IJE TRANSACTIONS C: Aspetcs Vol. 29, No. 12, (December 2016) 1757-1764

International Journal of Engineering

Journal Homepage: www.ije.ir

Modification of Equivalent Consumption Minimization Strategy for a Hybrid Electric Vehicle

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PAPER INFO

Paper history:
Received 30 July 2016
Received in revised form 17 October 2016
Accepted 11 November 2016

Keywords:
Hybrid Electric Vehicle
Equivalent Consumption Minimization Strategy
Real-time
Fuel Consumption
NOx Emission

ABSTRACT

Equivalent consumption minimization strategy (ECMS) is one of the main real-time control strategies for hybrid electric vehicles (HEVs). This paper proposes a method to modify this strategy. This modification reduces calculation time of ECMS and therefore, facilitates its application as the real-time controller. Dynamic programming (DP) method is employed to reach this aim. This method is applied on the considered HEV in different drive cycles and its results are used to reduce the calculation time of the ECMS. It is notable that the objective of DP in the urban cycles is to simultaneously minimize the fuel consumption (FC) and NOx emission, while the objective in the highway cycles is only the vehicle FC. In order to examine the success of the proposed modifications, the modified ECMS is compared with the basic ECMS in different drive cycles. It is demonstrated that the execution time of the modified ECMS is much less than that of basic ECMS, while the vehicle's FC and NOx levels slightly increase through application of the modified ECMS.

***doi**: 10.5829/idosi.ije.2016.29.12c.15*

NOMENCLATURE

H_{LHV}	Lower heating value	$s(t)$	Equivalence factor
N	Number of time steps	u	Control variable
P_{EM}	Electric Motor power	**Greek Symbols**	
		λ	Weight factor

1. INTRODUCTION

Hybrid electric vehicles (HEVs) are one of the main categories of the vehicles developed to reduce the vehicles' fuel consumption (FC) and emissions. In the HEVs, an electric motor (EM) is used beside the internal combustion engine (ICE) to assist the ICE in providing the HEV's required power. The most critical point in design of HEVs is the determination of the power distribution between the ICE and EM, recognized as the power management strategy (PMS). The HEV PMSs can be divided into three main categories. The first PMS group is the global optimization strategies such as PSO-based strategies [1, 2], Dynamic Programming (DP) [3-5] and Bees-based strategies [6]. These PMSs yield the global optimal power distribution among the introduced categories. Nevertheless, these strategies need *a priori* knowledge of the whole driving cycle and determine the optimal power distribution at the end of route. For this reason and due to high computational costs of this group, the global optimization strategies cannot be employed on a real engine control unit (ECU) [7]. The second group is the rule-based strategies such as Electric Assist Control Strategy (EACS) [8-10] as well as the controllers on the basis of fuzzy logic [11, 12]. These strategies manage the power distribution by referring to some predefined

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Please cite this article as: M. Delkhosh, M. Saadat Foumani, Modification of Equivalent Consumption Minimization Strategy for a Hybrid Electric Vehicle, International Journal of Engineering (IJE), TRANSACTIONS C: Aspetcs Vol. 29, No. 12, (December 2016) 1757-1764

rules. Using these rules, the power distribution is accomplished during driving. This type of PMS can be used in either forward or backward manner. Also, it can be used as the real-time and offline controller. The third group is the instantaneous optimization strategies, such as Equivalent Consumption Minimization Strategy (ECMS) [7, 13-15]. These PMSs are implemented in the real-time applications and give the suboptimal power distribution.

ECMS is one of the main PMSs categorized into instantaneous optimization strategies [16]. This PMS is based on considering a series of admissible candidate points at each instant of the driving, computing a cost function for each candidate point and choosing those with minimal cost function. Once the optimal point is determined, the suboptimal power distribution between the ICE and EM can be defined. At each moment of the driving, several candidate points can be considered. Comparing these points may impose high computational burden on the HEV microprocessor. Since this PMS is implemented on a real ECU, reducing the calculation costs facilitates its application [17-22]. Using more detailed models for the HEV components improves the model accuracy. Nevertheless, it increases the computational costs of the model and makes it more difficult to implement the controller on a real ECU. Storing the simulation results of components in some look-up tables may be a method to decrease the computational burden. However, it takes a long time to interpolate or extrapolate in the obtained look-up tables. The resultant computation issue is investigated in [23]. Consequently, finding a method to reduce the computational costs of the controller seems to be necessary [21].

