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Optimization of a Dual-Motor Coupled Powertrain Energy Management Strategy for a Battery Electric Bus Based on Dynamic Programming Method

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ABSTRACT As the global environment and energy problems are becoming increasingly serious, electric vehicles are expected to play an important role in current and future transportation. In this paper, the configuration of a coaxial series dual-motor coupled propulsion system is analyzed, and the optimization objective function is obtained for a power management strategy in which the control strategy is extracted based on a dynamic programming (DP) method. The simulation model of the powertrain is tested in MATLAB with different strategies under various driving cycles. The control strategies extracted from DP show that the DP/single-mode strategy (strategy based on DP under single-mode) reduces the energy cost by 8.0% and the DP/dual-mode strategy reduces it by 8.8% compared with the traditional proportional control strategy which simply distributes torques of the two electric motors according to default ratios. In addition, the DP/dual-mode strategy performs similarly well under the urban dynamometer driving schedule and UKBUS6 with reductions of 9.1% and 8.6%, respectively. Vehicle experiments are also performed with the YuTong ZK6120BEV under Chinese typical urban bus driving cycles. As a result, the DP/dual-mode control strategy reduces the energy consumption of the 6120BEV by 2.85% on average compared with the traditional proportional control strategy.

INDEX TERMS Dual-motor coupled powertrain, energy management strategy, battery electric bus, dynamic programming.

I. INTRODUCTION

Electric vehicles offer the significant advantages of low emissions and high energy conversion efficiency, and based on these benefits, applications of electric vehicles in public transportation are expected to make great contributions to addressing the growing environmental and energy problems [1]–[4]. The battery electric bus is especially outstanding due to its locally free emissions and obvious high efficiency.

As electric vehicle technology has further developed, more numerous applications of electric powertrains have appeared, including the single-motor driven powertrain, dual-motor coupled powertrain (DMCP) and multi-motor distributed powertrain. Each of these types has advantages and disadvantages. The single-motor driven powertrain has a simple structure and is easy to assemble but is not sufficiently flexible. Moreover, opportunities for continued improvement are rather limited. The multi-motor distributed powertrain is undoubtedly flexible but increases the unsprung mass to a great extent, which degrades the passing ability of the vehicle. DMCP is an innovative propulsion system that takes advantage of the lower cost, higher efficiency and better dynamic properties compared with the single-motor driven powertrain, and companies such as Siemens have already launched related products and successfully applied them to real vehicles.

However, the battery electric bus still suffers from current limitations, such as a long charging time, short endurance mileage, high price, unsatisfactory charging service and large weight [5]. Therefore, reducing the energy cost and enhancing the energy efficiency are fairly important and necessary for further application of battery electric bus. As a result, to achieve this goal, identification of an optimal and appropriate power management strategy is a high priority [6]–[8].

For a multi-power source system, the power management strategy has a direct influence on the economic performance of the system. A number of papers aimed at hybrid electric powertrain power management strategies have been published [1], [5]–[14], but studies of the novel DMCP on a battery electric bus is still much fewer than expected.

Currently, the theories that most power management strategies have adopted can be simply sorted into three varieties: the heuristic control technique [15], [16], static optimization method [17], [18] and dynamic optimization method or DP. As a control algorithm, DP considers the dynamic nature of the powertrain [19]–[21]. More specifically, the computational object is a time horizon rather than an instantaneous time. As a result, the power management strategies are more accurate with respect to transient conditions, but this approach is also more computationally expensive.

Hu *et al.* [22] established the kinetic equation of DMCP, analyzed the overall efficiency formula of the DMCP, and simultaneously formulated a mode shift strategy based on DP. Zhang *et al.* [2] extracted rules from DP and designed a power management strategy for DMCP that leverages the near optimality and adaption to multiple objectives. Wang and Sun also analyzed a dual-motor coupling propulsion system using optimization of the powertrain components, but details of the operational control strategy for the two motors were not included [23]. Coronado and Garza [24] established a control strategy that uses the electric motor speeds and the demand torque as the inputs. The control strategy can be tuned using two parameters: the transition speed and the transition torque request signal.

In this paper, DP is used to solve the optimal power management strategy problem for a dual-motor coupled electric bus. The propulsion system of the urban electric bus is analyzed, and the objective functions are defined to realize energy distribution control of the electric motors in single mode or dual mode. The DP problem is established and the rules are extracted simultaneously from DP. The simulation models are set up in MATLAB, and the energy consumption values of the different power management strategies are compared. Finally, bench and vehicle experiments are run to verify the control strategy, and the conclusions are presented. The results show that the control strategies extracted from DP work well in that they reduce the energy consumption more obviously than the traditional proportional control strategy.

II. ANALYSIS OF DMCP

The structure of the battery electric bus powertrain studied in this paper is shown in FIGURE 1. The torques of the main motor (M1) and the auxiliary motor (M2) are coupled on a common axis, the motors are controlled by motor controller 1 (MC1) and motor controller 2 (MC2), and the output torque of the drive assembly is the summation of M1 and M2, i.e.,

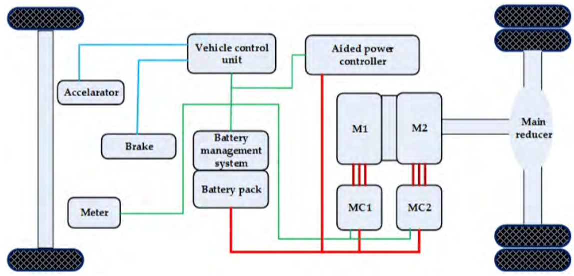

FIGURE 1. Configuration of the dual-motor coupled battery electric bus.

