IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 26, 2019, accepted August 15, 2019, date of publication August 20, 2019, date of current version September 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2936370

Research on the Efficiency Optimization Control of the Regenerative Braking System of Hybrid Electrical Vehicle Based on Electrical Variable Transmission

QIWEI XU[1], FUKANG WANG[1], XUEFENG ZHANG[1], AND SHUMEI CUI[2]

[1]State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China
[2]Department of Electrical Engineering, Harbin Institute of Technology, Harbin 150080, China

Corresponding author: Qiwei Xu (xuqw@cqu.edu.cn)

This work was supported by the Chongqing Science and Technology Commission of China under Project cstc2018jcyjA3148.

ABSTRACT Electrical variable transmission (EVT) is a novel electromechanical energy converter that can be applied in hybrid electrical vehicle (HEV). In this paper, the hybrid electrical vehicle based on EVT (EVT-HEV) and the efficiency optimization strategy of regenerative braking system (RBS) is studied. Firstly, this paper analyzes the dynamic coupling mode of EVT-HEV and establishes the expression of the dynamic coupling relationship between EVT and the engine. Then, four different braking modes including two novel ones are divided. Next, a hierarchical controller is proposed in which the rule-based control strategy is used for braking mode switching and neural network algorithm is used for the optimal efficiency control for the system. The simulation of the control strategy is carried out under New European Driving Cycle (NEDC) based on the joint platform of CRUISE and MATLAB software. And the results indicate that the proposed strategy can improve the performance of RBS in EVT-HEV. Thus the research in this paper can bring a new theoretical foundation for the application of EVT in HEV and is of great significance to enrich the energy management strategies of EVT-HEV.

INDEX TERMS Hybrid electric vehicle, electrical variable transmission, regenerative braking system, optimal efficiency control, neural network control.

I. INTRODUCTION

Electrical variable transmission (EVT) was firstly proposed by Professor Hoeijmakers [1], [2] in the Netherlands in 2001. As a novel electromagnetic continuously variable transmission, it can be applied in the electromechanical energy conversion such as hybrid electrical vehicle (HEV), wind power generation, underwater propulsion and so on. The hybrid electrical vehicle based on electrical variable transmission (EVT-HEV) can achieve the power distribution effect of Prius and processes the advantages as follows: 1) increasing the space utilization of the radial structure and possessing higher power and torque density; 2) the electromechanical energy conversion is more flexible due to the dual mechanical ports and dual electrical ports; 3) insolating the internal combustion engine (ICE) and road load so that ICE can operate in the optimal state.

The regenerative braking system (RBS) is an important system for energy management in HEV which can effectively improve the cruising range. In this paper, EVT-HEV is taken as the research object and the efficiency optimization control strategy of RBS is studied.

At present, the researches on RBS of the traditional HEV mainly include structural design, braking force distribution control and coordinated control with other systems on vehicle. The structure of the regenerative braking system is common in series and parallel structure. In [3]–[5], the author compares the series system with the parallel system from the aspects of regenerative braking efficiency and safety. The researches on braking force distribution control mainly focus on the distributing rate of the mechanical and the regenerative braking force to achieve the goals of improving the

The associate editor coordinating the review of this article and approving it for publication was Rui Xiong.

optimal regenerative braking efficiency, ensure the stability of the braking process, the braking comfort and improving the performance of the battery or the motor. In [6], a slip rate control strategies based on sliding mode control and a braking force control strategy based on ECE regulations are proposed to improve the efficiency of regenerative braking. In [7]–[9], the fuzzy control algorithm is used to control the proportion of regenerative braking force, so that the braking force can be combined with the maximum braking force curve or make the control process of regenerative braking more stable. In [10], considering the battery life, regenerative braking efficiency and safety, the braking force distribution method based on model predictive control is proposed. There are also other researches [11], [12], [16], [17] focusing on the control strategy of regenerative braking motors. The researches [13]–[15] on coordinated control with other vehicle systems is mainly coordinated with the ABS, the transmission control, the steering system to ensure the safety of the vehicle and improve the operating performance of the system.

The researches on RBS in EVT-HEV are mainly included in the energy management [18]–[22] in EVT-HEV as a small part and a few researches [23], [24] are solely about the control strategy of RBS in EVT-HEV. While all the researches on RBS in EVT-HEV are similar to the control strategy in the traditional HEV in which only one motor (the outer motor) is utilized to provide the regenerative braking force without considering the operating state of ICE. EVT possesses multiple mechanical ports and electrical ports and the energy conversion mode is more flexible than power coupling mechanism in the traditional HEV. The current researches don't make full use of the advantages of EVT and have the following shortcomings:

1) When the vehicle is in hybrid mode, the engine should be disengaged during the braking process thus all the energy of the engine is wasted.

2) When the braking process is over and the vehicle is in the condition of hybrid mode, the engine should increase the speed to drive the vehicle thus the engine switching is frequent.

3) When the vehicle is in pure electric mode, the regenerative braking torque is only provided by one motor and the mechanical braking torque supplements the deficient braking torque. Therefore the regenerative braking energy is not fully recovered.

In response to the problems existed in the current researches on RBS in EVT-HEV, this paper comprehensively considers the operating state of the engine and EVT under various working modes, analyzes the braking process of EVT-HEV in detail and proposes four different braking modes including two noble modes named as engine-motor coordinating braking mode (EMCB) and dual motor braking mode (DMB). Then a hierarchical controller is proposed in which the rule-based control strategy is used for braking mode switching and neural network algorithm is used for the optimal efficiency control for the system. The research in this paper can bring a new theoretical foundation for the application of EVT in HEV and is of great significance to enrich the energy management strategies of HEV. The innovation points of our research on RBS in EVT-HEV are listed as following:

1) EMCB mode is firstly proposed in this paper and it can keep the engine operating in the optimal state and the output energy can be transmitted into the battery during the regenerative braking process.

2) The engine is not disengaged in EMCB mode, thus when the braking process is over, the engine can keep operating in the optimal state and need not to switch the working state frequently.

3) DMB mode is firstly proposed in this paper. With DMB mode, the inner motor is utilized to supplement the deficient braking torque. Therefore, DMB mode can improve the energy recovery efficiency.

This paper is organized as follows. Section II analyzes the dynamic coupling mode of EVT in power transmission topology. Section III mainly analyzes the braking process in detail, divides four different braking modes and gives the rule-based braking mode switching strategy. Section IV establishes the equivalent efficiency model of different braking modes. To improve the operating efficiency of the RBS, the neural network algorithm is used to optimize the power distribution of the engine and EVT. Section V verifies the proposed control strategy through simulation based on CRUISE-MALTAB. Section VI concludes the paper.

II. THE TOPOLOGY STRUCTURE OF EVT-HEV

The topology structure of EVT-HEV is shown in FIGURE 1. The inner rotor of the inner motor (EM1) of EVT is connected to the output shaft of engine, and the outer rotor is connected to the final reduction drive as a common rotor of EM1 and the outer motor (EM2). The engine and the road load are decoupled by the rotational speed and torque control of EM1 and EM2. EM1 can adjust the engine to work in the optimal state and EM2 can be controlled to meet the road load requirement. Since EM1 and EM2 share the common external rotor, the magnetic field coupling between EM1 and EM2 exists in EVT. In recent years, many scholars have carried out extensive researches on the electromagnetic design, heat dissipation analysis and decoupling control of EVT [25]–[29] which laid the foundation for the application of EVT in HEV and make the control of EVT be equivalent

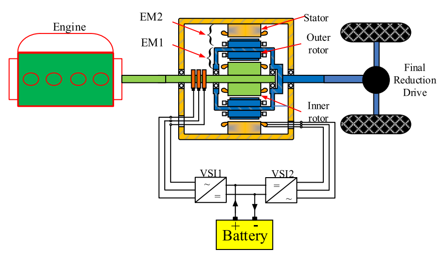

FIGURE 1. Structure of the separated EVT-HEV.