The goal of this paper is to facilitate the real-time application of the ECMS, while considering the FC and NOx of the HEV. For this aim, the DP strategy is used. As mentioned, owing to the extensive computing time and need for *a priori* knowledge of driving route, the DP cannot be used as the real-time controller. However, the results of its implementation in different types of regulatory driving cycles can be used to derive some offline rules which can be employed to modify the ECMS. Using the results of DP execution in different regulatory cycles, the number of the candidate points in the ECMS is reduced and therefore, its calculation time will decrease. Due to importance of the vehicle NOx emissions in the urban area, the DP objective in the urban driving is to simultaneously minimize the vehicle FC and NOx, while the objective in the highway driving is only the vehicle FC. Hence, the ECMS is modified for each of city and highway driving behaviors. In order to investigate the effectiveness of the proposed modifications, the modified strategy is compared with the basic ECMS.

The layout of the paper is as follows. First, the DP and ECMS strategies are briefly illustrated. The HEV simulation model and the characteristics of HEV components are presented. The optimal operating regions of the engine are defined through executing the DP method. Then, a modification on the ECMS is proposed. The modified ECMS is compared with the basic ECMS and DP from different viewpoints. Finally, the paper is concluded with some remarks.

2. DYNAMIC PROGRAMMING

The control strategy on the basis of DP is a global optimal controller which gives the best power distribution at each moment of the driving. This strategy needs *a priori* knowledge of driving route to determine the optimal power distribution between the HEV power sources [3]. Knowing the vehicle speed profile during the driving cycle, the DP determines the maximum and minimum values for the battery energy level at each moment of the driving. Then some candidate points between the minimum and maximum energy levels of the battery are defined at each moment of the driving. The DP compares these points to find the best optimal one. At the end of driving cycle, the trajectory from the initial to the final SOC which minimizes the considered cost function yields the optimal solution. Also, the optimal power distribution associated with the optimal SOC trajectory is determined. The objective function in this strategy can be considered as:

$$J_k(i) = \min_k \sum_k^N \left[\frac{FC(i,k)}{FC_{nom}} + \lambda \frac{NOx(i,k)}{NOx_{nom}} \right] \Delta t \tag{1}$$

where N means the time steps' number. Also k and i denote the indexes for the battery's energy and time, respectively. As a result, (i,k) represents a candidate point in the optimization process. The index 'nom' shows the nominal values of FC and NOx. Furthermore, λ is a weight factor whose value is a function of the penalty given to the NOx in the cost function. Full details of the DP theory can be found in paper [24].

3. EQUIVALENT CONSUMPTION MINIMIZATION STRATEGY

ECMS is categorized as the local optimization strategy. As demonstrated in [25, 26], the ECMS is equivalent to Pontryagin's minimum principle. By this controller, the power-split ratio between the ICE and EM is instantly optimized leading to instantaneous minimum FC, emissions or both. As oppose to the global optimization strategy, ECMS doesn't require *a priori* knowledge of driving route and can be used as the real-time controller. For instantaneous optimization, the cost of the EM use is expressed in terms of fuel and a local FC function is defined. By this definition, the global FC function (which is computed at the end of driving cycle) can be replaced by a local FC. This function as the sum of the ICE's FC ($\dot{m}_{ICE}\left(t,u\right)$) and the EM's equivalent FC ($\dot{m}_{EQ,EM}\left(t,u\right)$) is presented as [27, 28]:

$$\dot{m}_{EQ}\left(t,u\right)=\dot{m}_{ICE}\left(t,u\right)+s\left(t\right)\dot{m}_{EQ,EM}\left(t,u\right) \tag{2}$$

where $s\left(t\right)$ is the equivalence factor and u the control variable defined as the EM torque divided by the required torque. The calculation method of the equivalence factor is fully described in [29].
The EM's equivalent FC is computed as:

$$\dot{m}_{EQ,EM}\left(t,u\right)=\frac{P_{EM}\left(t,u\right)}{H_{LHV}} \tag{3}$$

In this equation, P_{EM} represents the EM power which is calculated according to the control variables. Also H_{LHV} means lower heating value of the gasoline which is equal to 43.448 kJ/gr.