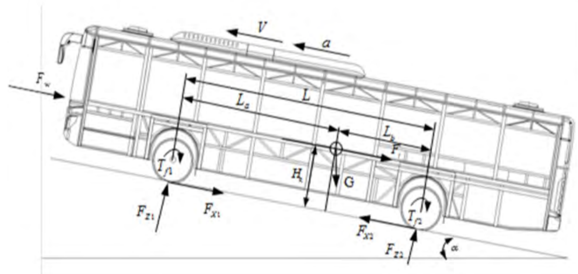

FIGURE 2. Force analysis of the battery electric bus.

$$T_{out} = T_1 + T_2 \tag{1}$$

The force analysis for the battery electric bus is shown in FIGURE 2, and the driving equation of the vehicle is written as follows:

$$F_t = F_f + F_w + F_i + F_j \tag{2}$$

Where Ft is the driving force, Ff is the frictional resistance, Fw is the windage resistance, Fi is the grade resistance and Fj is the acceleration resistance. To simplify the design and manufacture of electric motors and buses, miniaturization of electric motors conforms to the aims of modularization design and exploitation. Using the urban battery electric bus as an example, the core vehicle types include the 6- to 7-metre type, 8- to 9-metre type, 10- to 12-metre type and 16- to 18-metre type. Considering the empirical value of the drive assembly's output, the corresponding required torques are 1000 Nm, 2000 Nm, 3000 Nm and 4000 Nm. Using modularization design, we can satisfy the requirements for all of the abovementioned vehicle types by coupling the 1000 Nm electric motor and 2000 Nm electric motor(1000 Nm and 2000 Nm electric motors coupled for the 3000 Nm type bus, and two 2000 Nm electric motors coupled for the 4000 Nm type). As a result, motor manufacturers could eventually decrease their product prices as the varieties of electric motors decrease and the output increases.

III. ANALYSIS OF THE SYSTEMATIC ENERGY DISTRIBUTION CONTROL PROBLEM

The coaxial dual-motor coupled urban electric bus is a multi-power source system. The energy distribution control in this type of system must be built using explicit systematic requirements. This paper distributes the required control to each execution unit using the control algorithm, and herein, the state-space model is expressed as follows:

$$\begin{cases} \dot{x} = f(x) + g(x)v \\ v = Bu \\ y = h(x) \end{cases} \tag{3}$$

where x is the state vector of the system, y is the output vector, v is the generalized control vector, B is the efficiency matrix and u is the control vector, an $dx \in R^{nx}, y \in R^{ny}, v \in R^m, u \in R^p, B \in R^{m\times p}.f(x), g(x), h(x)$ are general nonlinear functions. For a multi-power source system, the quantity of execution units tends to be greater than that of the generalized requirement, i.e., $p > m$, and the solution of the system is not unique. The general optimized objective function of systematic energy distribution control problem can be described as follows:

$$minJ = \|Bu - v\| + \lambda \left\|u - u_p\right\| \tag{4}$$

where $u_{min} \leq u \leq u_{max}$, and by introducing the weighted factor λ, our optimized objective function contains the systematic error and controlling minimum. Additionally, $\|Bu - v\|$ is the systematic error, $\left\|u - u_p\right\|$ is the amplitude of the controlled variable, and when $u_p = 0$, the variable is minimum.

A. ANALYSIS OF THE SYSTEM'S EFFICIENCY

The power source for the battery electric bus propulsion system is high-voltage direct current supplied by the battery pack and is transformed into a three-phase alternating current by the DC/AC converter. The motors transform the electricity into mechanical energy to drive the vehicle. Many varieties of energy loss are unavoidable in the abovementioned process, including copper loss, iron loss, and mechanical loss, as shown in FIGURE 3. The efficiency of the system is defined as the specific value of output power and input power:

$$\eta = P_{out}/P_{in} \tag{5}$$

Considering that the system could operate as either a motor or a generator, we define P_{out} as the mechanical power of the system and P_{in} as the DC busbar power. The expression for the system power varies as the working mode changes. Under the motor mode, $P_{out} = \eta P_{in.,,,}$, meaning that a portion of the electricity is transformed into mechanical energy, and $P_{in} = \eta P_{out}$ under the generator mode, which means that a portion of the mechanical energy is transformed into electricity.

The efficiency of the motor system has a direct influence on the economy of the automobile. FIGURE 4 shows the efficiency characteristic diagram of M1, which shows how the motor performs relatively worse with respect to efficiency when operating under the low velocity zone and the low torque zone. Considering the complicated working conditions, the operating points of the motor vary with time, and thus the distribution of the operating points directly determines the energy cost of the system. The operating points of the dual-motor system studied in this paper are influenced by both the working conditions and the control strategies. Therefore, the objective of this paper is to find an optimal strategy that can allow the motor to work under the high efficiency points to further decrease the energy cost and improve the economy of the vehicle.

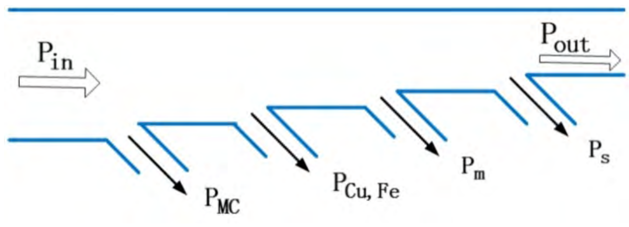

FIGURE 3. Power flow of the electric motor system.

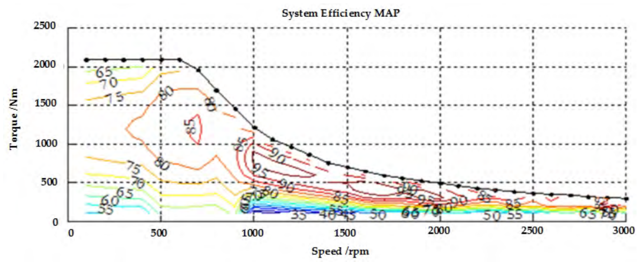

FIGURE 4. Efficiency MAP of the motor.

B. OBJECTIVE FUNCTION OF ENERGY DISTRIBUTION CONTROL UNDER SINGLE MODE

The electric motors studied in this work can operate in four quadrants, and for co-rotation, they can operate in both motor mode and generator mode, as does the inversion. For a coaxial series dual-motor propulsion system, the powertrain energy distribution control problem can be classified into two categories: single mode (both motors operate in the same mode, i.e., motor or generator mode) and dual mode (one motor operates in motor mode and the other operates in either mode).

Optimization of the objective function under a single mode aims to decrease the energy cost:

$$\begin{cases} minJ = P_{in} + \lambda \|u\| \\ u_{i,min} \leq u \leq u_{i,max} \end{cases} \tag{6}$$

where $u_{i,min}$, $u_{i,max}$ show the range of the main and auxiliary motor driving torque, P_{in} is the consumed power, λ is the weighting coefficient, $\|u\|$ is the rangeability of the control variable, and $minJ = P_{in} + \lambda \|u\|$ describes the optimization objective of energy distribution control under a single mode.

