Research Article

Powertrain Matching and Optimization of Dual-Motor Hybrid Driving System for Electric Vehicle Based on Quantum Genetic Intelligent Algorithm

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In order to increase the driving range and improve the overall performance of all-electric vehicles, a new dual-motor hybrid driving system with two power sources was proposed. This system achieved torque-speed coupling between the two power sources and greatly improved the high performance working range of the motors; at the same time, continuously variable transmission (CVT) was achieved to efficiently increase the driving range. The power system parameters were determined using the “global optimization method”; thus, the vehicle’s dynamics and economy were used as the optimization indexes. Based on preliminary matches, quantum genetic algorithm was introduced to optimize the matching in the dual-motor hybrid power system. Backward simulation was performed on the combined simulation platform of Matlab/Simulink and AVL-Cruise to optimize, simulate, and verify the system parameters of the transmission system. Results showed that quantum genetic algorithms exhibited good global optimization capability and convergence in dealing with multiobjective and multiparameter optimization. The dual-motor hybrid-driving system for electric cars satisfied the dynamic performance and economy requirements of design, efficiently increasing the driving range of the car, having high performance, and reducing energy consumption of 15.6% compared with the conventional electric vehicle with single-speed reducers.

1. Introduction

The global energy consumption continues to increase, while the oil resources are depleted with time; this is accompanied by worsening air pollution, causing governments and companies worldwide to consider energy conservation as the main consideration in future development of vehicle technologies [1]. The development of electric vehicles and related critical technologies is one of the most efficient approaches to realize energy conservation and environmental protection [2, 3]. The new-energy vehicles include hybrid vehicles, all-electric vehicles, and fuel cell vehicles; the development of such vehicles is essential for realizing national energy safety and environmental protection as well as the healthy and sustainable development of the automotive industry. In all-electric cars, batteries are used to store energy and electric motors are used for propulsion. Unlike hybrid cars, all-electric cars have

the advantages of zero emission, reduced noise, and simple structure—this promises a bright future for industries and, hence, has received much attention from governments and auto companies around the world [4–7]. The power system is an important component of an electric car, and it mainly comprises the motor propulsion system and mechanical transmission system. It functions by converting electrical energy from the energy storage device to mechanical energy for propelling the car to overcome any driving resistances and by converting the vehicle’s kinetic energy to electrical energy that is stored in the storage device during deceleration and braking—such a braking action is termed regenerative braking [8, 9]. An electric motor drive system is composed of an electric motor, an inverter, and an electric motor controller, and it is one of the factors determining a car’s overall performance. The requirements for the motor drive system of electric vehicles are much more stringent than

those for the motor drive system used for conventional industrial purposes: the drive system must have good speed and torque control capability, a wide speed range, relatively wide high performance working range, high power-to-weight ratio, good environmental adaptability, good reliability, and so forth [7, 10, 11].

Currently, the major motor drive systems for electric cars include the induction motor drive system, permanent magnet synchronous motor drive system, brushless DC motor drive system, switched reluctance motor drive system, and others that are designed by modifying the aforementioned systems. Among these systems, the permanent magnet synchronous motor drive system shows the best overall performance; the advantages of this system include high power density, small size, low weight, and high performance. It is the most popular motor drive system for electric cars [12–14]. The power system of all-electric cars mainly comprises a single motor and a transmission device. Such a structure yields low performance under low speed-low load, low speed-high load, and high speed-low load conditions; it also has a short driving range. With the development in motor control technology, consumers' expectations regarding car performance have increased; in particular, from the perspectives of driving comfort and safety, automatic transmission devices and larger driving range will be the trend for all-electric cars [15–17]. Improvement in the driving range depends on battery technologies as well as the powertrain and its controlling technologies. Development of a high-performance transmission system and fully functional impact energy management control strategies for improving driving range and overall performance is the main research direction for electric car technologies [18–22].

This paper describes a new dual-motor hybrid drive system for electric cars; this system has two power sources for the hybrid propulsion of the car under different circumstances. This system greatly widens the high-performance working range of the synthetic powering sources and efficiently increases the driving range of electric cars. Further, this system has the electric continuously variable transmission (ECVT) function, which allows the for continuously variable transmission (CVT) of the power system under hybrid propulsion of the dual-motor—thus, the limitation imposed on the running range of a power source by stepped transmission gearing is removed, and the driving range is improved by broadening the speed-ratio range of the transmission system. In addition to guaranteeing driving safety, the efficiency of brake energy recovery is improved, which further increases the driving range of the all-electric cars. At the same time, the CVT also improves the driving performance of the vehicle.

