motors can be shown in Figure 7. The electric consumption using DP is 84.58kWh per 100 kilometers, while 86.25kWh per 100 kilometers using offline global optimization method. The difference comes from the PI control of driver model.

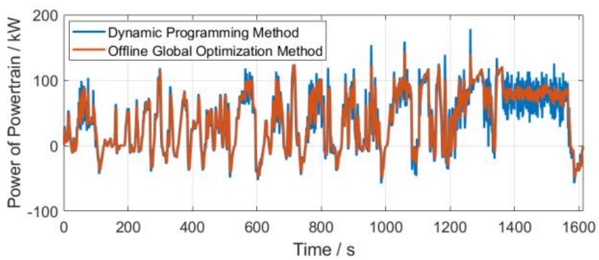

Fig 7 Comparison Of DP And Offline Global Optimization

As a result, visible improvement on the powertrain efficiency can be seen in Figure 8.

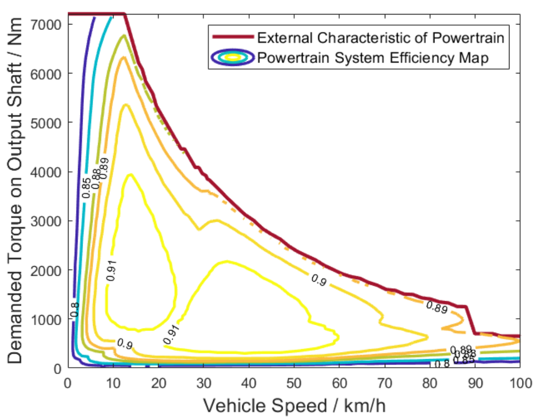

Fig 8 Powertrain System Efficiency Map

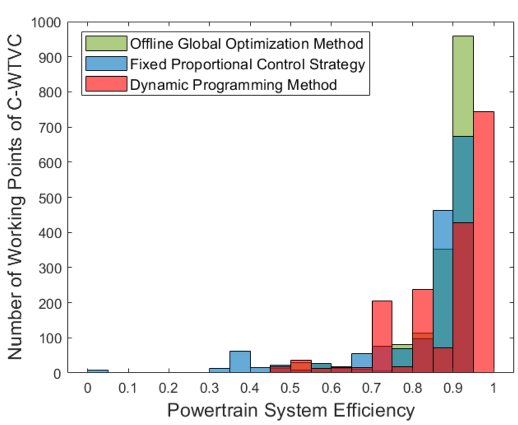

Fig 9 Efficiency comparison of two control strategies

As can be seen in Figure 9, the efficiency of the powertrain system using DP and offline global optimization method is significantly improved compared with fixed proportional control method, where the proportion is the ratio of the maximum torque of two motors.

6. CONCLUSIONS

Powertrain control strategies using DP and an offline global optimization method are proposed for a new dual-motor powertrain system. Simulations based on MATLAB/Simulink are operated to verify the feasibility and energy efficiency of the strategies proposed as well as the efficient gear shifting law. Results show that the strategies proposed have better performance than the fixed proportional control method, that the efficiency of powertrain system is significantly improved.

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REFERENCE

[1] Congbo Li, Ruijie Chen, Yue Li, et al. Comprehensive Gear Shift Schedule of a Two-speed PEV Powertrain for Low Energy Consumption [J]. China Mechanical Engineering, 2018, v.29； No.495(15):58-65+79.

[2] Congbo Li, Yue Li, Weihong Xiao, et al. Parameters optimization of dual-motor EV powertrain for energy consuption [J]. Computer Integrated Manufacturing Systems, CIMS, 2017, 23(8):1620-1628.

[3] Minghui Hu , Shuang Chen , Jianfei Zeng. Control Strategy for the Mode Switch of a Novel Dual-Motor Coupling Powertrain [J]. IEEE Transactions on Vehicular Technology, 2017, PP(99):1-1.

[4] Mousavi M S R, Pakniyat A, Wang Tao, et al. Seamless dual brake transmission for electric vehicles: design, control and experiment [J]. Mechanism & Machine Theory, 2015, 94: 96-188.

[5] Shuangqi Li, Hongwen He, Jianwei Li, Big data driven lithium-ion battery modeling method based on SDAE-ELM algorithm and data pre-processing technology, Applied Energy, Volume 242, 2019, Pages 1259-1273, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2019.03.154.