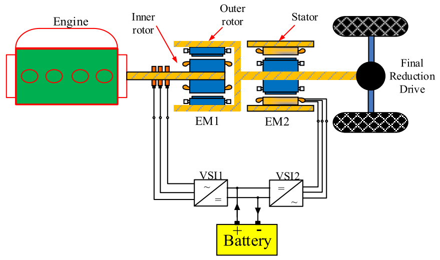

FIGURE 2. Structure of the separated EVT-HEV.

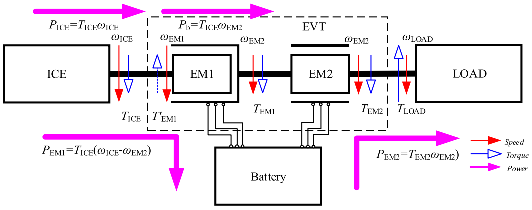

FIGURE 3. Analysis of the dynamic relationship and the power flow in hybrid driver mode.

as the control for EM1 and EM2 separately. The equivalent split topology of EVT-HEV is shown in FIGURE 2.

The operating mode of the EVT-HEV can be divided into the hybrid drive mode in which the engine is on and the pure electric mode in which the engine is off.

A. HYBRID DRIVE MODE

The dynamic relationship and energy flow analysis of the hybrid drive mode are shown in FIGURE 3. The engine output power is expressed as P_{ICE} which can be divided into two parts. One part of the energy expressed as P_{d} is transmitted through the magnetic field to drive the outer rotor and another part is transmitted into the battery with EM1 operating as generator which can be expressed as P_{EM1}. When the system is in steady state, the torque of engine expressed as T_{ICE} is equal to the electromagnetic torque of EM1 expressed as T_{EM1}.The speed of EM1 is the difference between the speed of engine and EM2.

The external rotor of EM2 is connected to the final reduction drive whose speed is linearly relative to the velocity of the vehicle. The driving torque of the vehicle is equal to the resistance T_{LOAD} and consists of two parts. One part is T_{ICE} transmitted through the magnetic field of EM1 and another part is the torque of EM2 expressed as T_{EM2}.

Then the relationship between the engine and EVT is described as equation (1) in which ω_{wheel} is the speed of wheel and i_{single} is the transmission ratio of final reduction drive, $\omega_{\text{ICE}}, \omega_{\text{EM1}}, \omega_{\text{EM2}}$ is the speed of ICE, EM1 and EM2 separately and P_{EM2} is the power of EM2.

$$\begin{cases} P_{\text{ICE}} = T_{\text{ICE}}\omega_{\text{ICE}} \\ P_{\text{EM1}} = T_{\text{EM1}}(\omega_{\text{ICE}} - \omega_{\text{EM2}}) = T_{\text{EM1}}\omega_{\text{EM1}} \\ P_{\text{d}} = P_{\text{ICE}} - P_{\text{EM1}} = T_{\text{ICE}}\omega_{\text{EM2}} = T_{\text{EM1}}\omega_{\text{EM2}} \\ T_{\text{LOAD}} = T_{\text{EM1}} + T_{\text{EM2}} = T_{\text{ICE}} + \frac{P_{\text{EM2}}}{\omega_{\text{EM2}}} \\ \omega_{\text{EM2}} = \frac{\omega_{\text{wheel}}}{i_{\text{single}}} \end{cases} \tag{1}$$

When the vehicle demand power is equal to the engine output power, EVT-HEV system operates as the continuously variable transmission (CVT) and the energy for EM2 operating can be fully provided by P_{EM1}. When the vehicle demand power is larger than the engine's output power, EVT-HEV operates in the auxiliary drive mode in which the engine is still operating at the optimal operating point and the power flow is similar to CVT but the battery provides some power for EM2 to supplement the demand power. When the vehicle demand power is less than the engine output power, EVT-HEV operates in the generator mode when the engine operates at the optimal operating point and the excess energy is stored in the battery through EM1. In addition to the slight difference in power flow at the battery, the three drive modes can be analyzed through the mathematical model described in equation (1).

B. PURE ELECTRIC DRIVE MODE

The dynamic relationship and energy flow analysis of the hybrid drive mode are shown in FIGURE 4. The vehicle is working in the electric drive mode in which the engine is off. When the vehicle requires little power, only EM2 is in the electric state to drive the vehicle. While EM1 is also in the electric state to provide power if the demand power is larger than the power that EM2 can provide. During this mode, the output torque of EVT is the sum of the torque of EM1 and EM2 and the speeds of EM1 and EM2 are equal and linearly relative to the wheel speed of the vehicle. The mathematic model for the electric drive mode is described as equation (2):

$$\begin{cases} T_{\text{LOAD}} = T_{\text{EM1}} + T_{\text{EM2}} \\ \omega_{\text{EM1}} = \omega_{\text{EM2}} = \frac{\omega_{\text{wheel}}}{i_{\text{single}}} \end{cases} \tag{2}$$

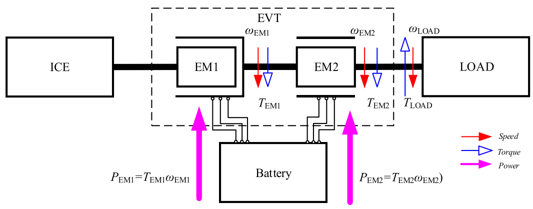

FIGURE 4. Analysis of the dynamic relationship and the power flow in electric driver mode.

III. THE BRAKING MODE SWITCHING CONTROLLER

The operating mode of EVT-HEV has many special features because the mode switching and energy conversion are various. Therefore, the regenerative braking process is more complicated. It is necessary to comprehensively consider the operating state of the components in different operating mode, the energy recovery efficiency and coordination of system operation. In order to reduce the switching frequency of the engine during regenerative braking, increase the energy recovery efficiency and ensure the system operating in the optimal state, this paper proposes four different braking modes including two noble modes named as EMCB and

DMB and designs a hierarchical controller for RBS in EVT-HEV to switch the braking mode and control the components in the EVT-HEV. The structure of the controller is shown in FIGURE 5.

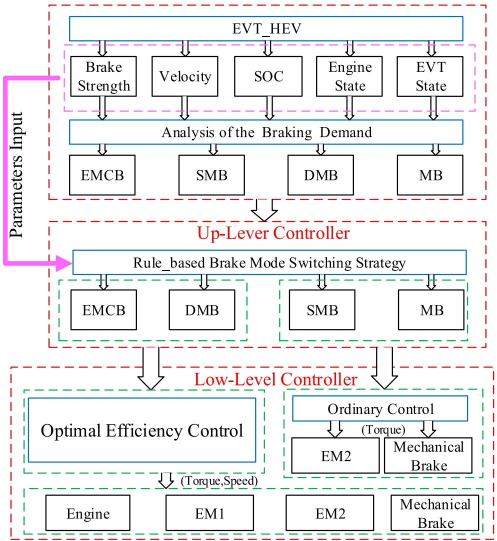

FIGURE 5. **Structure of the hierarchical controller.**

Firstly, the controller receives the information such as the braking strength, the battery SOC, the state of engine and EVT and analyzes the braking demand of EVT-HEV and all the input signals is considered to be accurate. The up-level controller is the rule-based braking mode switching controller to select the proper braking mode. The low-level controller based on neural network control is used to control the engine, EM1, EM2 and mechanical brake to ensure the system operating in the optimal state under EMCB and DMB mode. And when operating in the SMB and MB mode, the control is similar to the common used method in HEV which distributes the regenerative braking torque between single motor and mechanical brake.