In some literatures [17, 27, 30-32], the NOx emission is taken into account beside the FC. In this case, the overall cost function takes the following form:

$$\hat{\dot{m}}_{EQ}\left(t,u\right)=\frac{\dot{m}_{EQ}\left(t,u\right)}{max\left\{\left|\dot{m}_{EQ}\left(t\right)\right|\right\}} \tag{4}$$

$$\hat{\dot{m}}_{NOx}\left(t,u\right)=\frac{\dot{m}_{NOx}\left(t,u\right)}{max\left\{\left|\dot{m}_{NOx}\left(t\right)\right|\right\}} \tag{5}$$

$$\dot{m}_{f,EQ}\left(t,u\right)=\hat{\dot{m}}_{EQ}\left(t,u\right)+\lambda\hat{\dot{m}}_{NOX}\left(t,u\right) \tag{6}$$

As can be seen, the overall FC and NOx functions should be normalized before combining them to get an overall objective function.

At every sampling instant of the driving, the ECMS control variable changes within its predefined range. For each tentative value of u, the overall cost function is calculated. The optimal value of u and therefore, the suboptimal power distribution between the two machines is determined such that the defined cost function is minimized.

4. HEV SIMULATION MODEL

The considered vehicle is a parallel HEV equipped with CVT transmission. In order to simulate the HEV, the MATLAB model presented in [33] is employed. In this model, the experimental models of the ICE, EM and battery as well as the simulation model of the CVT transmission are used. The model accuracy is confirmed by comparing its simulation results with the experimental data. The specifications of the considered HEV are listed in Table 1.

5. OPTIMAL OPERATING REGIONS

As discussed, though the ECMS is more computationally more concise than DP, its application in a real-time mode still remains difficult. Hence, it should be modified to reduce its computational effort. As mentioned, the modified ECMS is developed based on the knowledge of the predefined optimal operating regions, achieved through executing the DP in different driving cycles. In this section, the DP is executed in several regulatory driving cycles. Obviously, the NOx emission of the vehicle in the urban driving is more important than highway driving [34]. Therefore, the DP is executed in some stages. In each stage, the importance weight of the NOx (λ) in the objective function is different. In the first stage, the objective of DP is to minimize the FC only ($\lambda=0$).This objective cannot be considered for urban driving and may be used for highway driving. Therefore, the DP is executed in some predefined highway routes, namely HWFET, EUDC and US06.

TABLE 1. The specifications of the considered HEV

Element	Characteristics
Internal combustion engine	
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	Asynchronous induction motor/generator
Maximum power	30 kW
Maximum torque	305 Nm
Maximum speed	6000 rpm
Minimum voltage	60 V
Peak efficiency	0.9
Battery	Lithium-ion polymer rechargeable
Number of Modules	96
Nominal Capacity	10.05Ah
Nominal Voltage	14.8V
Maximum Allowable Current	10.05A (charge), 120A (discharge)
Internal Impedance	15mΩ
Vehicle	Light passenger car
Cargo mass	136 kg
Total mass	1114kg
Frontal area	1.94m2
Rolling resistance	0.014
Drag coefficient	0.4
Wheel radius	0.264m
Differential	
speed ratio	3.778
efficiency	97%
Torque coupler	One-speed gear mate

The results are all gathered in Figure 1.

As it can be seen, the optimal regions are approximately distinct. Therefore, some lines can be drawn to separate them. In the low speeds and powers, the optimal mode is pure electric mode, where the ICE is turned off and the EM is used as the power generator. The reason is that the ICE is not efficient in low speeds and powers, and its bsfc values are high in these points. This fact is demonstrated in Figure 2. In this figure, the bsfc contours of the selected ICE as well as the optimum and full throttle curves are shown. The data shown in this figure is provided by the ICE manufacturer. According to Figure 1, in low speeds and high powers (the region above the black line) both the ICE and EM deliver the required power (discharge mode). In this region, the required power cannot be provided by the ICE, or the ICE is not efficient in this region. Therefore, the EM helps the ICE propel the HEV. In the points among the drawn lines (blue points), the optimal mode is charge mode. In this region, the ICE delivers a power more than the required value and the additional power is used to charge the battery. The reason is that the ICE is more efficient in high power values in terms of FC. This fact is also highlighted in Figure 2. According to this figure, the fuel-optimal curve is near the full throttle (maximum power) curve. As can be seen in Figure 1, there are a few numbers of points in which the optimal mode is pure thermal. These points lie between the charge mode (where the ICE provides the power more than the required power) and discharge area (where the ICE power is smaller than the required value). In this mode, the ICE merely propels the HEV and the EM is turned off.