The system power can be expressed as follows:

$$P_{in} = P_{1in} + P_{2in} + \cdots = \sum_{i=1}^{p} (P_{iout}(u_i)/\eta_{iout}(u_i)) \quad (7)$$

P_{in} is the total input power (namely, the instantaneous energy consumption), P_{iin} is the electric power of every single motor, $P_{iout}(u_i)$ represents the mechanical output power of each single motor under the corresponding state, $\eta_{iout}(u_i)$ is the efficiency of the motor system accordingly, and the specific values of $P_{iout}(u_i)$ and $\eta_{iout}(u_i)$ are decided by the systematic design and the motor efficiency experiment.

The optimization objective function of energy distribution control is shown as follows:

$$\begin{cases} minJ = \sum_{i=1}^{p} P_{iout}(u_i)/\eta_{iout}(u_i) + \lambda \|u_i\| \\ u_{i,min} \le u_i \le u_{i,max} \end{cases} \quad (8)$$

and under single-mode operation, we have $0 \le u_i \le u_{i,max}$, $u_{i,max}$ as the maximum current torque of the motor.

C. OBJECTIVE FUNCTION OF ENERGY DISTRIBUTION CONTROL UNDER DUAL MODE

Under dual-mode operation, the efficiency of the electric motor varies in different modes. To correct the state-space model, we extend the control efficiency matrix B, where $B_D = \left[B \; B_q \right] \in R^{m\times(p+q)}$, wwhereB is the matrix under motor mode, and B_q is the matrix under generator mode. We introduce u' to represent the generator control vector under dual-mode operation such that the system control vector changes to $\left[u^T \; u'^T \right]^T$, and the control distribution model under dual-mode is adapted as follows:

$$\begin{cases} \dot{x} = f(x) + g(x)v \\ v = B_D \left[u^T \; u'^T \right]^T \\ y = h(x) \end{cases} \quad (9)$$

The objective function is established for energy consumption optimization under dual-mode operation:

$$\begin{cases} minJ = P_{in} + \lambda \left\| \left[u^T \; u'^T \right]^T \right\| \\ u_{i,min} \le u \le u_{i,max} \\ u_{i,min}' \le u' \le u_{i,max}' \\ uu' = 0 \end{cases} \quad (10)$$

where u_i' is the upper and lower limit under generator mode, and $u_i u_i' = 0$ means that one electric motor can only operate under one mode, i.e., motor mode or generator mode.

Under dual-mode operation, the input power of the system contains not only the consumed power under motor mode but also the feedback power under the generator mode, where $\eta_{iout}(u_i)$ still represents the systematic efficiency under the motor mode, $\eta_{iout}(u_i')$ represents the efficiency under generator mode, $P_{iout}(u_i)$ is the mechanical output power under the motor mode, and $P_{iout}(u_i')$ is the mechanical recycling power under the generator mode, and thus the total input power of the system is written as follows:

$$P_{in} = \sum_{i=1}^{p} P_{iout}(u_i)/\eta_{iout}(u_i) - \sum_{i=1}^{q} P_{iout}(u_i')\,\eta_{iout}(u_i') \quad (11)$$

The optimization function of control distribution under dual-mode is stated as follows

$$\begin{cases} minJ = \begin{pmatrix} \sum_{i=1}^{p} P_{iout}(u_i)/\eta_{iout}(u_i) \\ - \sum_{i=1}^{q} P_{iout}(u_i')\,\eta_{iout}(u_i') \end{pmatrix} + \lambda \left\| \left[u_i \; u_i' \right]^T \right\| \\ u_{i,min} \le u_i \le u_{i,max} \\ u'_{i,min} \le u'_i \le u'_{i,max} \\ u_i u_i' = 0 \end{cases} \quad (12)$$

IV. ESTABLISHMENT AND SOLUTION OF THE dp PROBLEM

The control distribution optimization problem of the coaxial series DMCP can be described using the following discrete dynamic system:

$$x(k+1) = f(x(k), u(k)) \quad (13)$$

where $x(k)$ is the state vector, $u(k)$ is the control vector, and $f(x(k), u(k))$ is the state equation of the system. For the propulsion system discussed in this paper, the main motor and auxiliary motor are coaxial and torque coupled, which means that the two motors operate at the same speed. According to the quasi-static principle, we simplify the battery electric bus model, and by analyzing the model, we observe that the control distribution problem is primarily focused on the operating points, and the distribution can result in different system efficiencies, further leading to various electric powers.

The control variable u(k) consists of T1 and T2. For the powertrain discussed in this paper, we ignore the transmission efficiency loss, and the output torque isthus$T_e = T_1 + T_2$. For a certain moment, we can calculate the left torque when T1 or T2 is known, and thus only one controlled quantity exists. Using the analysis, we determine that the control strategy for the coaxial series DMCP is a torque distribution strategy that defines the allocation proportion of the main and auxiliary motors.

Herein, we translate the various electric powers into SOC of the battery pack as the quantity of state:

$$SOC(k+1) = SOC(k) - P_{in}(k)/V_{bat}(k)/Q_{bat} \quad (14)$$

Where Q_{bat} is the capacity of the battery.

The objectives of the control strategy are to minimize the cost function of energy cost under the constraint condition and to ensure the dynamic performance and real time response.

DP is based on the Bellman Optimality Principle [25], and Bellman notes that the characteristic of the optimal strategy in a multilevel decision-making process is such that when any level or state is chosen as the original level or original state, the remaining decisions must be an optimal strategy for the real original state or the original decision. As previously mentioned, we break up the entire DP problem into a series of minimum sub-problems described as follows:

Step $N-1$:

$$J_{N-1}^{*}\left(x\left(N-1\right)\right)=min_{u(N-1)}\left[L\left(x\left(N-1\right),u\left(N-1\right)\right)\right] \tag{15}$$

Step $k, 0 \leq k \leq N-1$:

$$J_{k}^{*}\left(x\left(k\right)\right)=min_{u(k)}\left[L\left(x\left(k\right),u\left(k\right)\right)+J_{k+1}^{*}\left(x\left(k+1\right)\right)\right] \tag{16}$$

where $J_{k}^{*}(x(k))$ is the optimal accumulated cost function (meaning that the state of the system is x (k) at moment k), and the optimal control strategy is obtained by the backward method. For coaxial series DMCP, the control strategy consists of instruction sequences for the electric motor torques, i.e., $u^{*}(1)\,u^{*}(2)\cdots u^{*}(N-1)$.