A. ANALYSIS OF THE BRAKING DEMAND OF EVT-HEV

The analysis of the driving process is analyzed below. The vehicle satisfies the driving equation which is shown in the equation (3):

$$F_t = F_f + F_w + F_i + F_j \tag{3}$$

In this equation, F_t is the driving force of the vehicle. F_f is the driving resistance of the vehicle which is usually the product of the gravity G and the rolling resistance coefficient f and can be expressed as $F_f = Gf$. F_w is the air resistance and its empirical expression is $F_w = C_D A u_a^2/21.15$ in which C_D is the air resistance coefficient related to the body shape design, A is the windward area, u_a^2 is the square of the vehicle velocity. F_i is the gradient resistance which is the gravity along the ramp when the vehicle is driving on the ramp, F_j is the accelerate resistance and the expression is $F_j = \delta ma$, where δ is the rotational mass conversion factor usually regarded as 1 in the analysis, m is the mass of vehicle and a is the acceleration.

In this paper, the equation (3) is deformed and analyzed with a as the function target according to the braking process. The deformed equation is shown in the equation (4):

$$F_a = ma = Gi + \frac{C_D A u_a^2}{21.15} - F_t + F_{brake} \tag{4}$$

In this equation, F_a is the braking force effected on the vehicle, F_t is the force coming from the engine, a is a positive value which is the absolute value of the deceleration and F_{brake} is the braking force which can be the mechanical braking force or the regenerative braking force provided by the motor.

According to the analysis of the drive modes in Section II, the braking process of EVT-HEV can be divided into four modes named as engine-motor coordinating braking mode(EMCB), single motor brake (SMB), dual motor braking mode (DMB) and mechanical brake (MB). The following is the introduction of the different braking mode.

1) ENGINE-MOTOR COORDINATE BRAKING MODE (EMCB)

EMCB IS featured as keeping the engine operating in the optimal state during the process of regenerative braking thus it can improve the fuel efficiency of EVT-HEV. In this mode, the previous state of the engine is on and the dynamics and energy flow relationship of the system is shown in FIGURE 6. The output power of engine is partly transmitted to EM2 through the magnetic field and drives the EM2 to generate electricity. and the other part is transmitted to the battery through EM1 operated as the generator.

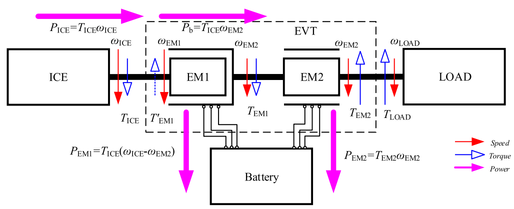

FIGURE 6. **Analysis of EMCB mode.**

The operating state can be analyzed by equation (4) in which F_t is the force produced by the engine at the optimal state and F_{brake} is the braking force that EM2 needs to provide. In this case the energy emitted by the engine and the kinetic energy of vehicle are equivalent to be recovered into the battery through EVT. In other words EM2 should provide the required braking torque as well as overcome T_{ICE} that is transmitted through EM1.

There are some special cases in EMCB mode. When the vehicle speed is too high or the required braking strength is too large, the EM1 is not able to work at optimal state or EM2 is required to provide larger torque. Thus the engine should work at idle speed or is shut down, EM1 should not work and disconnect the power transmission between engine and EM2. In this case the regenerative braking force is completely provided by EM2. The control idea is similar to the regenerative control of the traditional HEV which is that if the required braking force is smaller than the maximum braking torque of EM2, the braking force is completely provided by EM2. While if the required braking force is larger than the maximum braking torque of EM2, the excess regenerative braking force is provided by the mechanical brake.

2) DUAL MOTOR BRAKING MODE (DMB)

DMB is another advantage of the RBS in EVT-HEV which is featured as using EM1 to supplement the large brake force that EM2 can't provide individually while it is usually supplemented by the mechanical brake in the traditional control method for RBS in EVT-HEV. Thus DMB can improve the energy recover efficiency.

When operating in DMB mode, the regenerative braking torque of the dual motor acts on the outer rotor at the same time with the same direction. The analysis is carried out in equation (4) in which F_t is 0 and F_{brake} is the sum of the regenerative braking force provided by EM1 and EM2. The rotational speeds of EM1 and EM2 are the same which are proportional to the vehicle velocity. This mode possesses the advantages that the regenerative braking force provided by the dual motor can be fully utilized and the motor can respond quickly to the torque change. Thus it can improve the energy recovery efficiency and system operating coordination. The dynamics and energy flow relationship in DMB are shown in FIGURE 7.

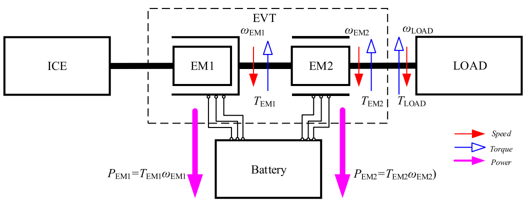

FIGURE 7. Analysis of DMB mode.

3) SINGLE MOTOR BRAKING MODE (SMB)

In SMB mode, the engine and EM1 stop working and only the EM2 works to provide the regenerative braking force. This mode is the same as the regenerative braking mode of the pure electric vehicle, and the control strategy is relatively simple. SMB is effected when EMCB mode is not available in hybrid mode or when only EM2 can provide all the regenerative braking force in electric mode. The analysis is carried out in equation (4) in which F_t is 0 and F_{brake} is the regenerative braking force provided by EM2. The dynamics and energy flow relationship in SMB are shown in FIGURE 8.

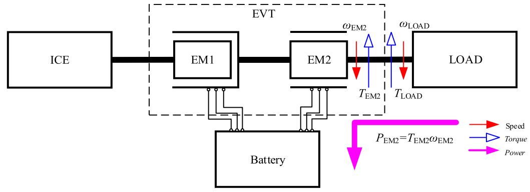

FIGURE 8. Analysis of SMB mode.

4) MECHANICAL BRAKING MODE (MB)

When the vehicle speed is low, the braking strength is emergency braking or SOC is higher than the maximum value, the efficiency and safety of regenerative braking process are poor. In this case the traditional mechanical brake (MB) is used for braking while EM1 and EM2 do not work and the power transmission between the engine and the road load is disconnected.

B. RULE-BASED STRATEGY FOR REGENERATIVE BRAKING MODE SWITCHING

The regenerative braking mode switching is a major problem in EVT-HEV. Determining the appropriate regenerative braking mode helps to improve the energy recovery efficiency and the coordination of system operation. This paper proposes four braking modes in EVT-HEV with the aims to reduce the engine state switching frequency and improve the regenerative braking efficiency. Then a rule-based braking mode switching algorithm for EVT-HEV is designed and the algorithm is easy to implement and has high real-time performance. This section uses the following logic thresholds as the references to formulate the rules for braking mode switching. The rule-based logic is shown in FIGURE 9.

1) Z_thres1 and Z_thres2 (brake strength threshold).
   - When the brake strength is slightly larger than Z_thres1, it is the emergency braking state but otherwise the normal braking state.
   - When the brake strength is larger than Z_thres2, it is one of the special cases analyzed in the EMCB in which EMCB is not available. On the contrary, EMCB is available.
2) SOC_low and SOC_high (SOC threshold).
   - When the battery SOC is greater than SOC_high, the battery is in the non-chargeable state, regenerative braking is not available and the engine should be shut down.

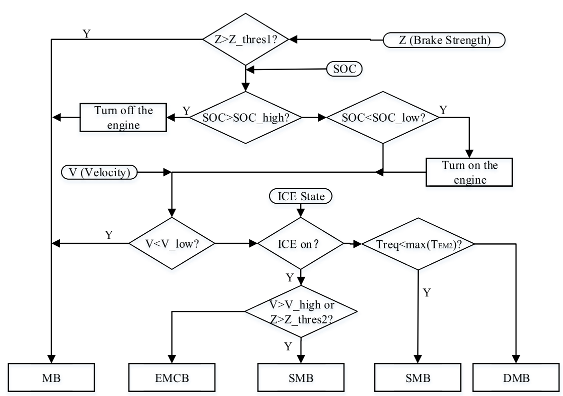

FIGURE 9. Rule-based strategy for the regenerative braking mode switching.