In the second stage, the DP is executed for the case of taking both the NOx emission and FC into account in the objective function (defined in Equation (1)).

In this stage, the NOx emission is considered to be as important as FC ($\lambda = 1$). According to the above-mentioned principle, the DP is executed in urban driving cycles (namely ECE, FTP-75, SC03 and NYCC). The results are shown in Figure 3.

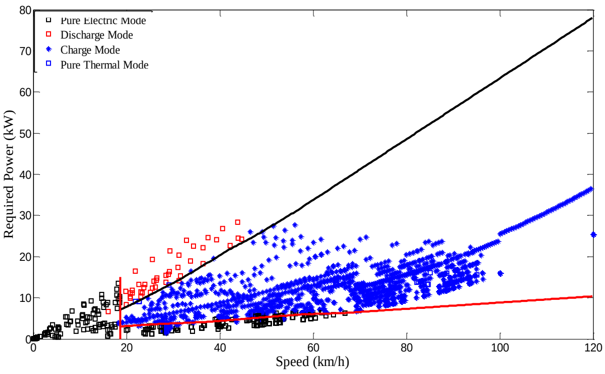

Figure 1. Results of executing DP in highway drive cycles for $\lambda = 0$

According to this figure, despite Figure 1, the optimal operating modes do not create separate regions. Only, the region of pure electric mode which lies on the low speed area can be defined. In the low speeds, the ICE is not efficient and also the required power is such a low value which can be supplied by the EM. Despite Figure 1, where the controller attempts to reach fuel-optimal curve, in Figure 3, the controller should find the points in which both the FC and NOx are low values. These aspects are in conflict with each other. Therefore, we cannot see the distinct optimal regions in this case. Regarding Figures 1 and 3, it seems that decreasing the importance weight of NOx emission in the objective function (λ), the optimal regions will become distinct. Hence, the value of λ is gradually reduced until the separate regions appear. The optimal modes for $\lambda = 0.8$, $\lambda = 0.6$ and $\lambda = 0.5$ are presented in Figures 4, 5 and 6, respectively.

According to these figures, the optimal regions become gradually distinct by reducing the value of λ.

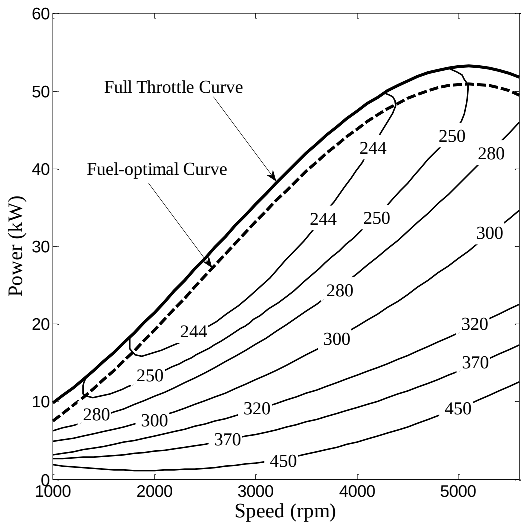

Figure 2. bsfc data of the vehicle's ICE (in gr/kWh)

