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METHOD FOR DETERMINATION OF THE HYBRID ELECTRIC VEHICLE ELECTRIC CONSUMPTION AND BATTERY REGENERATION

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Abstract: *More and more stringent emissions and fuel consumption regulations are stimulating an interest in the development of safe, clean, and high-efficiency transportation. It has been well recognized that electric, hybrid electric, and fuel cell-powered drive-train technologies are the most promising solutions to the problem of land transportation in the future [1]. The hybrid electric vehicles (HEVs) or simply hybrid vehicles use both electric motors (EM) and an ICE for delivering the propulsion power [2]. This power depends on the ICE and EM torques, which must be distributed and mixed in correct proportion and work sequence. The main attention is paid to the EM and battery (B) control which ensures the HEV ecological drive modes. The aim is these modes to be prolonged and thus the HEV electrical energy efficiency becomes the main factor for its economy, ecology, and drivability. The base components of this efficiency are the HEV electric consumption and battery regeneration which are factors for evaluating and improving the energy efficiency. HEV electric consumption is connected to the battery discharge during electric motors operation and control, and regeneration is linked to the battery recharge during regeneration braking. The electric consumption and battery regeneration can be measured by special equipment and evaluated by certain method and criteria. The physical measuring of these gives the accurate results, which*

are essential for the correct conclusions. This paper considers the method for determining the HEV electric consumption and battery regeneration.

INTRODUCTION

The methodology for evaluating the HEV electric consumption and battery regeneration is subdivided into the following modules:

1. Choice of a HEV and driving modes.
2. Choosing a route of travel.
3. Determination of a driving distance.
4. Recording of a travel time.
5. Selection of a measuring equipment.
6. Setting up the measuring equipment.
7. Measuring and recording of experimental results.
8. Selection of a criteria for evaluating the HEV electric consumption.
9. Selection of a criteria for evaluating the HEV battery regeneration.
10. Analysis and evaluation. Recommendations. Trends.

METHODOLOGY

According to the analysis of the existing various solutions in the structures and the propulsion layout of the HEVs, a representative configuration of a HEV of mixed (series-parallel) arrangement type was selected [1,2,3]. The series-parallel HEV block diagram is presented in Fig. 1 and the propulsion scheme is presented in Figure 2.

When the HEV is moving in urban traffic, the stop-and-go driving pattern applies. In this case, the primary power source PPS, which is ICE or B, is used too often. With frequent use of B energy, it must be recharged quickly. In this case, maintaining a high state of charge (SOC) of the B is necessary to provide the HEV power. Thus, the battery maximum SOC may be an appropriate control condition [7].

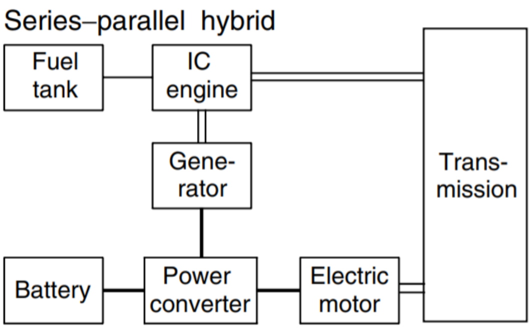

Fig.1. HEV block diagram

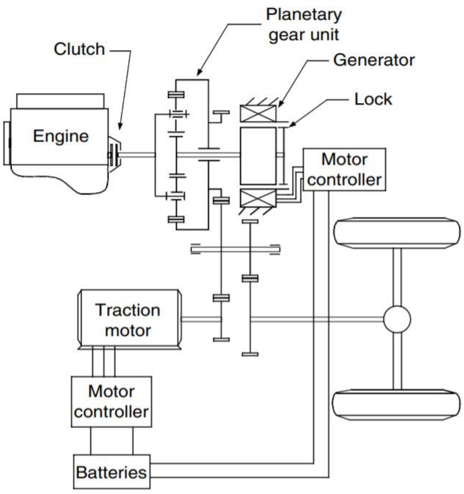

Fig. 2. Hybrid propulsion layout for determining energy efficiency

The operating modes of the HEV are selected respectively [4,5,6]:

EM Drive Mode: This mode is performed at an HEV low speed, which is understood as the minimum velocity characteristic under which the ICE cannot operate steadily. In this case, the EM provides power to the driving wheels while the ICE is off or idling. The power of the ICE, the EM, and the dilution of the B can be determined by the following dependencies [8]:

(1) $P_e = 0$, (2) $P_m = \dfrac{P_L}{\eta_{t,m}}$, (3) $P_{pps-d} = \dfrac{P_m}{\eta_m}$,

where: P_e is the ICE power, kW;

P_L – tractive or braking power, kW;
$\eta_{t,m}$ – efficiency of the transmission from the EM to driving wheels;
P_m – EM power, kW;
$P_{pps\text{-}d}$ – consumed power from B, kW;
η_m – EM efficiency.