Since two independent electric motors are used as the power sources in the dual-motor hybrid drive system, the dual motor cars are very different from conventional electric cars in terms of driving modes. Although the configuration of the transmission system remains the same, the dual-motor cars have several transmission patterns: the main/auxiliary electric transmission pattern, in which two motors can work in parallel or in series based on power demand; the hybrid drive transmission pattern, in which two motors work in parallel; and the speed-controlling electric transmission

pattern, in which the dominant motor exclusively provides acceleration, while the auxiliary motor adjusts the speed. Thus, there is a big difference between the design of the power system of the dual-motor electric cars and that of the current electric cars. In the present study, parameters design was conducted for the transmission system by using intelligent algorithms, in which the quantum genetic algorithm was introduced to match and optimize calculation, to obtain the optimal critical parameters for the power system.

2. System Structure and Working Modes of the Hybrid Drive System

A schematic of the dual-motor hybrid drive system proposed in the current study is shown in Figure 1. This system comprises a single-stage planetary gear set, two permanent-magnet synchronous motors, two brakes, and a clutch. The sun gear in the planetary gear is directly connected to the output shaft of motor B; ring gear c can be directly connected to the output shaft of motor A by rolling gear e or to the sun gear a through clutch C1; planet carrier d is connected to the axle through the universal transmission device to export power; the movable part of brake B1 is connected to the box body, while its fixed part is connected to the output shaft of motor A, and this part enables ring gear c to roll through brake B1; the movable part of brake B2 is connected to the box body, and the fixed part is connected to the output shaft of motor B, and this part enables sun gear a to roll through brake B2.

The determination of the working mode is one of the core issues in studying the power system. The goal is to properly distribute the desired torque among motors A and B based on the current condition of the car (speed, driving mode, pedal strength, etc.), in order to obtain good economy and dynamics. Rolling and braking of the sun gear and ring gears lead to their connection and disconnection, which enables switching between different working modes for the hybrid propulsion of the dual-motor car. Based on the working status of motors A and B, the brakes, and the clutch, eight working modes were determined in the current study, as shown in Table 1.

The dual-motor hybrid drive power system belongs to the category of multiple power sources: motors A and B can be used as the sources for mechanical power for the propulsion of the car as electrical power sources and as generators during braking actions [23, 24]. When braking and parking the car, the motors are shut down, both brakes are activated, and the clutch is released in order to meet the requirements for the car to park. When the car has to be maintained in neutral position, the motors are shut down, and the brakes and the clutch are all released. When the car is going at a relatively high speed, motor A exclusively powers the car, while brake B2 is used for braking; the sun gear is locked, and the power input of motor A is achieved by rolling the gear and ring gear while its power output is achieved via the planet carrier. This helps achieve the desired power output after deceleration at low speed ratio and meet the low torque requirement of the car. When the car is going at a relatively low speed,

FIGURE 1: Overall structure.

TABLE 1: Work mode summary.

Work mode	Motor A	Motor B	B1	B2	C1	Vehicle state
Parking braking	Off	Off	Off	Brake	Off	Stop
Neutral position	Off	Off	Off	Off	Off	Stop taxiing
Motor A driving	On	Off	Off	Brake	Off	Low and medium load
Motor B driving	Off	On	Brake	Off	Off	Low and medium load
Hybrid driving a	On	On	Off	Off	Off	Speed coupling, CVT
Hybrid driving b	On	On	Off	Off	On	Torque coupling, climbing
Regenerative braking a	On	Off	Off	Brake	Off	Braking, reduced speed
Regenerative braking b	Off	On	Brake	Off	Off	Braking, reduced speed

motor B exclusively powers the car, while brake B1 is used for braking: the rolling gear is locked, and the ring gear is therefore locked; power input and output of motor B are achieved by the sun gear and the planet carrier, respectively, to achieve power output after deceleration at large speed ratio and meet the high torque requirement. When the car is under median load, the brakes and clutch are all released, and the planetary gear set are unlocked; motors A and B achieve speed coupling and hybrid propulsion through the planetary gear set and thus achieve continuously variable transmission. When the car is under a large load (e.g., during climbing and overloaded start), both brakes are released and the clutch is attached, and the planetary gear set is locked to become a whole body for motors A and B to achieve torque coupling for the hybrid propulsion of the car. When the car is decelerating, regenerative braking of motor A or B is achieved by controlling the conditions of the two brakes. When switching the working mode, the motors regulate and control the system through zero speed torque, in order to achieve a relatively small resultant moment of the sun gear and ring gear. The motors are sufficiently used to regulate and achieve flexible switching between the modes, which can conveniently realize the release and attachment of the brakes and the clutch and reduce the impact when switching the gear.