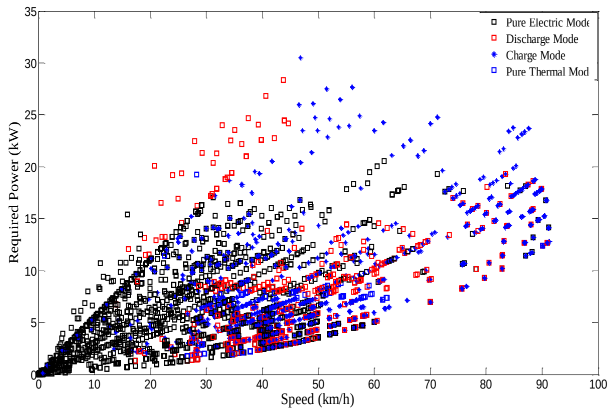

Figure 3. Results of executing DP in urban drive cycles for $\lambda = 1$

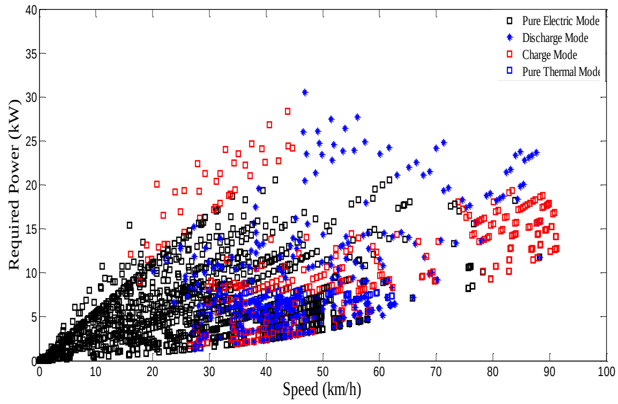

Figure 4. Results of executing DP in urban drive cycles for $\lambda = 0.8$

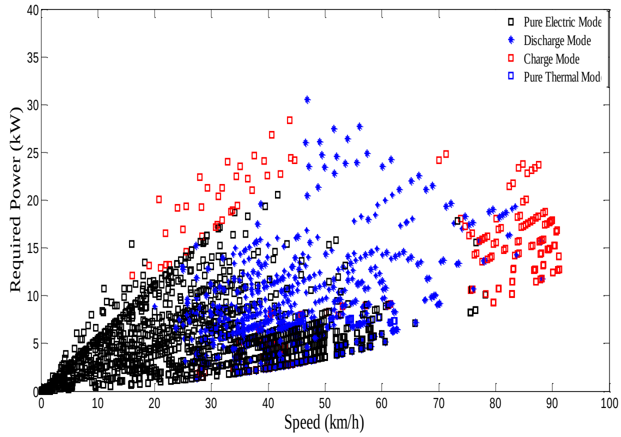

Figure 5. Results of executing DP in urban drive cycles for $\lambda = 0.6$

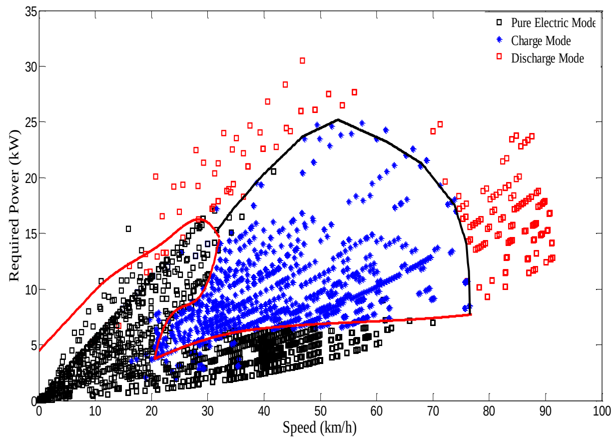

Figure 6. Results of executing DP in urban drive cycles for $\lambda = 0.5$

The largest λ for which the distinct regions with a good approximation is achieved, is 0.5. For this value some curves can be drawn to separate the optimal regions. However, the curves are different from the separation lines presented in Figure 1, where the objective is only the HEV's FC. Similar to the previous cases, in low speeds and powers, the optimal mode is pure electric. Nevertheless, despite Figure 1, the charge mode points lie in a closed area. Also, in the points above the black line, the optimal mode is discharge mode, where the EM assists the ICE in providing the required power. As can be seen, there is no point in which thermal mode is the optimal operating mode.

In the next section, the defined optimal regions presented in Figures 1 and 6 are used to modify the ECMS strategy to reduce its calculation time.

6. ECMS MODIFICATION

In this section a modification is suggested on the ECMS by using the results shown in Figures 1 and 6. The modified ECMS is developed to reduce the calculation time of the ECMS and facilitates its real-time application. It is notable that this modification can be used while the importance of NOx emission is considered to be less than that of the FC. This aim is reachable by constraining the variation range of the ECMS control variable (u). At each moment of the driving, the vehicle's required power can be computed according to its speed and acceleration, and its operating point (speed, power) is found. Next, using Figures 1 and 6, the optimal operation mode of the HEV is determined. As discussed before, Figure 1 is used for highway driving mode and Figure 6 for urban driving mode. Then, according to the selected mode of operation, the variation range of the control variable is narrowed down to the range corresponding to the selected operation mode, and then, the optimal power distribution is determined by the ECMS. For example, if the vehicle operation point lies on the charge mode area, the range of the control variable is narrowed down to $[-u_l, 0]$. The flowchart of this method is presented in Figure 7. This flowchart indicates that the mode selection is performed regarding the vehicle speed, required power and the optimal modes' figures (Figures 1 and 6). The figure reveals that the input of the strategy is the speed profile of the vehicle. The required power is calculated in the 'power calculator' block.