- When the battery SOC value is less than SOC_high, the battery is in the chargeable state and the regenerative braking is permitted. At this stage, the state of engine should be consistent with the previous state.
- When the battery SOC is less than SOC_low, the battery power is too low and the engine state needs to be started.

3) V_low and V_high (velocity threshold).

- When the velocity of the vehicle is lower than V_low, the efficiency during regenerative braking process is poor and it is suitable to work in MB mode.
- When the velocity of the vehicle is higher than V_high, it is one of the special cases analyzed in the EMCB in which EMCB is not available. On the contrary, EMCB is available.

Through the rule-based regenerative braking mode switching strategy, the different braking mode working conditions are clearly defined. It can be seen that the formulated strategy has the following characteristics:

1) When the engine is under 'on state', the optimal working state of engine can be maintained under various braking requirements until it enters into the situation SOC > SOC_high and then the engine operates under the 'off state'. When the engine is under 'off state' and SOC becomes lower than SOC_low, the engine starts again. Thus, the strategy has the advantage of reducing the engine switching frequency.

2) When the engine is under 'off state', only EVT is available during the braking process. Since the regenerative braking force provided by EM1 and EM2 is larger than that of the conventional single motor, the mechanical braking force of the driving wheel can be minimized. In addition, the torque control of the motor is better coordinated than the coupling control of the motor and mechanical brake. Therefore, the proposed strategy can improve the efficiency of regenerative braking and the coordination of RBS.

IV. OPTIMAL CONTROL STRATEGY FOR RBS BASED ON NEURAL NETWORK ALGORITHM

A. EQUIVALENT EFFICIENCY MODEL OF RBS IN EVT-HEV

After rule-based braking mode switching strategy is established, a reasonable power distribution of RBS is required for the different regenerative braking mode. In addition that MB mode and SMB mode is required to control a single object, EMCB mode and DMB mode require overall control of the engine and EVT because their torques and the speeds have a strong coupling, so it is an important control content to coordinate the power distribution of the engine and EVT to ensure the high operating efficiency of the system. This section firstly builds the equivalent efficiency model for the two noble modes and then proposes a coordinated control strategy for instantaneous optimal control for the purpose of improving the overall operating efficiency of the system.

1) EQUIVALENT EFFICIENCY MODEL FOR EMCB

In this mode, the engine works at the optimal ICE curve in which the $T_{\rm ICE}$ can be expressed as $T_{\rm ICE} = f(\omega_{\rm ICE})$. Output shaft of EM2 is directly connected to the vehicle load and its speed is proportional to the vehicle velocity which can be expressed as $\omega_{\rm EM2} = v \times i_{\rm single}/r$ in which v is the velocity of vehicle, r is the radius of the tire. According to the equation (4), the required braking torque of EM2 can be expressed as $T_{\rm 2m} = T_{\rm ICE} + T_{\rm req} = f(\omega_{\rm ICE}) + h(a)$ in which $T_{\rm req}$ is the required braking torque of the driving wheel and can be expressed as $h(a) = ma\, r\beta/i_{\rm single}$ in which β is the ratio of the braking force of driving wheel. For EM1, its speed is the difference between that of the engine and EM2 which can be expressed as $\omega_{\rm EM1} = \omega_{\rm ICE}\text{-}\omega_{\rm EM2}$ and torque of EM1 is equal to the torque of engine which can be expressed as $T_{\rm EM1} = T_{\rm ICE} = f(\omega_{\rm ICE})$. The system power model and equivalent efficiency model for EMCB mode are expressed in equation (5) and (6):

$$P = f(\omega_{\rm ICE})\omega_{\rm EM1}\eta_{\rm EM1} + (f(\omega_{\rm ICE}) + h(a))\omega_{\rm EM2}\eta_{\rm EM2} \quad (5)$$

$$\eta_{\rm equa} = \frac{f(\omega_{\rm ICE})\omega_{\rm EM1}\eta_{\rm EM1} + (f(\omega_{\rm ICE}) + h(a))\omega_{\rm EM2}\eta_{\rm EM2}}{f(\omega_{\rm ICE})\omega_{\rm EM1} + (f(\omega_{\rm ICE}) + h(a))\omega_{\rm EM2}} \quad (6)$$

According to the constraint relationship of each parameter, the equivalent model can be written as:

$$\eta_{\rm equa} = f(a, v, \omega_{\rm ICE}) \quad (7)$$

When the system efficiency reaches the most optimization that is $\max(\eta_{\rm equa})$, the control parameters and the input parameters satisfy the equation (8):

$$\omega_{\rm ICE} = y(a, v) \quad (8)$$

The torque and speed control parameters of the engine, EM1 and EM2 can be derived from the equation (9):

$$\begin{cases} T_{\rm ICE} = f(\omega_{\rm ICE}) \\ \omega_{\rm EM2} = \frac{v i_{\rm single}}{r} \\ T_{\rm EM2} = f(\omega_{\rm ICE}) + h(a) \\ \omega_{\rm EM1} = \omega_{\rm ICE} - \omega_{\rm EM2} \\ T_{\rm EM1} = T_{\rm ICE} \end{cases} \quad (9)$$

2) EQUIVALENT EFFICIENCY MODEL FOR DMB

In DMB mode, the engine does not work and EM1 and EM2 have the same speed which are proportional to the vehicle speed expressed as $\omega_{\rm EM1} = \omega_{\rm EM2} = v \times i_{\rm single}/r$. The sum of the torques of the two motors is the required braking torque of the vehicle expressed as $T_{\rm EM1} + T_{\rm EM2} = T_{\rm req} = h(a)$. The power model and equivalent efficiency model in this mode can be described as:

$$P = (h(a) - T_{\rm EM2})\omega_{\rm EM1}\eta_{\rm EM1} + T_{\rm EM2}\omega_{\rm EM2}\eta_{\rm EM2} \quad (10)$$

$$\eta_{\rm equa} = \frac{(h(a) - T_{\rm EM2})\omega_{\rm EM1}\eta_{\rm EM1} + T_{\rm EM2}\omega_{\rm EM2}\eta_{\rm EM2}}{(h(a) - T_{\rm EM2})\omega_{\rm EM1} + T_{\rm EM2}\omega_{\rm EM2}} \quad (11)$$

According to the constraint relationship of each parameter, the equivalent efficiency model can be written as:

$$\eta_{\rm equa} = f(a, v, T_{\rm EM2}) \quad (12)$$

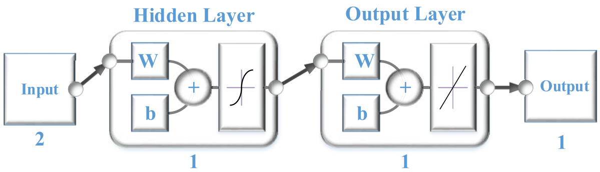

FIGURE 10. Structure of the neural network model.

When the system efficiency reaches the most optimization that is max(η_{equa}), the control parameters and the input parameters satisfy the equation (13):

$$T_{EM2} = y(a, v) \tag{13}$$

The torque and speed control parameters of EM1 and EM2 can be derived from the equation (14):

$$\begin{cases} \omega_{EM2} = \omega_{EM1} = \frac{v i_{single}}{r} \\ T_{EM1} = h(a) - T_{EM2} \end{cases} \tag{14}$$

B. MODELING AND TRAINING OF NEURAL NETWORK ALGORITHM

The torque and speed control strategy with the optimal efficiency is an instantaneous optimal control. While the braking of the vehicle is a transient process and the calculation of instantaneous optimization is large, so it is difficult to meet the braking demand and how to achieve real-time efficiency optimization is an important issue. The neural network algorithm [30], [31] can be used to quickly find the system control parameters under the optimal conditions based on the input information after training the results of the instantaneous optimization.

Neural network toolbox in MATLAB is applied in this paper. According to different braking mode, the neural network training model is set up with the vehicle braking deceleration, vehicle speed as input and the engine speed or EM2 torque as output. The model structure is shown in FIGURE 10 and the parameters of the model are shown in TABLE 1.