Assuming that there are N sampling points in the driving cycle, the DP method takes from sampling point N and ends up with point 1, determines the optimal solution of each point, and eventually finds the optimal control path according to the optimal solution under the original condition from point 1 to point N, thereby obtaining optimal control of the driving cycle. The objective of our optimization is to obtain the control vector u (k) that minimizes the accumulated cost function.

According to the above analysis, we define the accumulated cost function as follows:

$$J=lim_{N\rightarrow\infty}\sum_{k=0}^{N-1}L\left(x\left(k\right),u\left(k\right)\right) \tag{17}$$

We define the instantaneous cost function as follows:

$$L\left(x\left(k\right),u\left(k\right)\right)=L_{E-fuel}\left(k\right)+\lambda L_{\Delta T}\left(k\right) \tag{18}$$

The constraint of the control distribution optimization problem for coaxial DMCP is stated as follows:

$$\begin{cases} \mathrm{SOC_{min}} \leq SOC\,(\mathrm{k}) \leq \mathrm{SOC_{max}} \\ T_{i,min}\left(n_i\left(k\right)\right) \leq T_i\left(k\right) \leq T_{i,max}\left(n_i\left(k\right)\right) \\ \mathrm{n_{i,min}} \leq \mathrm{n_i}\,(\mathrm{k}) \leq \mathrm{n_{i,max}} \\ \mathrm{i}=1,2 \end{cases} \tag{19}$$

From the above analysis, the control distribution optimization problem for the coaxial dual-motor coupled propulsion system of a battery electric bus changes to a multistep decision problem that we can solve with the DP method under a known condition. The solution obtained based on DP is a group of optimal control paths. If the original state is certain, the optimal control strategy finds a path that can minimize the energy cost of the powertrain and simultaneously ensure that the response can follow the dynamic requirement [7].

TABLE 1. Basic parameters of the ZK6120BEV.

Designation	Parameter
Maximum total mass （kg）	18000
Curb weight （kg）	12800
Windward area（m^2）	7.98
Drag coefficient	0.65
Rolling radius （m）	0.465
Final ratio	6.2
Mechanical transmission efficiency	0.95
Effective depth of discharging	0.85

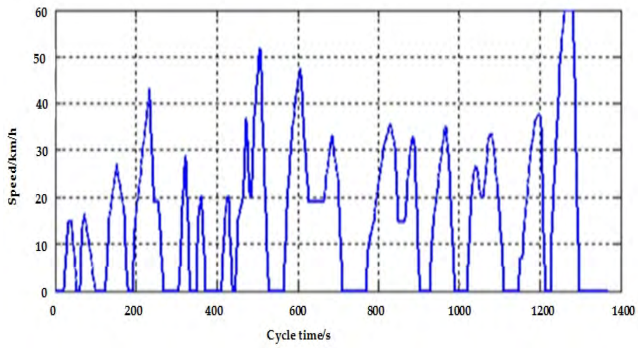

FIGURE 5. CUDC curve.

V. SIMULATION AND ANALYSIS

We realize the above DP problem using MATLAB programming and solve it with the kernel program of the DP algorithm, simultaneously choosing CUDC as the optimizing condition. CUDC is shown in FIGURE 5, the cycle time is 1314 seconds, and the mileage is approximately 5.8 km. We optimize the energy distribution control strategy of single-mode and dual-mode operation with DP under this condition. The contrast control method is the proportional control strategy which distributes torques of the two electric motors according to the default ratio TSR, and it's calculated by the following formula:

$$\boldsymbol{T}_{\mathbf{1}\_max}\left(\boldsymbol{n}\right)/(\boldsymbol{T}_{\mathbf{1}\_max}\left(\boldsymbol{n}\right)+\boldsymbol{T}_{\mathbf{2}\_max}\left(\boldsymbol{n}\right)) \tag{20}$$

The required torque obtained by the simulation is shown in FIGURE 6

The parameters of the model in the simulation is shown in Table 1 which derived from YuTong ZK6120 which is used in vehicle test, the parameters of the bench test are also the same.

A. SIMULATION ANALYSIS UNDER A SINGLE MODE

When the system operates in single mode, the SOC changes as shown in FIGURE 7 under the CUDC condition, and the distributions for torque and operating points are shown in FIGUREs 8-10. From the aforementioned FIGUREs, we observe that SOC decreases to 85.8% from 90%, and most operating points of M1 and M2 appear in the higher efficiency zone.

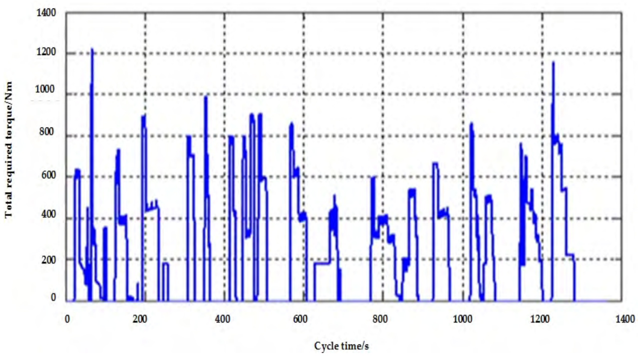

FIGURE 6. Total required torque under CUDC.

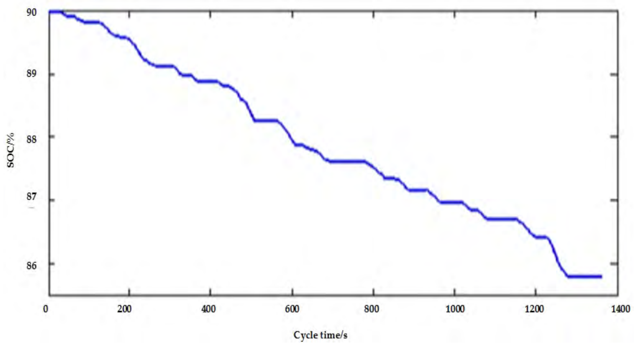

FIGURE 7. SOC curve under single-mode operation

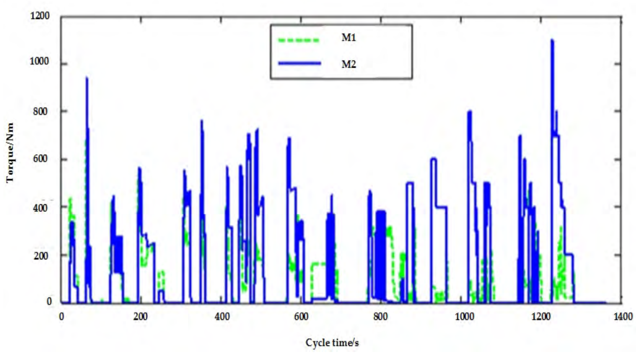

FIGURE 8. Torque distribution of M1/M2 under single-mode operation.