3. Parameter Matching for the Dual-Motor Hybrid Drive System

Parameter matching for the power system is an important step in the design and development of all-electric cars. This step focuses mainly on the selection of the system components and parameter design for the power system according to the design requirement of the vehicle. Compared to the structures of hybrid cars and fuel cell cars, structures of all-electric cars are relatively simple—the power system mainly comprises the electric motor, battery, and transmission system, which are also considered for parameter matching [25].

4. Calculation of the Total Power Demand

The dual-motor hybrid drive system is the direct powering source for a vehicle, and, therefore, its parameters were determined by considering the requirements for regular driving as well as the dynamic performance [26, 27]. The regular driving requirements are as follows:

- (a) must be able to drive on a ramp with $\alpha_{\max}$ as required at the minimum and stable speed;

- (b) must be able to drive at a constant speed at the maximum $u_{\max}$;
- (c) must be able to achieve the time requirement of a vehicle to accelerate from 0 to 100 km/h.

The dynamic performance requirements are as follows.

- (a) The maximum power $P_{\alpha \max}$ is determined based on the maximum gradeability:

$$P_{\alpha \max} = \frac{u_i}{3600\eta_T} \left(mgf \cos \alpha_{\max} + mg \sin \alpha_{\max} + \frac{C_D A u_i^2}{21.15} \right), \quad (1)$$

where u_i is the lowest stabilized speed, m is vehicle mass, g is gravitational acceleration, f is rolling resistance coefficient, C_D is coefficient of aerodynamic drag, A is frontal projected area, and η_T is mechanical efficiency.

- (b) The maximum power is determined based on the maximum speed $u_{\max}$:

$$P_{u \max} = \frac{u_{\max}}{3600\eta_T} \left(mgf + \frac{C_D A u_{\max}^2}{21.15} \right). \quad (2)$$

- (c) At the end time during acceleration, the power output of the motor is the highest, and the maximum power demand during acceleration is as follows:

$$\begin{aligned} P_{j \max} &= \frac{1}{3600\eta_T} \left(\frac{\delta m v_m^2}{3.6dt} \left[1 - \left(\frac{t_m - dt}{t_m} \right)^x \right] \right. \\ &\quad \left. + mgf v_m + \frac{C_D A}{21.15} v_m^3 \right), \end{aligned} \quad (3)$$

where δ is correction coefficient of rotating mass, v_m is the speed at the end time during acceleration, t_m is acceleration time, and x is the fitting coefficient.

According to the maximum power of the three indicators of dynamic performance described above, the total power demand P_{peak} should meet all the abovementioned requirements; that is,

$$P_{\text{peak}} \geq \max(P_{u \max}, P_{\alpha \max}, P_{j \max}). \quad (4)$$

5. Parameter Matching for Electric Motors

Since electric motors have satisfactory working properties, including rated property over long working hours and peak property for short working hours, the output rated power of these motors can fulfill the power requirement for the maximum speed, while the peak power achieved by the electric motors in a short working time can fulfill the car's requirements for acceleration and climbing. Selection of the electric motors for propulsion includes the parameter

selection of motors A and B. The preliminary standards are as follows: motor B should mainly fulfill the requirements for climbing and acceleration, and the sum of the rated power of the two motors should fulfill the demand for total power. The external characteristics of the electric motors are as follows: below the rated speed, they work in a constant torque mode; above the rated speed, they work in a constant power mode. The relevant parameters for motor selection include rated power, peak power, rated speed, and the maximum speed. Since the system uses the planetary gear set, the transmission properties of the planetary gears should be taken into account when matching the motor parameters:

$$\begin{aligned} n_s + k n_r - (1 + k) n_c &= 0, \\ T_s : T_r : T_c &= 1 : k : -(1 + k), \end{aligned} \quad (5)$$

where n_s is the sun gear speed, n_r is the gear ring speed, n_c is the planet carrier speed, T_s is the sun gear torque, T_r is the gear ring torque, T_c is the planet carrier torque, and k is the planetary gear parameters; it is equal to the gear ratio between the gear ring and the sun gear.