TABLE 1. Parameters of the neural network model.

Parameters	Value
Hidden Layer Size	1
Input Layer Size	2
Output Layer Size	1
Number of Data for Training	80
Number of Data for Testing	20
Minimum Gradient	1.00e-05

According to the equivalent efficiency model in Section IV, the mapping relationship between the input and output variables of the neural network model in equation (15) can be generated according to the target to reach the maximum equivalent efficiency. For different braking mode, 100 groups of data are obtained through the instantaneously optimized algorithm in which 80 groups are used for training and the rest for testing.

$$\begin{cases} T_{EM2} = y(a, v) \\ \omega_{ICE} = y(a, v) \end{cases} \tag{15}$$

Based on the training and testing of the data through the MATLAB toolbox, the neural network training performance under different braking mode is shown in TABLE 2.

Based on the results of neural network training, the control maps of the expected torque and speed of EVT are obtained and shown in FIGURE 11-14. Following the control maps, the braking system is controlled to allow the vehicle to achieve optimal operating efficiency at different braking strength and velocity.

TABLE 2. Training performance of different braking mode.

Braking mode	Epoch	Gradient	Performance (Mean square error)
EMCB	12	1.25e-6	0.00178
DMB	10	3.27e-6	0.00274

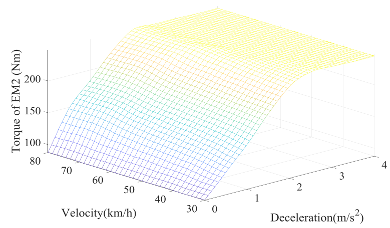

FIGURE 11. EM2 torque control map in EMCB.

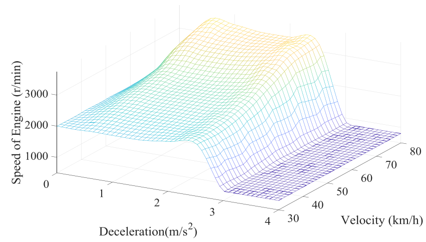

FIGURE 12. Engine speed control map in EMCB.

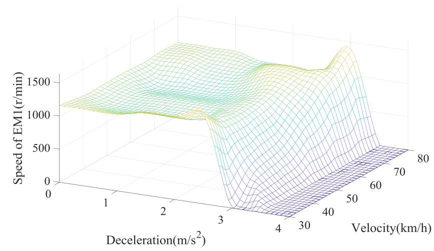

FIGURE 13. EM1 speed control map in EMCB.

V. SIMULATION AND RESULT ANALYSIS

Based on the CRUISE-MATLAB platform, this paper verifies the rule-based braking mode switching strategy and the optimal efficiency control strategy based on neural

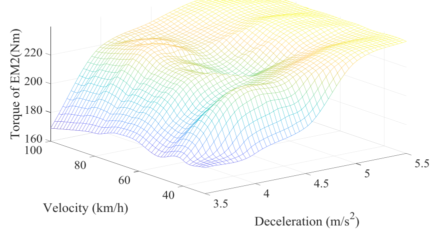

FIGURE 14. **EM2 torque control map in DMB.**

TABLE 3. **Important parameters for simulation.**

	Maximum Torque(Nm)/ Speed(r/min)		Power(kW)
Engine	130/3500		60
	Rated Torque(Nm)	Rated/ Maximum Speed(r/min)	Rated Power (kW)
EM1	130	2000	30
EM2	240	3000	60
Vehicle	Rolling Radius(m)	Final Ratio	Curb Weight(kg)
Value	0.317	3.59	1559
Threshold	Z_thres1 &Z_thres2	SOC_low &SOC_high (%)	V_low &V_high(km/h)
Value	0.55/0.35	40/85	30/80

network algorithm. The important parameters for simulation are shown in TABLE 3.

Firstly, the simulation is carried out under NEDC which is a typical cycle conditions. The state of EVT, the engine, the braking mode and SOC are shown in FIGURE 15.

The engine state, the braking mode and SOC variation are shown in FIGURE 15a under the Test 1 in which the initial value of SOC is 70% and the vehicle is working in the hybrid driving state. The SOC is in chargeable state, so the engine remains the 'on state'. When the vehicle velocity is 30-80km/h, the braking mode is EMCB. When the vehicle velocity is lower than 30km/h, MB mode is used for braking which is in line with the proposed switching rule. At this time, EVT does not provide torque which acts as the clutch to disconnect the power transmission. When the vehicle velocity is higher than 80km/h, EM2 speed is higher than the engine speed and its rated speed. EM1 does not work and the regenerative braking force is provided only by EM2 which is similar to SMB mode.

The engine state, the braking mode and SOC variation are shown in Figure 15b under the Test 2 in which the initial value of the SOC is 82% and the vehicle is working in the hybrid driving state. During 0-897s, the battery is in the chargeable state and the operating state is similar to that in FIGURE 15a. After 897s, SOC is larger than 85% and the battery enters into the non-chargeable state. Then the engine is turned off and the braking mode is changed into SMB mode. After that, the driving state is electric driving mode. Due to the small braking intensity of NEDC cycle, the regenerative braking process in this period is only under SMB mode.

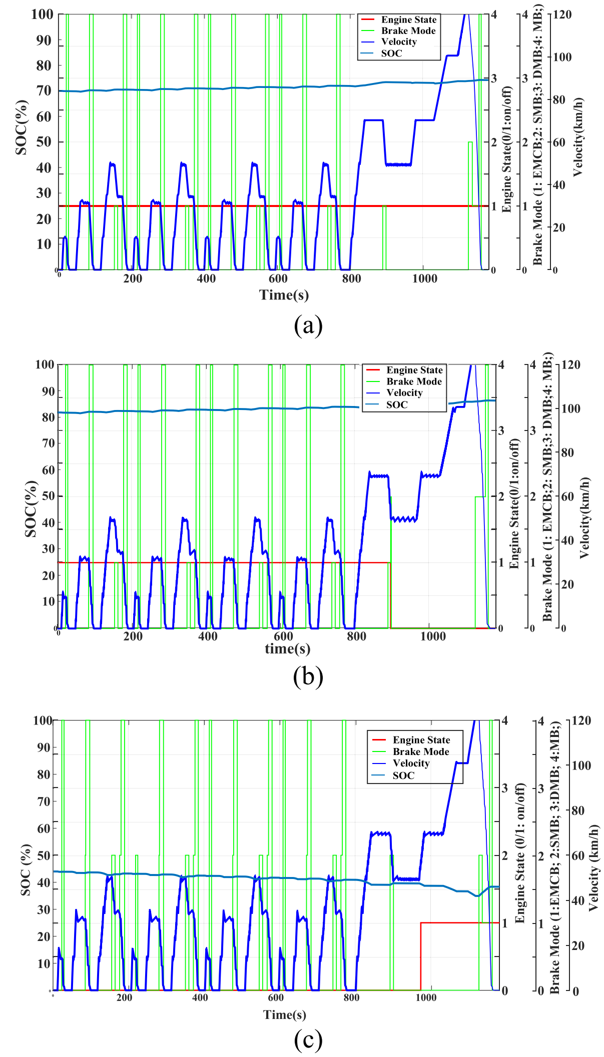

FIGURE 15. **Braking mode, SOC and engine state variation. (a) Test 1: Hybrid driving mode and initial value of SOC is 70%. (b) Test 2: Hybrid driving mode and initial value of SOC is 82%. (c) Test 3: Electric driving mode and initial value of SOC is 43%.**

The engine state, the braking mode and SOC variation are shown in FIGURE 15c under the Test 3 in which the initial value of the SOC is 43% and the vehicle is working in the electric driving state. During the period of 0-971s, the vehicle is in electric driving mode and the regenerative braking process is in SMB mode. After 971s, the SOC is lower than 40% and the battery is not enough to provide the energy for electric driving mode. The braking mode is changed into EMCB mode and the subsequent drive mode is the hybrid drive mode.