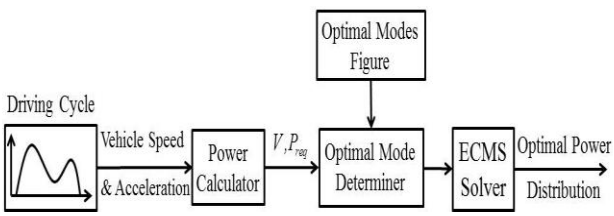

Figure 7. The strategy of determining the optimal power distribution

Using the optimal modes' figures and the vehicle speed and required power, the optimal mode is determined in the associated block. After determining the optimal mode, the solver used in ECMS defines the optimal power distribution between ICE and EM.

The modifications on the supervisory controller are as follows:

- If the HEV operation point lies on the "discharge mode" area (red squares' area), the range of control variable for urban and highway driving will be $0 < u \le u_r$. According to Figure 1, some of the blue square points lie on this area. Therefore, the control variable range for the highway driving is changed to $0 \le u \le u_r$.
- If the operation point lies on the "pure electric mode" region (black squares' area), it is not necessary to compare candidate points corresponding to control variable values. In these instants, the optimal value of the control variable is zero, where the EM itself propels the vehicle.
- If the operation point lies on the "charge mode" region (blue stars' area), the range of control variable will be $-u_l \le u < 0$. Since some of the black square points (pure electric mode) lie on this region (see Figures 1 and 6), the search for finding the optimal control variable will be conducted in range $-u_l \le u < 0 \,\&\, u = 1$. Also, for highway driving (Figure 1), some of the blue square points (pure thermal mode) lie on the charge mode area. Therefore, the control variable range for highway driving will be $-u_l \le u \le 0 \,\&\, u = 1$.

Applying the suggested modifications to the control variable range (which is $\left[-u_l, u_r\right]$ in basic ECMS), this range is narrowed and therefore, the number of candidate points will decrease, which leads to a reduction in the ECMS execution time. According to Figures 1 and 6, the lines drawn to separate the optimal regions for highway driving (Figure 1) and the ones for urban driving (Figure 6) are different. Therefore, for example, it is possible that the optimal mode for an individual operating point in urban driving is pure electric mode, while the optimal mode for this point in highway driving is charge mode.

The modified ECMS should be tested by comparison with the basic ECMS. It is worth mentioning that the comparison is implemented for the cycles considered in modifying process of the ECMS (namely SC03, ECE, HWFET) and the ones not considered (namely UDDS, IM240). The PMSs are compared in terms of the execution time, the vehicle FC and NOx. The results are reported in Tables 1, 2 and 3. It is worth noting that the simulations were implemented on a computer with Intel Core i7 CPU (2.4GHz) and 8GB RAM.

According to the tables, the execution time of the ECMS significantly decreases by applying the proposed modification. This reduction for the city cycles is more than that of highway cycles. The reason is that the area of the black points (the area in which no optimization is necessary) in city cycles (Figure 6) is larger than this area for highway cycles (Figure 1). The comparison of the vehicle FC presented in Table 3 reports an increase in the vehicle FC through application of the modified ECMS. The reason is that narrowing the range of control variable reduces the number of candidate point and therefore, the point selected by the modified ECMS may not be the most optimal point.

TABLE 2. Execution time reduction with the modified ECMS relative to the basic ECMS in city and highway driving cycles

Execution Time (sec)					
	City Cycle			Highway Cycle	
	SC03	UDDS	ECE	IM240	HWFET
Basic ECMS	138	327	61	80	245
Modified ECMS	50	84	15	33	67
Difference (percentage)	64%	74%	75%	59%	73%

TABLE 3. Fuel consumption of the vehicle for the case of using basic ECMS and the modified ECMS in city and highway driving cycles

Fuel Consumption (L/100km)					
	City Cycle			Highway Cycle	
	SC03	UDDS	ECE	IM240	HWFET
Basic ECMS	4.26	3.57	3.53	5.05	4.08
Modified ECMS	4.48	3.77	3.55	5.34	4.27
Difference (percentage)	-5.2%	-5.6%	-0.6%	-5.7%	-4.7%