6. Parameter Matching for Electric Motors

Based on the working mechanism and mode of the system, the matched motor parameters as well as the transmission properties of the planetary gear, the range of the planetary gear set parameter k , and the main deceleration ratio i_0 can be calculated. In order to fulfill the requirement of the maximum gradeability and the maximum speed, k and i_0 should satisfy the following conditions:

$$\begin{aligned} (1 + k) \cdot i_0 &\leq \frac{0.377 r n_A}{u_i}, \\ (1 + k) \cdot i_0 &\geq \frac{(f \cos \alpha_{\max} + \sin \alpha_{\max}) mgr}{T_{B \max} \eta_T}, \end{aligned} \quad (6)$$

$$n_{c \max} \leq \frac{n_{B \max} + k n_{A \max}}{1 + k},$$

$$n_{c \max} \geq \frac{u_{\max} \cdot i_0}{0.377 r},$$

where n_A is the rated power of motor A, $T_{B \max}$ is the peak torque of motor B, $n_{c \max}$ is the maximum speed of planet carrier, and $n_{A \max}$ is the peak speed of motor A.

7. Parameter Matching for the Battery Pack

In the current study, a lithium-ion battery pack with good properties was used. The rated voltage of a single lithium-ion battery unit is 3.2 V in the market. The battery pack has 100 units, providing a total voltage of 320 V. the capacity of the battery pack must be able to fulfill the requirements of the driving range of a car, as calculated below:

$$C = \frac{1000 P_e \cdot s}{U \cdot \xi_{\text{SOC}} \cdot v_e}, \quad (7)$$

TABLE 2: Parameter of electric vehicle.

Parameter	Value
Mass (kg)	1250
Full mass (kg)	1550
Coefficient of drag	0.33
Radius (m)	0.302
Frontal area (m ²)	2.46
Maximum speed (km/h)	≥130
Acceleration time (s)	≤14 (0~100 km/h)
Maximum gradeability (%)	≥30
Maximum range per charge/km	≥120

where P_e is the vehicle power at a constant speed, s is the driving range of design requirements, U is the battery voltage, ξ_{SOC} is battery discharge capacity coefficient effectively, which is the product of battery average efficiency and motor average efficiency, and v_e is the constant speed.

8. Results for Parameter Matching of the Dual-Motor Hybrid Drive System

Table 2 lists the technical parameters determined according to the project requirement, and Table 3 presents the preliminary matching results of the system parameters according to the abovementioned matching standards.

9. Parameter Optimization for the Dual-Motor Hybrid Drive System in All-Electric Cars

The performance of all-electric cars is largely dependent on the performance levels as well as the reasonable design of the system components. An important and feasible technical approach to improve the performance involves proper configuration and optimization of the critical parameters for the current system components [28]. Based on the operating characteristics of all-electric cars as well as the particularity in evaluating their performance, the current study took into account the dynamic and economic performance of the cars and set the acceleration time and driving range as the objective functions to develop the dual-objective function of dynamics and economic performance; this function aimed to improve the driving range of all-electric cars while fulfilling the car's dynamics requirement [29, 30].

10. Development of Objective Functions for Optimization

10.1. Dynamic Performance Objective Function. The objective function for dynamic performance was built by considering the acceleration time, that is, the time that a car takes to accelerate from a speed of 0 to 100 km/h. The shorter the time,

TABLE 3: Powertrain parameter of electric vehicle.

Parameter	Value
Motor	
Motor type	Permasyn motor
Motor A rated power/kW	17.6
Motor A peak power/kW	35.2
Motor A rated speed/r/min	2536
Motor A maximum speed/r/min	6078
Motor A peak torque/Nm	132.54
Motor B rated power/kW	14.3
Motor B peak power/kW	30.5
Motor B rated speed/r/min	2498
Motor B maximum speed/r/min	5964
Motor B peak torque/Nm	116.59
Powertrain	
Planetary gear parameters	3.2
Final ratio	2.5
Battery	
Type	Lithium-ion battery voltage
Total voltage/V	320
Nominal capacity/Ah	60
Cells	100
Single section voltage/V	2.5~3.4

the better the dynamic performance. The acceleration time t can be expressed as follows:

$$f_1(X) = t = \frac{1}{3.6} \int_0^{100} \frac{\delta mg}{F_i - F_f - F_w} dv, \quad (8)$$

where F_i is vehicle traction, F_f is vehicle rolling resistance, and F_w is vehicle air reaction.

