



A New Framework for Advancement of Power Management Strategies in Hybrid Electric Vehicles

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ABSTRACT

Power management strategies play a key role in the design process of hybrid electric vehicles. Electric Assist Control Strategy (EACS) is one of the popular power management strategies for hybrid electric vehicles (HEVs). The present investigation proposes a new framework to advance the EACS. Dynamic Programming method is applied to an HEV model in several drive cycles, and as a result, some optimal operating regions are found. The obtained regions are almost distinct, and consequently, some threshold lines can be defined to separate them. The obtained threshold lines are used to eliminate some parameters of the EACS to reduce its sensitivity to the driving behavior. It is shown that by applying the mentioned modification, the sensitivity of the EACS decreases without a significant increase in the HEV's FC. All in all, our findings indicate the effectiveness of the proposed methodology to improve the EACS strategy for HEV supervisory control applications.

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NOMENCLATURE

FC	Fuel consumption	H_{SOC}	Higher limit of the battery SOC
H_{SOC}	Higher limit of the battery SOC	L_{SOC}	Lower limit of the battery SOC
L_{SOC}	Lower limit of the battery SOC	$P_{ICE,max}$	ICE maximum power
$P_{ICE,max}$	ICE maximum power	P_{req}	Required power
P_{req}	Required power	Q	Cost function
Q	Cost function		

1. INTRODUCTION

One of the existing solutions for reducing the fuel consumption (FC) and emissions of automobiles is to use an internal combustion engine (ICE) in combination with an electric motor (EM) as the vehicle's power sources. These types of vehicles are called hybrid electric vehicles (HEVs). One of the main concerns in the area of HEV design is to determine proper power split between the ICE and EM for a given power demand by the vehicle's supervisory controller [1, 2]. The HEV supervisory control strategies can be categorized into three groups: (i)

the approaches based on global optimization techniques, for instance Dynamic Programming [3-5] and PSO algorithm [6-8], (ii) the techniques with the instantaneous optimization of an overall FC function which is calculated by converting the electric energy consumption to an equivalent FC [9-11], and (iii) the methods on the basis of some predefined rules, such as Electric Assist Control Strategy (EACS) [12, 13] and fuzzy logic [14, 15]. It is notable that the first group cannot be employed as real-time controller because it requires priori knowledge of the vehicle's driving cycle, and also, is

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very time consuming [16, 17]. One of the popular supervisory control strategies which is currently used in HEVs (such as Toyota Prius [13] and Honda Insight [15]) is EACS. The EACS approach is based on some predefined rules and parameters which determine the mode of HEV operation with regard to the vehicle speed, demanded power and energy level of the battery. The aim of this strategy is to ensure that the ICE operates in its optimal working region [18].

Some of the issues concerned with the EACS are the way of determining the optimal values of its parameters as well as the generality of the optimization results. Different investigations have been implemented on the optimization of the EACS parameters to reach an optimal controller for a given driving cycle [6, 19-24]. The sensitivity of the optimization results to the pattern of driving cycle is another concern in finding the optimal parameters [6, 19-21, 25]. To the best of our knowledge, there are a few numbers of studies on the methods of decreasing the sensitivity of the EACS approach to the driving cycle [26].

In this work, the DP method is employed to further advance the EACS strategy. To do so, a set of optimal operating regions are found through executing the DP in different driving cycles. It will be shown that these optimal regions are approximately distinct, and also, some threshold lines can be defined to separate them. Using these lines, a modification is implemented on the EACS. The thresholds can be utilized in the EACS strategy to eliminate a number of its parameters, which causes a reduction of its sensitivity to the driving behavior. In this study, the application of the identified thresholds in the EACS will be thoroughly studied and the corresponding revised HEV supervisory controller is obtained. The modified EACS strategy is then compared with its basic counterpart from different perspectives. The comparison is accomplished in the cycles which are considered in defining the optimal regions and also the ones which are not used for this purpose.

The outline of the paper is given, as follows. First, the DP and EACS strategies are described. Next, the considered HEV model is introduced, and then, the threshold lines obtained from executing the DP in different driving schedules are presented. Then, the obtained thresholds are used in the EACS approach, and consequently, some parameters of the EACS method are eliminated. Then, the modified EACS is compared to the standard EACS in terms of the vehicle's FC as well as the sensitivity to the driving cycle type. Finally, the paper is concluded with some remarks.