It can be seen that the braking mode can be switched properly and reduce the switching frequency of the engine during regenerative braking process following the braking mode switching strategy. The switching of the engine only occurs at the high and low threshold of SOC.

The speed and torque variation of the engine, EM1 and EM2 and the mechanical braking torque are shown in

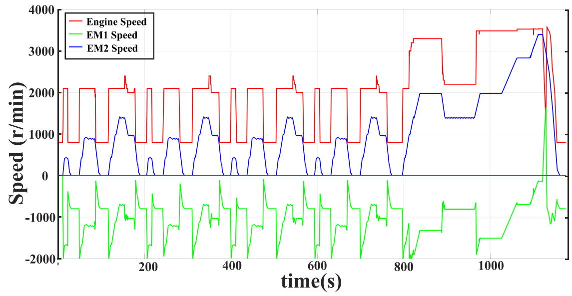

FIGURE 16. Variation of the speed of engine and EVT.

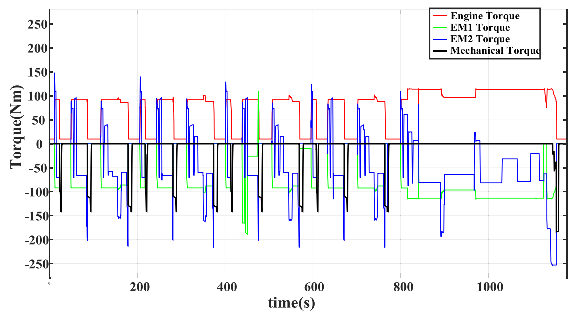

FIGURE 17. Variation of the torque of engine, EVT and mechanical brake.

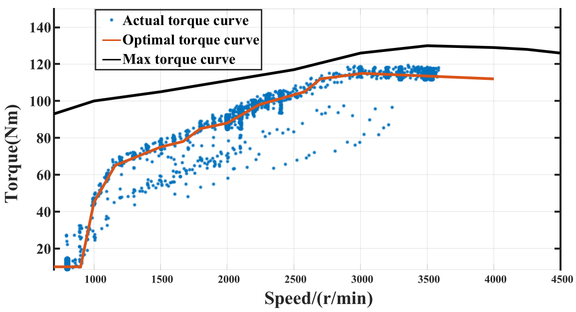

FIGURE 18. Torque distribution diagram of ICE.

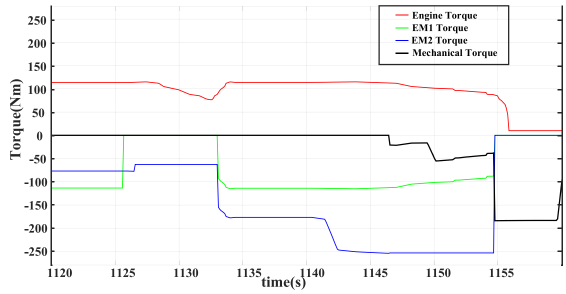

FIGURE 19. Enlarged view of the torque variation under test4 (the part of test 1).

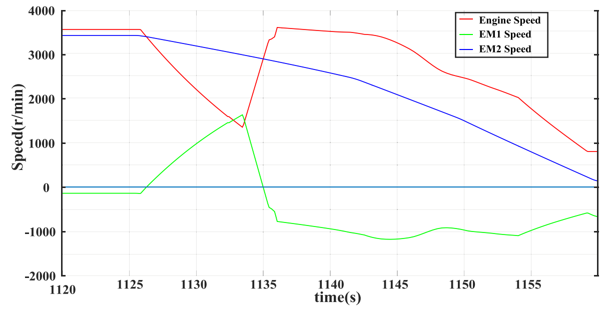

FIGURE 20. Enlarged view of the speed variation under test4 (the part of test 1).

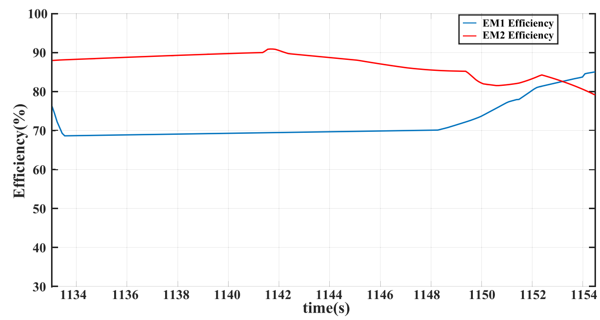

FIGURE 21. Enlarged view of the efficiency variation under the EMCB mode of test 4 (the part of test 1).

FIGURE 16 and 17 under Test 1. It can be seen that EM1 does not work in SMB and MB mode but works as the generator in EMCB mode, EM2 operates as the generator during all the regenerative braking process and the mechanical brake is only effected in MB mode.

The torque distribution diagram of ICE is shown in FIGURE18. It indicates that the engine torque is mainly concentrated around the optimal ICE curve even during the braking process which is due to the advantage of EMCB mode. And the scatters below the optimal ICE curve are the torque distribution with the engine in the idling state. This is because that EVT or EM1 does not work and the engine does not transfer power to the road load in MB mode and SMB mode.

The enlarged view of the torque, speed and the efficiency variation are shown in FIGURE 19-21 under Test 4 which is the final deceleration phase of Test1. In the initial stage of Test 4, the vehicle velocity is higher than 80km/h. According to the mode switching rule, SMB mode is applied in which EM1 does not work, the engine speed decreases continuously and EM2 provides the required regenerative braking torque. When the vehicle speed is lower than 80km/h, EMCB mode is entered in which the speed and torque of the engine and EVT are distributed according to the optimal efficiency control. The average efficiency of EM1 is 75.9% and the average efficiency of EM2 is 86.8% during the process. After 1147s, the torque of EM2 reaches the maximum value and then remains at its maximum, while the insufficient braking torque is provided by the mechanical brake.

The equivalent efficiency proposed in section IV can indicates how much energy has been converted into electricity. In the traditional regenerative braking control [18]–[24], [32]–[35] under hybrid drive mode, the engine is disengaged, thus all the energy of engine is wasted during

TABLE 4. Wasted fuel comparison between the traditional regenerative braking control and the noble regenerative braking control with emcb under test 4.

	Fuel Consumption (L)	Wasted Fuel (L)	Engine State
Traditional Control	0.12	0.12	Idle State
Noble Control	0.34	0.0646	Optimal State

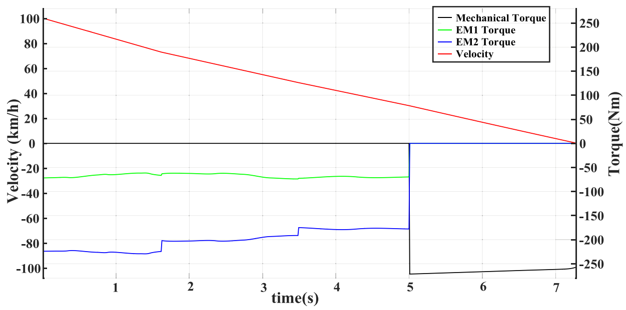

FIGURE 22. Torque variation in DMB mode.

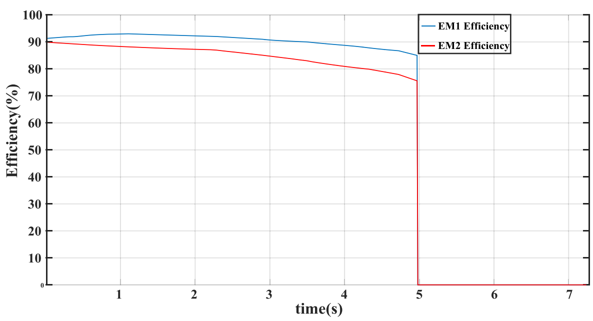

FIGURE 23. Efficiency variation in DMB mode.

the braking process. While with EMCB mode the engine operates in the optimal state and the output energy is transmitted into the battery. Fuel Consumption of the traditional regenerative braking control and the noble regenerative braking control with EMCB under Test 4 is compared in TABLE 4. It can be seen that the wasted fuel with the regenerative braking process with EMCB is decreased by 46.1% compared with the traditional control and verify that EMCB mode can improve the fuel economy of EVT-HEV.