10.2. Economy Objective Function. The driving range of a fully charged car was used as the evaluator for economy under the NEDC cycle. The energy consumption at constant speed as well as under uniformly accelerated motion was calculated independently and then summed up; the electric car's driving range for the entire cycle was obtained based on the summation:

$$f_2(X) = L = \frac{W_b}{\sum W} \cdot S, \quad (9)$$

where S is the distance under the NEDC cycle, W_b is the battery actually stored energy, and $\sum W$ is the total energy consumption.

11. Fundamentals of Quantum Genetic Intelligence Optimization Algorithms

A highly accurate calculation procedure is to be adopted for multiobjective optimization, which is a time-consuming process. Most scholars tend to apply similar techniques to set the objectives and constrain the model to conduct optimization

FIGURE 2: The proposed algorithm for quantum genetic algorithm.

design in order to avoid directly solving the multiobjective optimization; thus, better optimization efficiency can be achieved.

Quantum genetic algorithm is a combination of the quantum algorithm and genetic algorithm, which is a newly developed intelligent algorithm that evolved from probability theory and has better overall performance and ability to explore data as compared to the performance and ability of the genetic algorithm. In recent years, the quantum algorithm has gained the attention of experts and scholars in the area of multiobjective optimization [31, 32]. In 1996, Narayanan conducted an analysis on the concept of quantum mechanics and integrated them into genetic algorithms; quantum-inspired genetic algorithm that can solve the TSP problem successfully was proposed based on this work. Quantum genetic algorithm could conduct chromosome coding by considering the probability amplitude of qubits, and it updated the chromosome by introducing a quantum door mechanism, which added the advantage of quantum computing to the algorithm [33]. Although quantum genetic algorithm is a recent development and relative theories and methods are not yet mature, this method exhibited excellent performance and showed great potential in dealing with many complicated problems.

In this algorithm, a gene refers to a qubit. A qubit contains all the possible information that a gene can carry, which means that every operation on the gene will exert influence on all the possible information at the same time. A qubit can be in the 0 state, in the 1 state, or in any superposition between the two.

The state of a qubit can be expressed as follows:

$$|\varphi\rangle = \alpha |0\rangle + \beta |1\rangle, \quad (10)$$

where α and β two amplitude constants that can be fit into the following equation:

$$|\alpha|^2 + |\beta|^2 = 1, \quad (11)$$

where $|\alpha|^2$ gives the probability of the qubit to be found in the 0 state and $|\beta|^2$ gives the probability of the qubit to be found in the 1 state. This is also called normalization state. Similarly, a system with n qubits can be expressed as follows:

$$\begin{bmatrix} \alpha_1 & \alpha_2 & \dots & \alpha_n \\ \beta_1 & \beta_2 & \dots & \beta_n \end{bmatrix}. \quad (12)$$

This system can have 2^n states. For these states, $|\alpha_i|^2 + |\beta_i|^2 = 1$, $i = 1, 2, \dots, n$. The calculation steps are as shown in Figure 2.

12. Designing of Optimization Variables and the Constrain Conditions

The motor propulsion parameter, battery parameter, and planetary gear parameter affect the dynamic and economic performances of a dual-motor hybrid drive system. Therefore, in the current study, the critical parameters of the power system that are highly associated with vehicle performance were chosen as the variables for optimization; these parameters were planetary gear properties, main deceleration ratio,

rate powers of motors A and B, peak power, rated revolution, the maximum revolution, and the battery capacity C . Thus, vehicle performance can be expressed as a function of these parameters, as follows:

$$\begin{aligned} X &= [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}]^T \\ &= [k, i_0, P_{A0}, P_{B0}, P_{A \max}, P_{B \max}, n_{A0}, n_{B0}, n_{A \max}, n_{B \max}, C]^T. \end{aligned} \quad (13)$$