2. DYNAMIC PROGRAMMING (DP)

This technique is one of the global optimization methods which can be used to determine an optimal power

management for HEVs. It is based on the Bellman's principle [27] and can be applied to linear and non-linear optimization problems. The DP-based power management strategy is developed on the basis of the charge sustaining condition, in which the same SOC (battery state of charge) at the end of drive cycles as that of the starting point is achieved. In this approach, the maximum and minimum levels of the battery's SOC at each moment of the driving are determined. The maximum level of battery's energy is calculated through considering the maximum allowable energy which can be transferred to the battery. Also, the minimum level of battery's energy is found by considering the maximum allowable value which can be supplied by the battery to propel the vehicle. In order to force the power management controller to sustain the battery's energy, the values of the battery's maximum and minimum energies at the beginning and end of driving cycles are set to be equal. After defining the maximum and minimum achievable values of the battery's energy at each moment of the driving, some points between the minimum and maximum value are considered as the candidate points.

At each moment of the driving, the objective is defined as [28]:

$$Q_j(i) = \min_j \sum_i^N FC(i, j) dt \quad (1)$$

where i is an index for the time, j is an index for the battery's energy, N is the number of time steps in the driving cycle, and FC is the vehicle's fuel consumption. At each moment of the driving, the controller attempts to find an optimal candidate point for which the defined objective is minimal. Figure 1 shows the optimal values of the battery's energy which are obtained using the DP in the ECE driving cycle. The battery SOC is considered 50% at the beginning of the driving cycle and the maximum charge and discharge rate of the battery is calculated according to the battery and motor/generator characteristics. In this figure, the blue points denote the candidate points and the black points represent the optimal points determined by DP. As can be seen, these points lie among the minimum and maximum values of the battery's energy. As discussed before, using the DP approach, the battery's SOC at the end of a driving cycle will be equal to its value at the beginning of driving cycle. This fact is shown in Figure 1. It is notable that in this figure, the moments in which the vehicle is at standstill are not considered.

3. ELECTRIC ASSIST CONTROL STRATEGY (EACS)

EACS is one of the common control strategies employed in HEVs, based on some predefined rules. In this

strategy, the ICE is the main power supplier while the EM assists the ICE in propelling the vehicle. In the moments the ICE is not efficient (namely, low speeds and powers) and the battery SOC is adequate, the EM alone provides the required power. In this case, if the battery SOC is not adequate, the ICE operates in its efficient point (high powers) and the additional power is stored in the battery. If the ICE cannot provide the HEV required power, and also the battery SOC is adequate, the EM helps the ICE provide the required power. Also, during the braking, the braking energy is absorbed by the battery, until the battery SOC reaches its upper limit.

Some of the rules of this strategy are illustrated in Figure 2. The EACS rules are completely described in literature [26].

The EACS performance depends on the values of its parameters. Therefore, the strategy should be optimized to find the optimum parameters for a certain drive cycle, otherwise, the application of EACS will result in non-optimal solutions. One of the main problems for the optimization of the EACS parameters is the generality of the results [26]. In other words, there is no guarantee that the optimized EACS parameters for a driving cycle will be optimal for other cycles. This problem is due to the large number of the EACS parameters.

In what follows, an idea based on the DP approach will be used to reduce the EACS parameters, and thus, its sensitivity to the drive cycle type.

4. HEV MODELING

The considered vehicle in this paper is a parallel HEV, which includes an ICE, EM, torque coupler, continuously variable transmission (CVT), and two clutches as shown in Figure 3. The utilized CVT is a full-toroidal unit. Also, it is notable that the employed EM functions as a generator at the moments of battery charging. The main characteristics of the HEV components are summarized in Table 1.