Hybrid Drive (EM + ICE) Mode: When the load is greater than the power that the ICE can provide, in this case the ICE and the EM must both provide power to the driving wheels. This mode is called hybrid drive mode. In this case, the ICE is adjusted to the optimum operating mode by adjusting the throttle to obtain power P_e. The required residual power is provided by the EM. The power of EM is determined by (4) and the power consumed by B is according previous (3):

$$(4)\quad P_m = \frac{P_L - P_e \eta_{t,e}}{\eta_{t,m}},$$

where: $\eta_{t,e}$ is the efficiency of transmission from ICE to driving wheels.

Battery Charge Mode: When the load is less than the power that the ICE can provide under optimal mode, and the SOC of the B is less than the maximum, then the ICE continues to operate in optimum mode, producing P_e power. In this case, the EM is controlled by its controller to operate as a generator, driven by the residual power of the ICE. The power of the EM and the charging power of the B are determined by:

$$(5)\quad P_m = \left(P_e - \frac{P_L}{\eta_{t,e}} \right) \eta_{t,e,m} \eta_m,$$

$$(6)\quad P_{pps-c} = P_m,$$

where: $\eta_{t,e.m}$ is the efficiency of transmission from ICE to EM.

ICE Drive Mode: When the load is less than the power that the ICE can provide under optimal mode, and the SOC load rate of the B has reached its maximum value, the propulsion is by ICE only. In this case, the EM is switched off and the ICE provides all the power to move the HEV. ICE power, EM power, and B power can be represented by [8]:

$$(7)\quad P_e = \frac{P_L}{\eta_{t,e}}, \qquad (8)\quad P_m = 0, \qquad (9)\quad P_{pps} = 0.$$

Regenerative Braking Mode: When the HEV stops and the required braking power is less than the maximum regenerative braking power that the EM provides, then the EM is switched from the controller to operate in generator mode and produces brake power that equals the set brake power. In this case, the ICE is off or idling. The EM power and the B charging power are:

$$(10)\quad P_{mb} = P_L \eta_{t,m} \eta_m,$$

$$(11)\quad P_{pps-c} = P_{mb}.$$

Hybrid Braking Mode: When the required braking power is greater than the maximum regenerative braking power provided by the EM in generator mode, the mechanical braking system must be applied. In this case, the EM must be controlled by the controller to produce maximum regenerative braking power, and the mechanical braking system must provide the remaining braking power. The EM power, the B charging power, and the braking power of the mechanical braking system are:

$$(12)\quad P_{mb} = P_{mb,\max} \eta_m,$$

$$(13)\quad P_{pps-c} = P_{mb}.$$

It should be noted that for better braking performance, the braking forces to the front and rear wheels must be proportional to their normal loads.

Start-Stop Mode: This mode can be used at low travel speeds and low acceleration values. When the ICE is running, the algorithm maintains a maximum SOC of B. When the SOC level of the B reaches its maximum value, the ICE is switched off and the HEV is driven only by the EM. When the SOC level of B reaches the minimum allowable value, the ICE is started and the algorithm is repeated.

The route of travel is selected as a representative run between two endpoints on a pendulum or a roundabout route in each urban area. For this purpose, a city map and the corresponding GPS navigation are used. At this step must be selected the traffic period, i.e. the clock time of driving the route of travel.

The driving distance is calculated by the selected route of travel according to the map or GPS data. The distance is verified by the HEV board or trip computer.

The travel time is recorded from the beginning to the end of the journey along the specified route. The distance traveled and the travel time are recorded by the on-board gauges of the HEV and compared with the readings of the GPS navigator system data.

The measuring equipment must meet the conditions for mobility, measurement accuracy within ± 1%, HEV compatibility, pre-test, set up and adjustment with calibrated equipment, placement of displays and monitors inside the HEV, recording of measured results. To measure the electricity consumption and battery regeneration, it is suitable to use wattmeter, but it is recommended that a current clamp meter must be used to non-interrupted measurements.