TABLE 4. NOx emission of the vehicle for the case of using basic ECMS and the modified ECMS in city and highway driving cycles

NOx Emission (gr/km)					
	City Cycle			Highway Cycle	
	SC03	UDDS	ECE	IM240	HWFET
Basic ECMS	1.49	1.28	1.27	1.82	1.46
Modified ECMS	1.50	1.31	1.28	1.82	1.47
Difference (percentage)	-0.7%	-2.3%	-0.8%	0%	-0.7%

On the other hand, the lines drawn to separate the optimal area do not separate these regions completely, and there are some overlaps among the optimal regions. Therefore, the point chosen by the modified ECMS may not be the optimal point defined by the DP. According to Table 3, similar to the vehicle FC, its NOx slightly increases through application of the modified ECMS.

In summary, through application of the modified ECMS, the FC increases about 5% and the NOx growth is negligible, whereas its execution time remarkably decreases. Therefore, the proposed modification seems to be beneficial, and can be used to facilitate the application of ECMS on a real ECU.

7. CONCLUSION

This paper focused on the minimization of the ECMS execution time in case of considering the vehicle's FC and NOx emission as the objective functions. To this goal, the execution results of DP in some of regulatory driving cycles were used to modify ECMS. The DP was executed on a baseline HEV in several regulatory cycles and the optimal operating modes at the cycles' points were determined. The results demonstrated that the optimal modes create some optimal regions, for the case of considering FC as the objective function. It was found that if NOx emission is considered as the second objective with the importance weight equal to the FC's weight, the optimal regions have some overlaps and cannot be separated. Hence, the importance weight of NOx was gradually reduced until the obtained optimal areas become approximately distinct. It was found that the highest importance weight for which the optimal areas are approximately distinct is 0.5 (importance weight of NOx is half of FC's weight). Using the achieved optimal regions, a modification was proposed to reduce the number of the candidate points in the ECMS strategy, which results a reduction in its execution time. It is worth mentioning that for the highway driving, Figure 1 (in which the objective function is only FC) was used, while Figure 6 (in which both the vehicle's FC and NOx emission create the objective function) was used for urban driving. It was shown that the execution time of the resulted strategy is much less than that of basic ECMS, while the vehicle's FC and NOx levels slightly rise through employing the modified ECMS. Therefore, in case of applying the proposed modifications on the ECMS, its application as the real-time controller is facilitated.

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Modification of Equivalent Consumption Minimization Strategy for a Hybrid Electric Vehicle

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PAPER INFO

Paper history:
Received 30 July 2016
Received in revised form 17 October 2016
Accepted 11 November 2016

Keywords:
Hybrid Electric Vehicle
Equivalent Consumption Minimization Strategy
Real-time
Fuel Consumption
NOx Emission

چکیده

استراتژی کنترلی ECMS یکی از مهمترین استراتژی‌های کنترلی برخط برای خودورهای هیبرید الکتریکی است. در این مقاله روشی برای بهبود این استراتژی کنترلی پیشنهاد می‌شود. در این بهبود، مدت زمان محاسبات ECMS کاهش یافته و در نتیجه، استفاده از این استراتژی به عنوان استراتژی برخط تسهیل می‌شود. برای رسیدن به این هدف، از روش برنامه-نویسی پویا استفاده می‌شود. این روش روی خودروی موردنظر در سیکل‌های رانندگی مختلف استفاده شده و از نتایج آن برای کاهش زمان محاسبات استراتژی ECMS استفاده می‌شود. شایان ذکر است که تابع هدف برای روش برنامه‌نویسی پویا در چرخه‌ی شهری عبارت است از: کاهش همزمان مصرف سوخت و آلایندگی NOx، و برای چرخه‌ی خارج شهر عبارت است از: کاهش مصرف سوخت. برای بررسی میزان اثربخش بودن اصلاحات پیشنهادی، استراتژی بهبود یافته‌ی ECMS با نوع پایه‌ی آن در چرخه‌های مختلف رانندگی مقایسه می‌شود. نتایج نشان می‌دهد که زمان اجرای استراتژی بهبود یافته بسیار کمتر از نوع پایه است، در حالی که در صورت استفاده از استراتژی بهبود یافته، شاهد کمی افزایش در میزان مصرف سوخت و آلایندگی خواهیم بود.

***doi**: 10.5829/idosi.ije.2016.29.12c.15*