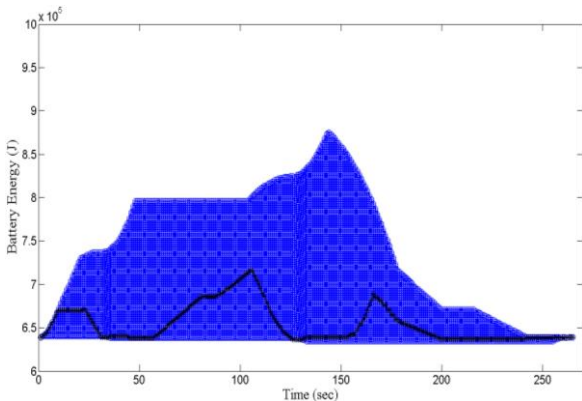


Figure 1. Optimal values of the battery’s energy in ECE achieved by DP

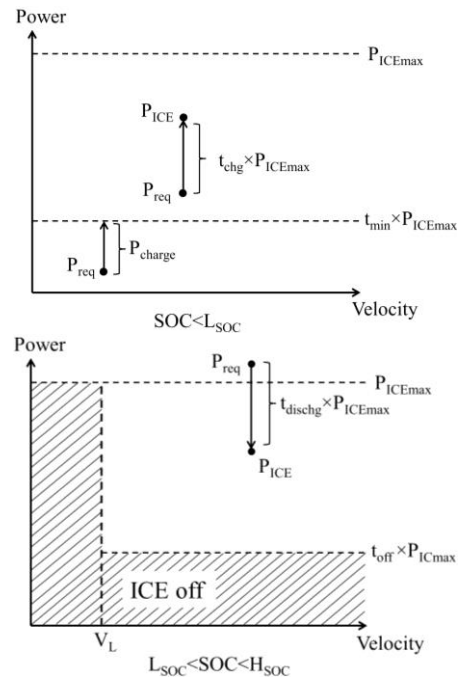


Figure 2. Illustrations of the first four rules of the EACS technique [26]

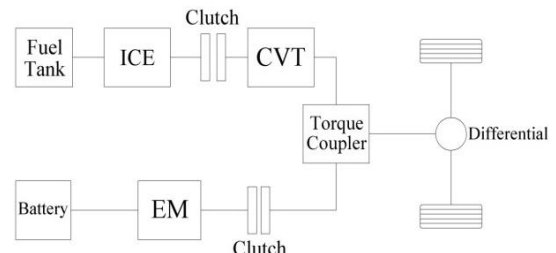


Figure 3. Driveline layout of the studied HEV

In this study, a MATLAB-based model is used to simulate the baseline HEV’s behavior as well as the considered control strategies. This model is comprehensively described in literature [26]. In this model, some experimental data for the FC of the ICE, the EM’s efficiency (in the both motor and generator modes) and the battery’s efficiency data, along with the devised simulation models of the full-toroidal CVT, vehicle’s subsystems, and also the considered control strategies are all integrated. The CVT model used in this simulation model is fully explained in literature [32, 33]. As discussed in these literatures, the model inputs are the CVT’s input torque, speed and speed ratio, and also, the model calculates the CVT’s efficiency as a function of these inputs. This model has been verified in the above references through comparing its results with some experimental data. Due to the model complexity, incorporating this model into the full HEV model increases the calculation time, which is not desirable.

TABLE 1. Specifications of the HEV subsystems

Element	Characteristics
Internal combustion engine [29]	
Volume	1.3L
Maximum power	53.2 kW at 5200 rpm
Maximum torque	113 Nm at 2800 rpm
Peak efficiency	0.34
Electric motor/generator [30]	
Asynchronous induction motor/generator	
Maximum power	30 kW
Maximum torque	300 Nm
Maximum speed	6000 rpm
Peak efficiency	0.9
Minimum voltage	60 V
Battery [31]	
Lithium-ion polymer rechargeable	
Number of Modules	96
Nominal Capacity	10.05Ah
Nominal Voltage	14.8V
Internal Impedance	15mΩ
Maximum Allowable Current	10.05A (charge), 120A (discharge)
Vehicle [29]	
Light passenger car	
Frontal area	1.94m ²
Rolling resistance	0.014
Drag coefficient	0.46
Wheel radius	0.264m
Cargo mass	136 kg
Total mass	1224kg
Power train [32]	
Continuously variable transmission	
Efficiency	Variable with respect to input torque, speed and speed ratio
Differential speed ratio and efficiency	3.778, 97%
Torque coupler	One-speed gear mate

Hence, this model was simulated for different input values and some lookup tables of the CVT's efficiency versus its input torque, speed, and speed ratio were developed for using in the full HEV model. Obviously, the use of these tables instead of the CVT model decreases the calculation time. In order to investigate the accuracy of the developed full HEV model, a number of validations were performed. Some of the validation results are described, as given below.

First, the FC of the non-hybrid version of the studied vehicle calculated by the model was approximately equal to the experimental data points supplied by the car manufacturer. For example, the FC extracted from the model and experiments in the FTP driving cycle are 5.57 L/100km and 5.60 L/100km, respectively.