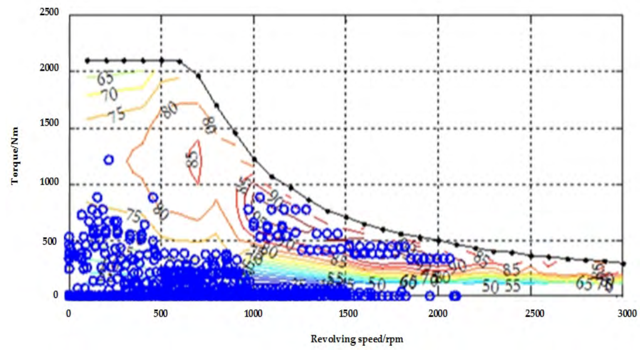

FIGURE 9. Operating point distribution of M1 under single-mode operation.

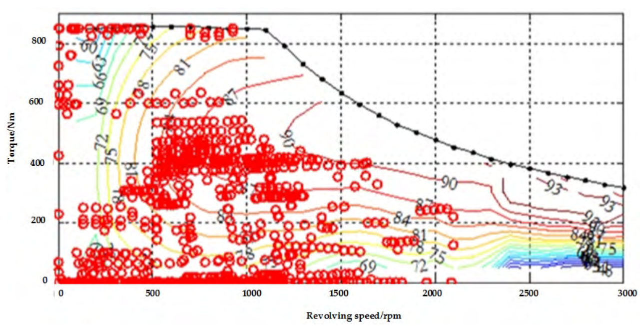

FIGURE 10. Operating point distribution of M2 under single-mode operation.

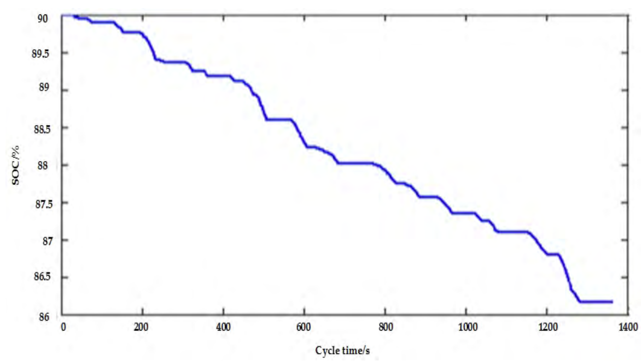

FIGURE 11. SOC curve under dual-mode operation.

From FIGURE 9 and 10, we note that all operating points are distributed within the scope of 0-2100 rpm because the highest speed in this cycle is 60 km/h. In addition, many points appear in the low speed and low torque zone. Considering this phenomenon, we conclude that the control strategy under single mode cannot avoid the lower efficiency zone, and in theory, the dual-mode control strategy is more flexible, and the optimization effects should be more significant.

B. SIMULATION ANALYSIS UNDER DUAL-MODE OPERATION

Considering that the torque range of M1 is larger than that of M2, we change the constraint conditions of M2 to operation under dual mode, and the simulation results for dual-mode operation are shown in FIGUREs 11-14.

From the above figures, we observe that SOC decreases from 90% to 86.2%, and most operating points of M1 and M2 are in the high efficiency zone. Simultaneously, inverse torque operating points appear for M2, i.e., M2 operates in generator mode occasionally. Dual mode makes the torque distribution more flexible compared with the proportional control strategy, additional operating points appear in the high efficiency zone, and simultaneously, the efficiency of M1 under low speed and low torque condition increases as the result of M2 operating as a generator.

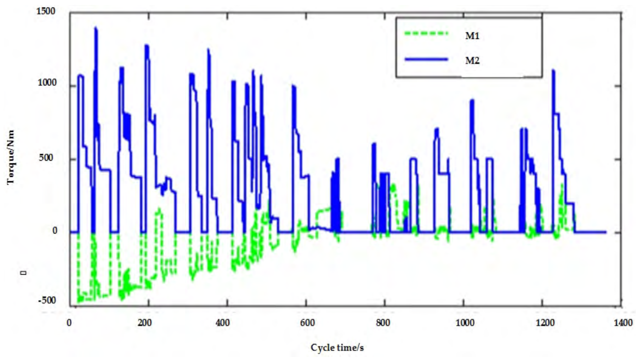

FIGURE 12. Torque distribution of M1/M2 under dual-mode operation.

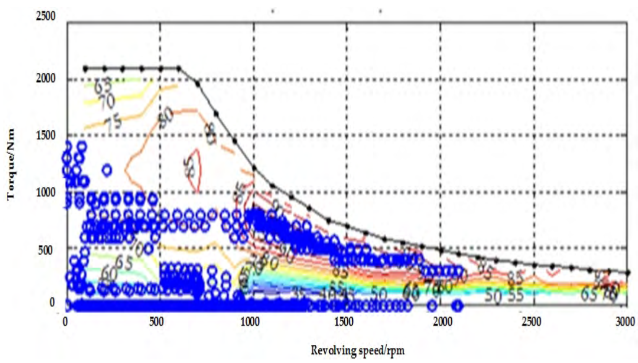

FIGURE 13. Operating point distribution of M1 under dual-mode operation.

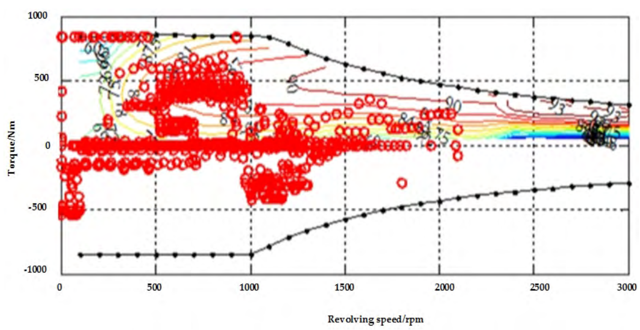

FIGURE 14. Operating point distribution of M2 under dual-mode operation.