Under specific driving conditions, in order to maximize the driving range while maintaining the dynamic index, the vehicle should meet the performance standards for the maximum stable speed as well as the maximum gradeability. For these requirements and the design objective, the constraints are as follows:

$$\begin{aligned} 0 &\leq P_{\max A} + P_{\max B} \leq P_{\text{total}}, \\ t &= \frac{1}{3.6} \int_0^{100} \frac{\delta mg}{F_i - F_f - F_w} dv \leq 13, \\ 120 &\leq L = \frac{W_b}{\sum W} \cdot S, \\ -0.02 &\leq \Delta \text{SOC} \leq 0.02, \quad -0.2kWh \leq \Delta E_{\text{bat}} \leq 0.2kWh, \end{aligned} \quad (14)$$

where ΔSOC is the change rate of SOC and ΔE_{bat} is the change rate of battery energy consumption.

13. Development of a Mathematical Optimization Model

The abovementioned analysis suggests that the optimization of parameters in the current study was in fact the global optimization for solving multiobjective and multiconstraint nonlinear functions. Conventional optimization algorithms usually require an accurate expression of mathematical functions and are therefore not suitable for global optimization in the current study. Intelligent optimization algorithms were mostly developed by simulating certain behavior from nature and biosphere that has similar thinking and behavioral standards as humans; hence, they were more suitable for the iterative optimization process, as described in the previous section. In the current work, the quantum genetic intelligent optimization algorithm described above was used [34]. In order to convert the dual-objective optimization of dynamic and economic performances into a single objective optimization, the dynamic function and the economy function were weighted and then summed up. Since the acceleration time of the dynamic index and driving range of the economy index had different magnitudes, they were normalized; that is, the dynamic function and economy function were divided by their respective designing objectives. The new objective optimization function was as follows:

$$f(X) = \frac{\omega_1 \cdot f_1(x_1, x_2, x_3)}{a} + \frac{\omega_2 \cdot f_2(x_1, x_2, x_3)}{b}, \quad (15)$$

where ω_1 and ω_2 are weighting factors, they are greater than zero, and a, b are the design objective of dynamics and economy.

14. Optimization and Simulation for All-Electric Cars with the Double-Motor Hybrid Driving System

14.1. Development of the Simulation and Optimization Model. Optimization calculation was conducted by the combined simulation of Matlab/Simulink and AVL-Cruise software. The API function provided by the AVL-Cruise software was used to develop the optimization model and vehicle control strategy on Simulink, while vehicle model development and the simulation calculation for vehicle performance were conducted on the Cruise software. Signals including load (traction and braking), SOC, and speed were transferred via the interface of AVL-Cruise to Matlab/Simulink, which was used to analyze these signals using its control strategy and optimization calculation. The analysis results were sent back to AVL-Cruise via the interface. Simulation on the power system was conducted on the AVL-Cruise model. Figure 3 shows a schematic of the data transfer between Cruise and Simulink.

The output values of the model have to be combined to a vector by a multiplexer (MUX). After a successful simulation step, Simulink transfers this output vector into the Matlab Workspace by the Matlab object "Block Parameters: To Workspace," where CRUISE can access it. CRUISE gets this vector and puts its elements onto the databus where they can be used by other components.

14.2. Optimization Results. Quantum genetic algorithm was used to perform the global optimization on the parameters of the dual-motor hybrid drive system based on the results of the combined simulation optimization scheme. Figure 4 shows motions of the vehicle under the NEDC cycle. Algorithm parameters were set as follows: the maximum number of iteration was 400 and the population size was 100. After 400 iterations, the optimal objective value tended to remain the same. Figure 5 shows the convergence trend of the objective value of the function in each generation of iteration, and Table 4 lists the parameters in the transmission system after optimization.

14.3. Comparison of Simulation Results before and after Optimization. In order to verify experimentally the optimization results for the power system parameters of the all-electric cars equipped with the dual-motor hybrid drive system, the parameters obtained from preliminary matching as well as those from global optimization were simulated and verified on the combined simulation platform of Matlab/Simulink and AVL-Cruise. Measurements were made for the driving cycle of NEDC, and the simulation results of the vehicle's dynamic performance and economy before and after optimization were compared and verified. The comparison results are presented in Table 5 and Figures 6, 7, 8, and 9.

FIGURE 3: Data exchange Cruise-Simulinktm for Matlab API.