In order to validate full vehicle model, its results are compared against the results of ADVISOR, which is widely used in the automotive industry for the modeling

and simulation of HEVs, and also for validating HEV models. In the case of employing an equal ICE and EM, the FC values extracted from our MATLAB-based model and the ADVISOR software were approximately the same. For instance, the FC of the vehicle in the SC03 driving cycle calculated by the model was 4.05 L/100km, while the value calculated by ADVISOR was 4.08 L/100km.

It is notable that there was no experimental data available for the engine's FC for transient conditions. Therefore, similar to other HEV simulation packages available in the market, such as ADVISOR and Autonomie (which are widely used by automotive companies), the engine's dynamics and the transient responses of the CVT as well as the other components have not been taken into account.

5. OPTIMAL OPERATING MODES BY DP

As discussed previously, the DP technique determines a global optimal operating mode for the HEV at each moment of the driving. In this section, the vehicle motion is considered in city and highway driving cycles (namely ECE, Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test (HWFET), New York City Cycle (NYCC), HUDDS, Inspection and Maintenance Driving Cycle (IM240), and Japan 1015) and the optimal operation modes of the HEV are found using the DP method. Here, it is attempted to consider different types of the drive cycles to cover various driving scenarios to make the results more general. The DP results for the considered driving cycles are shown in Figure 3.

As it can be seen, the points of the HEV operation modes form approximately several distinct regions. In the cases of low speeds and powers, the best operation mode is pure electric for which the ICE is turned off. This is due to the low efficiency of the ICE in these cases. In the moments that the required power is high and the vehicle speed is relatively low, both of the ICE and EM propel the vehicle and the battery is discharged (discharge mode). In these speeds, the ICE cannot provide the total required power and requires some assistance from the EM. In the moments that the required power and speed are high values, the ICE provides a power more than the required amount and the additional power is used to charge the battery (charge mode). The reason for the operation of ICE for generating more power than the required value is that, in the selected working point, the ICE is more efficient in terms of the FC.

In the region between the discharge mode and charge mode, there are some points for which the optimal operating mode is the thermal mode, where the EM is turned off. However, as it can be realized from the figure, the number of points for which the optimal mode is thermal mode is very small compared to the other modes.

Therefore, an individual region is not considered for the thermal mode.

6. MODIFIED ELECTRIC ASSIST CONTROL STRATEGY

As mentioned previously, one of the concerns about the EACS technique is its sensitivity to the driving behavior, which is due to its large number of parameters. In this section, a method is proposed to decrease the number of EACS parameters. As stated in the previous section and also according to Figure 4, if the vehicle speed or the required power is a low value, the optimal state is to employ the EM to propel the HEV. In Figure 4, the “pure electric mode” region is separated from the rest of operating regions by the two red lines. These lines are similar to the lines of parameters V_L and t_{off} in Figure 2.

According to the second rule of the EACS approach, for the cases that the vehicle speed is lower than V_L or the required power is smaller than $t_{off} P_{E,max}$, the EM alone provides the entire required power. Therefore, the parameters V_L and t_{off} can be eliminated and the red lines in Figure 4 can be used to determine the “pure electric mode” region. In other words, in order to determine the “pure electric mode” region, it is not necessary to optimize the values of the parameters V_L and t_{off} . Consequently, using the proposed method, the number of the EACS parameters can be reduced from 7 to 5. As a result, the sensitivity of the EACS approach to the driving behavior can be reduced. However, as can be seen in Figure 4, the red lines do not completely separate the optimal regions. Therefore, the vehicle’s FC may increase by using the modified EACS.

6.1. Comparison of the Standard and the Modified EACS

As discussed before, the proposed modification was applied to the EACS approach to reduce its sensitivity to the driving behavior. Therefore, the standard EACS (S-EACS) should be compared with the modified EACS (M-EACS) in terms of the sensitivity to the driving cycle type. On the other hand, because of the concerns about the potential FC growth through employing the M-EACS, the two control strategies should also be compared in terms of the vehicle’s FC. To this aim, a two-stage comparison is accomplished. At the first stage, for each control strategy, the optimal controller is obtained by optimizing the parameters in one of the considered drive cycles. Then, the resulting optimal controllers are compared. At the second stage, the optimal controller is applied to the HEV model in the other considered drive cycles, and also the vehicle’s FCs are calculated for these cycles. The calculated FC values in this way are then compared with the optimum FC values found by separately optimizing the control strategy for each of these driving cycles. This comparison yields the sensitivities of these control strategies to driving patterns.