FIGURE 22 and 23 show the deceleration condition under Test 5 to verify the performance of DMB mode. Test 5 is described as the following: EVT-HEV drives in electric mode. When the velocity is between 100km/h and 80km/h, the initial braking intensity is 0.42. When the velocity is between 75km/h and 50km/h, the braking intensity is 0.38 and when the velocity is between 50km/h and 30km/h. The braking intensity is 0.35 and the initial SOC is 50%. The torque of EM1 and EM2 is distributed according to the optimal efficiency control strategy and EM1 and EM2 operate in the optimal state in which the average efficiency of EM1 is 90.4%

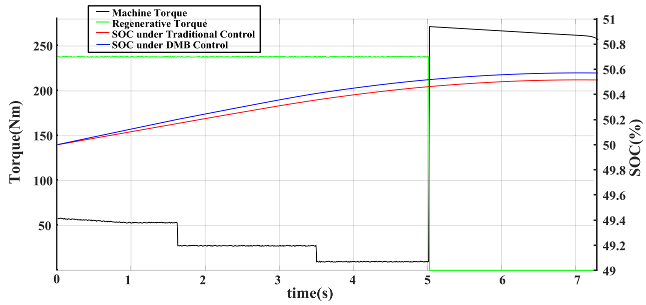

FIGURE 24. Braking torque, SOC variation under traditional control and SOC variation under DMB mode.

TABLE 5. Recovered energy comparison between the traditional regenerative braking control and the noble regenerative braking control with DMC under test 5.

	Initial SOC (%)	Final SOC (%)	Change Value (%)
Traditional Control	50	50.4625	0.4625
Noble Control	50	50.5175	0.5175

and the average efficiency of EM2 is 84.8%. When the vehicle speed is lower than 30km/h, the vehicle enters MB mode.

FIGURE 24 shows the braking torque and SOC variation with the traditional regenerative braking control under Test 5 and the SOC is compared with that in DMB mode. In the traditional regenerative braking control [6]–[10] under electrical drive mode, the regenerative braking torque is only provided by one motor and the mechanical braking torque supplements the deficient braking torque. While with DMB mode, the insufficient part can be provided by EM1 so that more energy can be recovered. TABLE 5 indicates that the recovered energy can be increased by 11.9% under DMB mode.

VI. CONCLUSION

In this paper, EVT-HEV is taken as the research object and the efficiency optimization control strategy of its regenerative braking system is studied. Firstly the braking process of EVT-HEV is analyzed in detail and four braking modes named as EMCB, SMB, DMB and MB are proposed. Then a hierarchical controller is proposed in which the rule-based control strategy is used for braking mode switching and neural network algorithm is used for the optimal efficiency control for the system. Based on the results of the simulation on CRUISE_MATLAB platform, the main results of our research are listed as following:

1) With rule-based mode switching control strategy, EVT-HEV can switch to the proper braking mode. And due to the function of EMCB, the engine can keep operating in the optimal state during both the braking and driving state and the state switching of the engine only occurs when SOC reaches the high and low threshold therefore it can reduce

the switching frequency of the engine and improve the fuel economy of the vehicle.

2) With the optimal efficiency control based on the neural network algorithm, EVT and engine can be operated with high efficiency and ensure RBS in EVT-HEV to work in the optimal state.

3) EMCB mode can keep the engine operating in the optimal state and the energy can be transmitted into battery during braking process. The results of simulation indicate that the wasted fuel with EMCB mode can be reduced by 46.1% compared with the existed control strategy in which the engine is disengaged and all the energy is wasted.

4) DMB mode can make full use of the braking torque of EM1 and EM2 therefore the recovered energy under DMB mode can be increased by 11.9% compared with the existed control strategy in which only EM2 is utilized.

Based on our novel research on the RBS in EVT-HEV, the control strategy proposed in this paper can solve the shortcomings of the current researches on RBS in EVT-HEV, bring a new theoretical foundation for the application of EVT in HEV and is of great significance to enrich the energy management strategies of EVT-HEV.

However, it should be noted that the erroneous input signals have important influences on the performance of RBS in EVT-HEV and need to be further studied in our following research. In addition, we will also focus on the construction of test bench to further supplement the research on EVT-HEV.

APPENDIX

The abbreviations used in this paper are listed as following:

Abbreviation	Full name
EVT	Electrical variable transmission
HEV	Hybrid electrical vehicle
EVT-HEV	Hybrid electrical vehicle based on Electrical variable transmission
ICE	Internal combustion engine
EM1	Inner motor
EM2	Outer motor
SOC	State of charge
RBS	Regenerative braking system
NEDC	New European Driving Cycle
EMCB	Engine-motor coordinating braking
DMB	Dual motor braking
SMB	Single motor braking
MB	Mechanical braking
CVT	Continuously variable transmission

REFERENCES

[1] M. J. Hoeijmakers and J. A. Ferreira, "The electric variable transmission," *IEEE Trans. Ind. Appl.*, vol. 42, no. 4, pp. 1092–1100, Jul./Aug. 2006.

[2] M. J. Hoeijmakers and M. Rondel, "The electrical variable transmission in a city bus," in *Proc. 35th Annu. IEEE Power Electron. Spec. Conf.*, Aachen, Germany, Jun. 2004, pp. 2773–2778.

[3] M. Boisvert and D. Mammosser, "Comparison of two strategies for optimal regenerative braking, with their sensitivity to variations in mass, slope and road condition," in *Proc. 7th IFAC Symp. Adv. Automot. Control*, Tokyo, Japan, Sep. 2013, pp. 626–630.

[4] C. Lv, J. Zhang, Y. Li, and Y. Yuan, "Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles," *Energy Convers. Manage.*, vol. 92, no. 1, pp. 469–482, Mar. 2015.

[5] C. Qiu and G. Wang, "New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles," *Energy Convers. Manage.*, vol. 119, pp. 389–398, Jul. 2016.

[6] K. Itani, A. De Bernardinis, Z. Khatir, and A. Jammal, "Comparison between two braking control methods integrating energy recovery for a two-wheel front driven electric vehicle," *Energy Convers. Manage.*, vol. 122, pp. 330–343, Aug. 2016.

[7] G. Zhao and J. Liu, "Fuzzy PID control on combined braking system of tracked vehicle with braking energy recovery system," in *Proc. Int. Conf. Comput., Mechatronics, Control Electron. Eng. (CMCE)*, Aug. 2010, pp. 515–518.

[8] L. Zhe, Z. Ling, R. Yue, Y. Wei, L. Yinong, G. Feng, L. Yusheng, and X. Zhoubin, "A control strategy of regenerative braking system for intelligent vehicle," in *Proc. IET Int. Conf. Intell. Connected Vehicles (ICV)*, Chongqing, China, 2016, pp. 1–7.

[9] C. Qiu, G. Wang, M. Meng, and Y. Shen, "A novel control strategy of regenerative braking system for electric vehicles under safety critical driving situations," *Energy*, vol. 149, pp. 329–340, Apr. 2018.

[10] H. Liu, X. He, L. Chu, and J. Tian, "Study on control strategy of regenerative braking for electric bus based on braking comfort," in *Proc. Int. Conf. Electron. Mech. Eng. Inf. Technol.*, Aug. 2011, pp. 1037–1040.

[11] B. Long, S. T. Lim, J. H. Ryu, and K. T. Chong, "Energy-regenerative braking control of electric vehicles using three-phase brushless direct-current motors," *Energies*, vol. 7, no. 1, pp. 99–114, Dec. 2014.