FIGURE 4: NEDC drive cycles and vehicle state of motion.

FIGURE 5: Convergence of QGA.

Adoption of the optimized parameters for the power system led to a decrease of 0.21s in the time required for accelerating from 0 to 100 km/h and an increase of 14.1 km/h in the maximum speed. In terms of economy, at the end of a driving cycle, the energy consumption was reduced

TABLE 4: Compared parameters before and after optimization.

Parameter	Original	Optimized
Motor		
Motor A rated power/kW	17.6	16.8
Motor A peak power/kW	35.2	35.6
Motor A rated speed/r/min	2536	2455
Motor A maximum speed/r/min	6078	7569
Motor A peak torque/Nm	132.54	138.47
Motor B rated power/kW	14.3	14.5
Motor B peak power/kW	30.5	31.7
Motor B rated speed/r/min	2498	2593
Motor B maximum speed/r/min	5964	6579
Motor B peak torque/Nm	116.59	116.74
Powertrain		
Planetary gear parameters	3.2	3.5
Final ratio	2.5	3.6
Battery		
Nominal capacity/Ah	63.53	56.11

TABLE 5: The simulation results compared before and after optimization.

Parameter	Original	Optimized
Acceleration time (s) (0~100 km/h)	12.06	11.85
Maximum speed (km/h)	138.6	152.7
Maximum gradeability (%)	30.71	33.65
NEDC energy consumption/KJ	6840.8	6278.9
Maximum range per charge/km	125.6	136.67

by 8.21%, and the driving range was increased by 8.81% after optimization. At the same time, the dual-motor hybrid-driving system for electric cars reduced energy consumption of 15.6% compared with the conventional electric vehicle with single-speed reducers. Figure 6 shows the time required for accelerating from 0 to 100 km/h and the distance curve of the car before and after optimization. A considerable decrease in the acceleration time after optimization as well as the enhancement in vehicle dynamics can be clearly observed. Figure 7 shows the SOC curve under NEDC before and after optimization. It shows that while the initial state of the battery was the same, the SOC after optimization was higher than that before optimization at the end of a cycle; in other words, the battery consumption was lower and the economy was higher after optimization. Figure 8 shows the change in the overall system efficiency of the transmission system before and after optimization under different circumstances. Figure 8 shows that, after optimization, the overall efficiency increased, and the power system parameters after optimization allowed the electric motors to work more frequently in the high performance range; this decreases the working torque of the motor. The working current of the all-electric cars as well as the winding loss was thus decreased, thereby improving the working performance of the motor. Figure 9 shows the system energy consumption before and after optimization: the energy consumption at the end of a cycle after optimization in all cases was lower than that before optimization.

15. Summary

The current study proposed a new dual-motor hybrid drive system for all-electric cars; this system enables speed and torque coupling between the two powering sources as well as continuously variable transmission (CVT) under some circumstances. This system was also able to broaden the high performance working range of the electric motors efficiently and, thus, greatly widened the driving range of the electric cars while maintaining the dynamic performance. Dual-objective optimization functions were developed for the transmission system parameters of this dual-motor hybrid drive system. By assigning the weight factors, the quantum genetic intelligence algorithm was used for optimization calculation, which exhibited good convergence. Satisfactory results were obtained by this method within limited time

FIGURE 6: Simulation curve of accelerating time and distance.

FIGURE 7: SOC curve of battery pack on NEDC drive cycles.

in dealing with multiobjectives and multiparameter problems, indicating positive practical value and applicability for parameter optimization in the design of different hybrid electric cars. A simulation and optimization platform for electric cars was built based on the combined simulation of Matlab/Simulink and AVL-Cruise software, on which the optimization, simulation, and verification of the parameters in the transmission system were conducted. Results showed that this platform is feasible and highly efficient and that it can enhance the developmental efficiency of electric cars greatly. The method explored in the current study is suitable for the hybrid drive system for matching and optimizing the parameters of the transmission system. Results from the simulation analysis showed that dynamics and economy

FIGURE 8: System efficiency curve on NEDC drive cycles.

FIGURE 9: Energy consumption curve on NEDC drive cycles.

parameters such as acceleration, gradeability, the maximum speed, and driving range of the electric cars equipped with the dual-motor hybrid drive system met the design requirement, had high performance, and saved energy.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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