Considering the above-mentioned process, the control strategies are optimized in SC03, IM240, Japan 1015, HWFET and EUDC. The optimization tool employed in this section is Backtracking Search Optimization Algorithm (BSA), which is one of the newest evolutionary algorithms (EA). This method has several advantages over the other EA techniques, such as CLPSO, PSO, ABC, etc. This method and its advantages over the mentioned methods are completely described in literature [34]. The results, which are the vehicle’s FCs in the considered driving cycles (in L/100km), are shown in Table 2. Obviously, in order to compare the strategies in terms of the vehicle’s FC, it is essential to eliminate

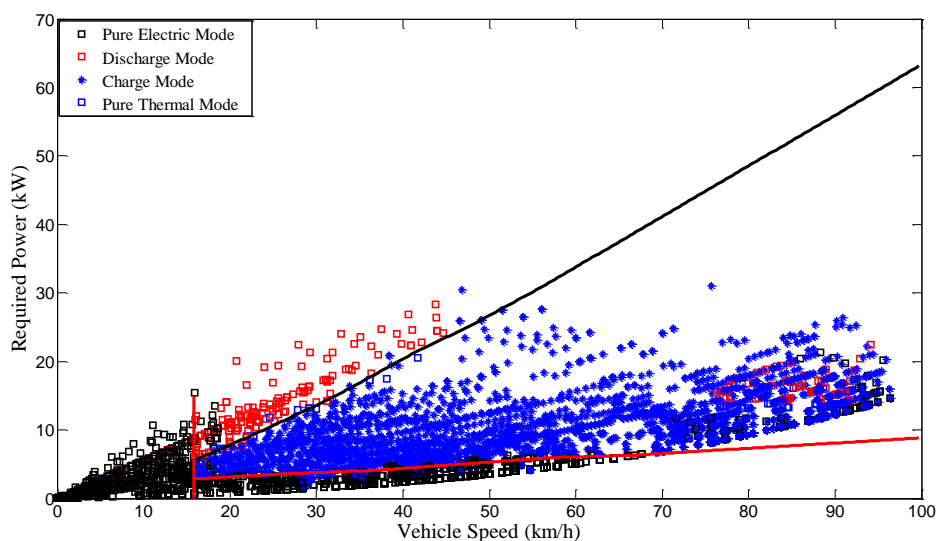


Figure 3. Operation modes of the HEV determined by DP

the impact of the difference between the final SOC (SOC at the end of the driving cycle) and the initial SOC (SOC at beginning of the drive cycle). To this aim, different initial SOC values are considered in the drive cycle until the final SOC will be very close to the considered initial value ($|InitialSOC - FinalSOC|/InitialSOC \leq 0.01$). This method is called "Dichotomy method" [21, 35]. The results shown in Table 2 reveal that in some driving cycles, the difference between the FCs of the S-EACS and the M-EACS is almost zero. Also, the maximum difference occurs for SC03, where the difference is 1.61%. As discussed before, the reason for the increase in the vehicle's FC through using the M-EACS is that the defined lines for V_L and t_{off} do not fully separate the optimal regions.

As an example, the optimized parameters of the S-EACS and the M-EACS for SC03 are shown in Table 3.

The second stage of the comparison between the S-EACS and the M-EACS is accomplished for each of SC03, IM240, HWFET, and Japan 1015. The comparison results against the optimized parameters for SC03 are shown in Tables 4 and 5. The reduction percentages given in the third rows of these tables reveal the sensitivity of each control strategy.

As shown in Tables 4 and 5, the sensitivity of the M-EACS is much smaller than that of the S-EACS. For example, the vehicle's FC for the optimized S-EACS in HWFET is 3.926 L/100km, while if the optimized S-EACS in SC03 is applied in HWFET, the vehicle's FC will be 3.930 L/100km. Therefore, the difference between the resulting FC values is 0.10%. According to Table 5, the difference for the M-EACS in HWFET is zero.