[12] S. Geraee, H. Mohammadbagherpoor, M. Shafiei, M. Valizadeh, F. Montazeri, and M. R. Feyzi, "Regenerative braking of electric vehicle using a modified direct torque control and adaptive control theory," *Comput. Electr. Eng.*, vol. 69, pp. 85–97, Jul. 2018.

[13] C. Lv, J. Zhang, Y. Li, and Y. Yuan, "Novel control algorithm of braking energy regeneration system for an electric vehicle during safety–critical driving maneuvers," *Energy Convers. Manage.*, vol. 106, pp. 520–529, Dec. 2015.

[14] J. Han and Y. Park, "Cooperative regenerative braking control for front-wheel-drive hybrid electric vehicle based on adaptive regenerative brake torque optimization using under-steer index," *Int. J. Automot. Technol.*, vol. 15, no. 6, pp. 989–1000, Oct. 2014.

[15] L. Li, X. Wang, R. Xiong, K. He, and X. Li, "AMT downshifting strategy design of HEV during regenerative braking process for energy conservation," *Appl. Energy*, vol. 183, no. 1, pp. 914–925, Dec. 2016.

[16] X. Nian, F. Peng, and H. Zhang, "Regenerative braking system of electric vehicle driven by brushless DC motor," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5798–5807, Oct. 2014.

[17] J. Liu, Z. Su, and J. Chen, "Comparison of two electric braking methods with regenerative capability of brushless DC machine and their four-quadrant operation," in *Proc. 33rd Youth Academic Annu. Conf. Chin. Assoc. Automat. (YAC)*, Nanjing, China, May 2018, pp. 1116–1120.

[18] Q. Xu, S. Cui, L. Song, and Q. Zhang, "Research on the power management strategy of hybrid electric vehicles based on electric variable transmissions," *Energies*, vol. 7, no. 2, pp. 934–960, Feb. 2014.

[19] Q. Xu, X. Jiang, J. Sun, and S. Cui, "Comparison analysis of power management used in hybrid electric vehicle based on electric variable transmission," in *Proc. UKACC 11th Int. Conf. Control*, vol. 2, Belfast, U.K., Aug./Sep. 2016, pp. 1–7.

[20] Y. Cheng, K. Chen, C. C. Chan, A. Bouscayrol, and S. Cu, "Global modeling and control strategy simulation for a hybrid electric vehicle using electrical variable transmission," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Harbin, China, Sep. 2008, pp. 1–5.

[21] Y. Cheng, C. Espanet, R. Trigui, A. Bouscayrol, and S. Cui, "Design of a permanent magnet electric variable transmission for HEV applications," in *Proc. IEEE Vehicle Power Propuls. Conf.*, Lille, France, Sep. 2010, pp. 1–5.

[22] A. Abdelsalam and S. Cui, "Parametric design and robust control strategy for HEV based on permanent magnet electrical variable transmission," *Res. J. Appl. Sci., Eng. Technol.*, vol. 4, no. 15, pp. 2323–2333, May 2012.

[23] A. A. Abdelsalam and S. Cui, "A fuzzy logic global power management strategy for hybrid electric vehicles based on a permanent magnet electric variable transmission," *Energies*, vol. 5, no. 2, pp. 1175–1198, Jan. 2012.
[24] A. Abdelsalam and S. Cui, "Control and analysis of regenerative power distribution on electrical variable transmission using fuzzy logic on HEV system," in *Proc. Int. Conf. Elect. Mach. Syst.*, Aug. 2011, pp. 1–6.
[25] Q. Xu, J. Sun, Y. Su, W. Chen, J. Huang, and S. Cui, "Study on the magnetic coupling and decoupling algorithm of electrical variable transmission," in *Proc. ICSEE*, Aug. 2017, pp. 146–155.
[26] C. Shu-Mei, H. Wen-Xiang, and Z. Qian-Fan, "Research on power density improvement design of an HEV using induction machine based electrical variable transmission," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Harbin, China, Sep. 2008, PP. 1–4.
[27] X. Sun, M. Cheng, S. Zhu, and J. Zhang, "Coupled electromagnetic-thermal-mechanical analysis for accurate prediction of dual-mechanical-port machine performance," *IEEE Trans. Ind Appl.*, vol. 48, no. 6, pp. 2240–2248, Nov./Dec. 2012.
[28] P. Zheng, R. Liu, P. Thelin, E. Nordlund, and C. Sadarangani, "Research on the cooling system of a 4QT prototype machine used for HEV," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 61–67, Mar. 2008.
[29] R. Liu, H. Zhao, P. Zheng, X. Gan, R. Zhao, and B. Kou, "Experimental evaluation of a radial-radial-flux compound-structure permanent-magnet synchronous machine used for HEVs," *IEEE Trans. Magn.*, vol. 45, no. 1, pp. 645–649, Jan. 2009.
[30] S. S. Shetty and O. Karabasoglu, "Regenerative braking control strategy for hybrid and electric vehicles using artificial neural networks," in *Proc. Int. Conf. Eng. Appl. Neural Netw.*, vol. 459, 2014, pp. 103–112.
[31] H. Gao, Y. Gao, and M. Ehsani, "A neural network based SRM drive control strategy for regenerative braking in EV and HEV," in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, Cambridge, MA, USA, Jun. 2001, pp. 571–575.
[32] Y. C. Du, C. Qin, S. You, and H. Xia, "Efficient coordinated control of regenerative braking with pneumatic anti-lock braking for hybrid electric vehicle," *Sci. China Technol. Sci.*, vol. 60, no. 3, pp. 399–411, Mar. 2017.
[33] B. Liu, L. Li, X. Wang, and S. Cheng, "Hybrid electric vehicle downshifting strategy based on stochastic dynamic programming during regenerative braking process," *IEEE Trans. Veh. Technol.*, vol. 67, no. 6, pp. 4716–4727, Jun. 2018.
[34] M. Lv, Z. Chen, Y. Yang, and J. Bi, "Regenerative braking control strategy for a hybrid electric vehicle with rear axle electric drive," in *Proc. Chin. Autom. Congr. (CAC)*, Jinan, China, Oct. 2017, pp. 521–525.
[35] L. Li, Y. Zhang, C. Yang, B. Yan, and C. M. Martinez, "Model predictive control-based efficient energy recovery control strategy for regenerative braking system of hybrid electric bus," *Energy Convers. Manage.*, vol. 111, pp. 299–314, Mar. 2016.

QIWEI XU was born in Heilongjiang, China, in 1983. He received the B.S., M.S., and Ph.D. degrees from the Harbin Institute of Technology, Harbin, China, in 2006, 2008, and 2013, respectively, all in electrical engineering. He is currently an Associate Professor with Chongqing University, Chongqing, China. His current research interests include the design and control of special electric machines, the electric drive system of electric vehicles, and the control and simulation of hybrid electric vehicles.

FUKANG WANG received the B.E. degree in vehicle engineering from Nanjing Agricultural University, China, in 2017. He is currently pursuing the M.E. degree in vehicle engineering with Chongqing University, China. His main research interest includes the energy management of hybrid electric vehicles.

XUEFENG ZHANG is currently pursuing the master's degree with Chongqing University. His main research interests include electric vehicle driving systems and energy management strategy.

SHUMEI CUI was born in Heilongjiang, China, in 1964. She received the Ph.D. degree in electrical engineering from the Harbin Institute of Technology (HIT), Harbin, China, in 1998.

She has been a Professor with the Department of Electrical Engineering, HIT, where she is also the Vice Dean of the HIT Institute of Electromagnetic and Electronic Technology and the Dean of the HIT Electric Vehicle Research Centre. Her research interests include the design and control of micro and special electric machines, the electric drive system of electric vehicles, the control and simulation of hybrid electric vehicles, and the intelligent test and fault diagnostics of electric machines.

Dr. Cui is a Vice-Director Member of the Micro and Special Electric Machine Committee and the Chinese Institute of Electronics and a member of the Electric Vehicle Committee and the National Automotive Standardization Technical Committee.