Considering the applicability of the control strategy, adoption of CUDC only is not sufficient to reflect readiness for operation, and thus we introduce UDDS and UKBUS6 as driving cycles optimized by DP. The curves of the driving cycles and optimization results are shown in FIGURE 15 and FIGURE 16.

C. ANALYSIS OF ENERGY CONSUMPTION OF THE SYSTEM

The energy consumption of the system is shown in Table 2. We observe that the DP algorithm can effectively reduce the energy consumption of the bus, and the overall economy can be enhanced using the optimal control strategy by more than 8% compared with the traditional proportional control strategy. At the same time, DP shows better performance under dual-mode operation.

Table 3 presents the energy consumption under the UDDS and UKBUS6 working conditions.

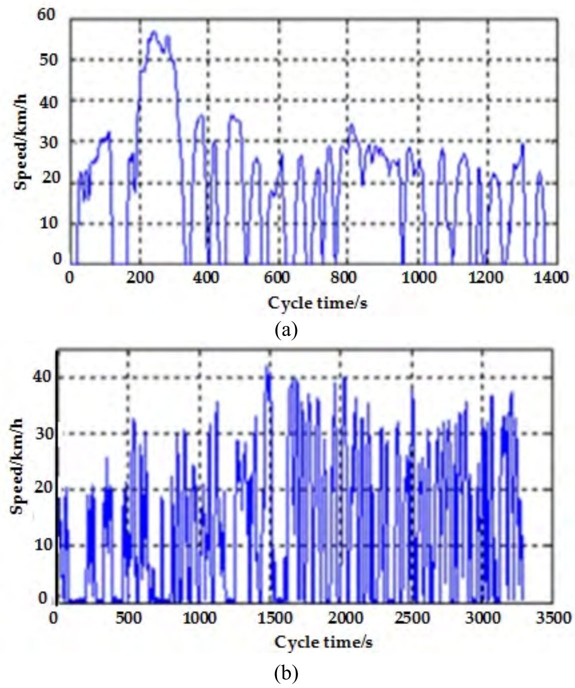

FIGURE 15. Curves of different driving cycles. (a) UDDS. (b) UKBUS6.

TABLE 2. Energy consumption of 6120BEV with different control strategies under CUDC.

Control strategy	Energy consumption （kWh/100 km）	Percentage of advance
proportional control strategy	120.1	--
DP/single-mode	110.5	8.0%
DP/dual-mode	109.5	8.8%

TABLE 3. Energy consumption of 6120BEV with different control strategies under UDDS and UKBUS6

Driving cycle	Control strategy	Energy consumption (kWh/100 km)	Percentage of advance
UDDS	proportional control strategy	110.3	--
	DP/dual-mode	100.29	9.1%
UKBUS6	proportional control strategy	131.4	--
	DP/dual-mode	120.1	8.6%

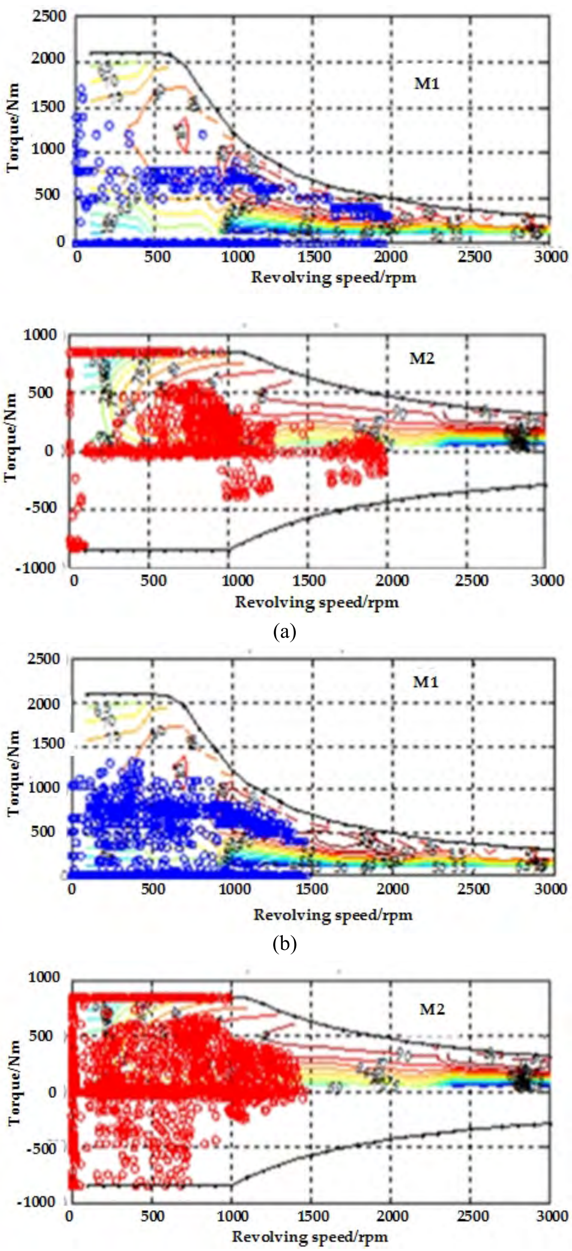

FIGURE 16. Distribution map under different working conditions under dual-mode operation. (a) Distribution map under UDDS. (b) Distribution map under UKBUS6.

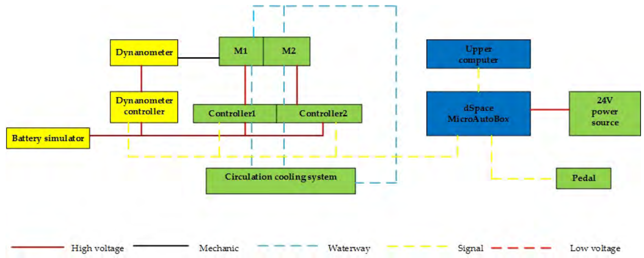

FIGURE 17. Configuration of the experimental bench.

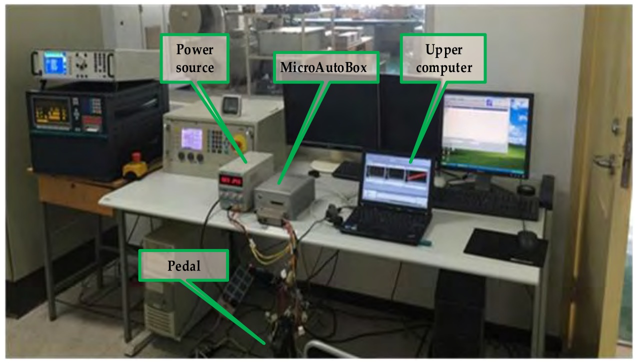

FIGURE 18. Control module of the bench.