TABLE 2. Optimization results (FC in L/100km) for the standard EACS and the modified EACS in different driving cycles

	SC03	IM240	HWFET	Japan 1015	EUDC
Standard EACS	4.469	5.054	3.926	4.496	5.67
Modified EACS	4.541	5.066	3.926	4.496	5.69
Difference (%)	1.61	0.24	0	0	0.35

TABLE 3. Optimized parameters of the standard EACS and the modified EACS for SC03

	L_{SOC}	H_{SOC}	t_{min}	t_{chg}	t_{dischg}	t_{off}	$V_L(m/s)$
Standard EACS	0.34	0.73	0.24	0.02	0.09	0.1	6.5
Modified EACS	0.3	0.7	0.19	0.02	0.12	-	-

Another conclusion that can be drawn from Tables 4 and 5 is that, if the SC03-optimized form of M-EACS is used in the other considered drive cycles, the results is better than that of the S-EACS. This point can be recognized by taking a look at the first rows of Tables 4 and 5. For example, the vehicle's FC for the case of applying the SC03-optimized S-EACS in IM240 is 5.187 L/100km. This value for the M-EACS is 5.068 L/100km, which is lower than that of the S-EACS. Therefore, the use of the non-optimal version of the M-EACS in the other driving cycles gives better results compared to the case of using the non-optimal version of the S-EACS.

It is worth mentioning that the same comparison was accomplished for the other driving cycles (namely IM240, HWFET, Japan 1015 and EUDC), and similar results were observed. For example, the comparison results for the EUDC case are shown in Tables 6 and 7. Note that in defining the threshold lines in Figure 4, EUDC and SC03 were not considered. Therefore, the impact of modifications is precisely investigated in this case.

7. CONCLUSION

In this investigation, the EACS strategy was modified based on some thresholds which were defined through executing the DP approach for a given HEV in several driving cycles. It was revealed that by finding an optimal mode (namely, one of the pure electric, pure thermal, charge, or discharge modes) at each point of the HEV operating region, some distinct areas can be obtained. For example, for the low speeds or powers, the optimal mode was the EV mode, where the EM alone propels the HEV. Therefore, some dividing lines could be drawn among the optimal regions, which were called the threshold lines. The obtained threshold lines were utilized to eliminate some parameters of the EACS technique. It was demonstrated that by using these lines, the two of the EACS parameters can be eliminated. The modified EACS was compared to the standard EACS to evaluate the effectiveness of the proposed modifications. It was shown that the M-EACS has a lower sensitivity to the pattern of driving cycle, as compared to the S-EACS. Moreover, it was found that by applying the M-EACS, the vehicle's FC increase is up to 1.61%. It is notable that there was no FC increase in some of the studied drive cycles. Finally, it was indicated when the control strategy was optimized over one of the considered driving cycles and then applied during the other ones, the performance of the M-EACS is better than that of the S-EACS. By analyzing the findings, it was concluded that the modification of the EACS based on the proposed idea was beneficial to reduce its sensitivity to the driving cycle pattern, which is an important consideration for practical applications.

TABLE 4. FC (L/100km) comparisons with the optimized values over SC03 and considered drive cycles for the S-EACS

	IM240	HWFET	Japan 1015	EUDC
Optimized in SC03	5.187	3.930	4.504	5.680
Optimized in Considered Cycle	5.054	3.926	4.496	5.670
Reduction (%)	3.04	0.10	0.18	0.18

TABLE 5. FC (L/100km) comparisons with the optimized values over SC03 and considered drive cycles for the M-EACS

	IM240	HWFET	Japan 1015	EUDC
Optimized in SC03	5.068	3.927	4.497	5.691
Optimized in Considered Cycle	5.066	3.926	4.496	5.690
Reduction (%)	0.04	0.03	0.02	0.02

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A New Framework for Advancement of Power Management Strategies in Hybrid Electric Vehicles

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استراتژی کنترلی نقش مهمی در طراحی خودروهای هیبرید الکتریکی ایفا می‌کند. استراتژی کنترلی EACS یکی از مهمترین استراتژی‌های کنترلی برای خودروهای هیبرید الکتریکی است. در این مقاله روشی برای بهبود این استراتژی کنترلی پیشنهاد می‌شود. در این بهبود استراتژی برنامه‌نویسی پویا روی مدل خودروی هیبرید الکتریکی در سیکل‌های رانندگی مختلف اعمال شده و تعدادی ناحیه بهینه برای کارکرد خودرو تعیین می‌شود. نواحی بدست آمده تقریباً مجزا هستند و در نتیجه، تعدادی خط جدا کردن آن‌ها قابل رسم است. از این خطوط برای حذف تعدادی از پارامترهای استراتژی EACS استفاده می‌شود که نتیجه آن کاهش حساسیت استراتژی کنترلی به نحوه رانندگی خواهد بود.

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