VI. EXPERIMENTAL VERIFICATION OF THE CONTROL STRATEGY

A. BENCH TEST BASED ON DsPACE

We construct a rapid controller experimental bench based on dSpace with an existing dual-motor powertrain to perform experimental verification of the optimization of the dual-motor coupled propulsion system. The configuration of the bench is shown in FIGURE 17.

In this work, we adopt CUDC as the working condition, and to get more convincing test results, we additionally introduce 0-40km/h driving cycle to our bench and vehicle tests which is shown in FIGURE 21. We download the control strategies extracted from the proportional control model and the DP model to the MicroAutoBox to perform our experiments.

From FIGURE 20-22, we observe obvious differences between the two strategies, namely, the one extracted from DP makes the torque distribution more flexible and the electric motors operate under higher efficiency points.

As a result of considering only the energy consumption of the propulsion system and because the efficiency problem of the battery does not exist in the bench, the energy consumption of the powertrain is less than the simulated value obtained above. From lateral comparison of data in Table 4, we note that the DP strategy decreases energy consumption to a larger extent than the proportional strategy, by 2.78% and 3.17%, showing that the optimal control strategy can enhance the economy of the battery electric bus effectively.

B. VEHICLE EXPERIMENT

According to the characteristics of the dual-motor propulsion system, we update the network topology of the battery electric bus, and the CAN network topology of the vehicle after the upgrade is shown in FIGURE 23.

In the experiment, our dual-motor powertrain is installed on a YuTong ZK6120, which is a 12-metre battery electric bus that adopts full CAN meters, and the parameters of the bus are listed in Table1.

To better access the control effects of the proportional strategy and the optimal strategy extracted from DP, we design a vehicle experiment similar to the bench simulation. The method applies circulating tests on a chassis dynamometer

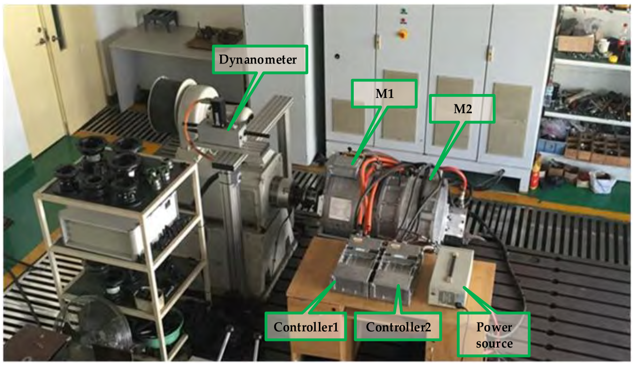

FIGURE 19. Test module of the bench.

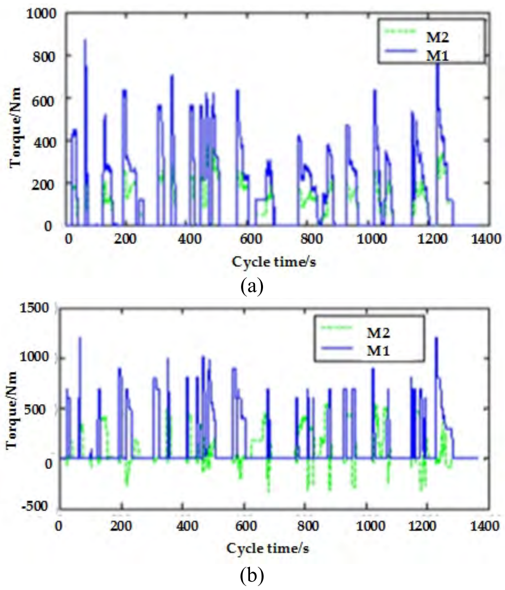

FIGURE 20. Torque distribution of different control strategies under CUDC. (a) Proportional control strategy. (b) DP/dual mode.

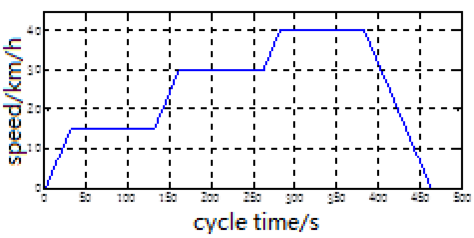

FIGURE 21. 0-40km/h driving cycle.

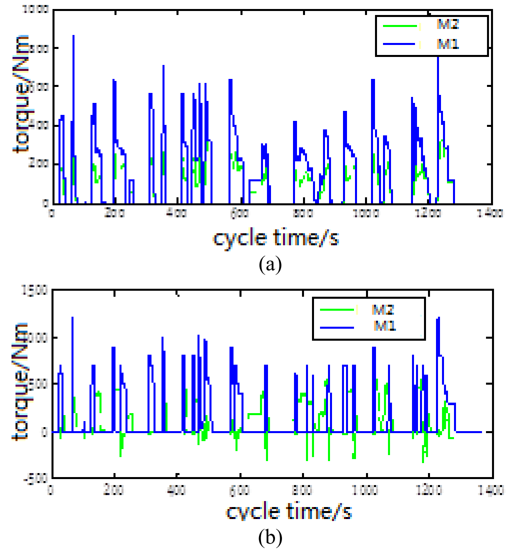

FIGURE 22. Torque distribution of different control strategies under 0-40km/h driving cycle. (a) Proportional control strategy. (b) DP/dual mode.

TABLE 4. Energy consumption of the bench with different control strategies under CUDC and 0-40km/h driving cycle.

Control strategies	Energy consumption (kWh/100 km)		percentage
proportional control strategy	CUDC	100.9	--
	0-40km/h	50.4	--
DP/dual-mode	CUDC	98.1	2.78%
	0-40km/h	48.8	3.17%

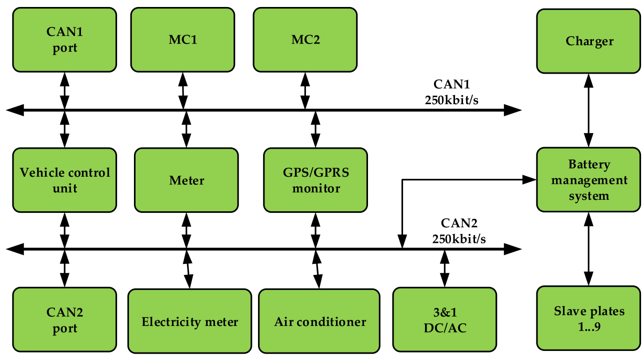

FIGURE 23. Vehicle CAN network topology.

under CUDC and 0-40km/h driving cycle with the above-mentioned vehicle, and the dynamometer simulates the road resistance according to the cycle speed. The driver can view the driving cycle through the aided monitor and controls the vehicle to follow the objective speed while the fan simultaneously simulates the wind resistance. During the driving cycle, devices such as the CAN card record the vehicle messages and other information. The experimental process is shown in FIGURE 25.

FIGURE 26-27 shows the situations of speed following under different driving cycles..

The energy consumption curves of a single test under different control strategies are shown in FIGURE 28-29, and the difference between them is the consumption difference value in one cycle. We process the data obtained from the two experiments and obtain the energy consumption for 100 km, as shown in Table 5. The optimal control strategy decreases the energy consumption to a greater extent than the

FIGURE 24. Battery electric bus adopted in the experiment.

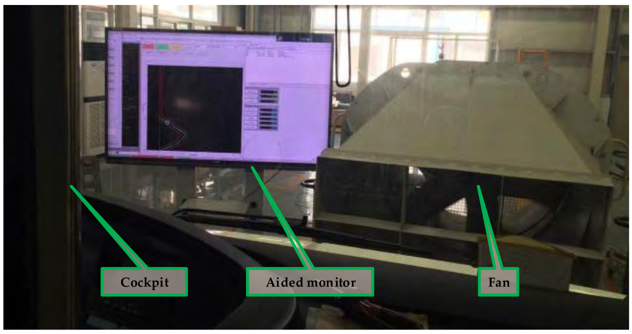

FIGURE 25. Vehicle experiment.

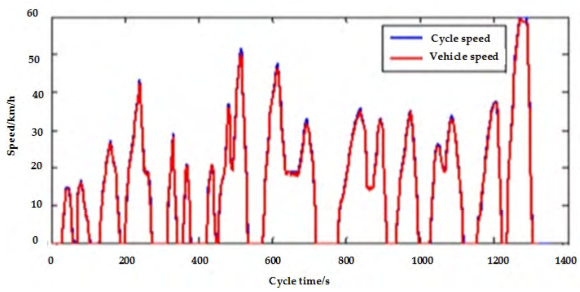

FIGURE 26. Situations of speed following under CUDC.

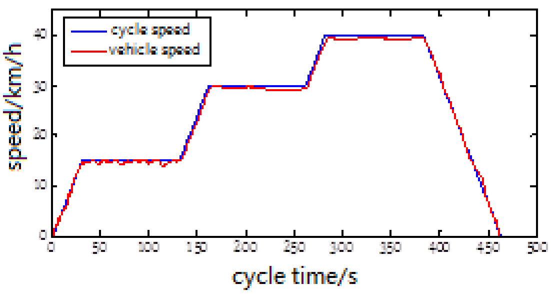

FIGURE 27. Situations of speed following under 0-40km/h driving cycle.

proportional control strategy, by 2.9%/ 2.8% and 6.57%/ 5.77%.The results are obviously lower than that of the simulation(8.8%), this could attribute to the extraction process and

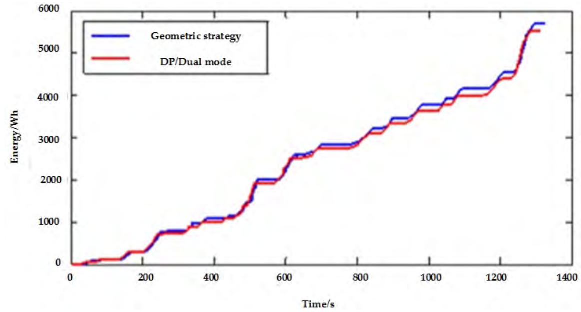

FIGURE 28. Energy consumption under different strategies under CUDC.

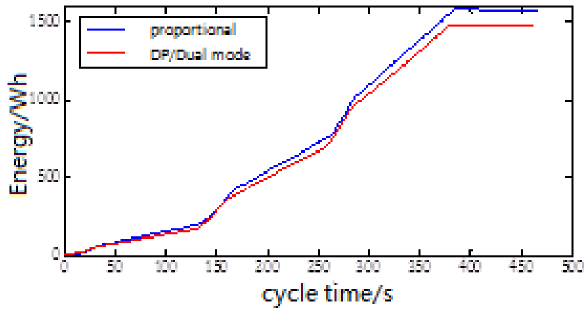

FIGURE 29. Energy consumption under different strategies under 0-40km/h driving cycle.

TABLE 5. Energy consumption of 6120BEV in vehicle test.

Vehicle test		Energy consumption (kWh/100 km)	Percentage
Proportional strategy 1/2	CUDC	100.1/99.6	--
	0-40km/h	49.42/49.21	--
DP/dual mode 1/2	CUDC	97.24/96.8	2.9%/2.8%
	0-40km/h	46.17/46.37	6.57%/5.77%

the influence of the battery. Meanwhile 8.8% is the theoretical limit which is hard to achieve.

VII. CONCLUSION

This paper analyzed the configuration of propulsion systems on an electric bus and performed optimization studies on power management of a multi-power propulsion system using global optimization theory based on DP. We established a mathematically optimal model in which SOC is chosen as the state variable and the torque of the electric motors serves as the control variable. Simultaneously, an evaluation function was defined based on energy consumption of the system. We performed the optimization process in MATLAB under variations of the bus driving cycles and extracted control strategies to verify the control effect in the simulation model. The simulation result shows that the power management strategies extracted from DP could optimize the operation points of the electric motors with obvious positive effects and consequently improve the efficiency of the system and decrease the energy consumption. Finally, bench and vehicle tests were performed, and the control strategies based on DP method showed better properties than the traditional proportional strategy. Our optimization offers lessons for other multi-power propulsion system such as the multi-motor distributed powertrain.

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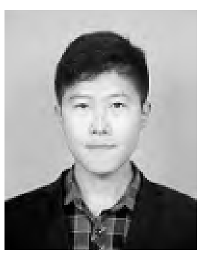

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