The criteria for evaluating the HEV electric consumption [9] is related to the amount of the energy consumed by the EM. Three criteria are proposed: 1) distance criterion for estimating the electricity consumed $Q_{D,c}$ (14) relative to the HEV driving range; 2) mass criterion for estimating the electricity consumed $Q_{M,c}$ (15) relative to the HEV mass; 3) combined criterion for estimating the electricity consumed $Q_{DM,c}$ (16) relative to the both HEV driving range and HEV mass.

(14) $Q_{D,c} = \dfrac{Q_{disch} + Q_{rech}}{100L}$, kWh/100km, (15) $Q_{M,c} = \dfrac{Q_{disch} + Q_{rech}}{G_{HEV}}$, kWh/kg,

(16) $Q_{DM,c} = \dfrac{Q_{disch} + Q_{rech}}{G_{HEV} L}$, kWh/kgkm

where: Q_{disch} is the electricity consumed in drive (traction) mode, kWh;

Q_{rech} – electricity consumed in network recharging mode (in case of plug-in HEV), kWh;

L – driving distance, km;

G_{HEV} – HEV mass, kg.

The criteria for evaluating the HEV battery regeneration is related to the amount of the energy regenerated to the B. Three criteria are proposed: 1) distance criterion for estimating the electricity regenerated $Q_{D,r}$ (17) relative to the HEV driving range; 2) mass criterion for estimating the electricity regenerated $Q_{M,r}$ (18) relative to the HEV mass; 3) combined criterion for estimating the electricity regenerated $Q_{DM,r}$ (19) relative to the both HEV driving range and HEV mass.

(17) $Q_{D,r} = \dfrac{Q_{regen}}{100L}$, kWh/100km, (18) $Q_{M,r} = \dfrac{Q_{regen}}{G_{HEV}}$, kWh/kg,

(19) $Q_{DM,r} = \dfrac{Q_{regen}}{G_{HEV} L}$, kWh/kgkm,

where: Q_{regen} is the electricity regenerated in regenerating or generating mode, kWh.

The HEV electric consumption and battery regeneration can be calculated for a given mode of motion, a given section of motion, for a specified time, for a given cycle of motion [10], for two or several HEVs. In this way, the indicators of several HEVs can be compared and a comprehensive assessment of their efficient use for a given territory can be made.

TRENDS

The vehicle's electric consumption can be estimated by measuring the voltage and current in the on-Board power grid. The most promising trend in current measurement today, in addition to the well-known current sensors on the Hall effect, is the use of current sensors on the magnetoelectric (ME) effect. Previously, the paper [11] showed the capabilities and technical characteristics of the current sensor. The sensor operates on the ME effect and can measure current in the range up to 500 A. The sensitive element of such a sensor is materials based on magnetostrictive-piezoelectric composite layered structures. The ME current sensor can operate in different modes, in resonant and non-resonant modes. It is assumed that the use of ME current sensors in the measuring of the HEV electric consumption and battery regeneration will optimize these measurements and improve the method accuracy for their determination.

CONCLUSION

A methodology for determining the hybrid electric vehicle electric consumption and battery regeneration is proposed.

A distance criteria, mass criteria and combined criteria of electricity consumption and battery regeneration are proposed as quantitative characteristics of one or more HEVs.

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МЕТОДИКА ЗА ОПРЕДЕЛЯНЕ НА КОНСУМИРАНАТА И РЕКУПЕРИРАНАТА ЕЛЕКТРИЧЕСКА ЕНЕРГИЯ ПРИ ХИБРИДНИ АВТОМОБИЛИ

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Ключови думи: *хибридни автомобили, електрически, консумация, рекуперация, методика*

Резюме: *Все по-строгите регулации за емисиите и разхода на гориво стимулират интерес към развитието на безопасен, чист и високоефективен транспорт. Известно е, че електрическите задвижвания, хибридните задвижвания и задвижванията с горивни клетки, са най-обещаващите решения на проблема за сухопътния транспорт в бъдеще [1]. Хибридните електрически превозни средства (HEVs) или просто хибридните автомобили (ХА) използват както електродвигатели (ЕД), така и двигател с вътрешно горене (ДВГ) за осигуряване на задвижващата мощност [2]; тези превозни средства имат по-ниски емисии в сравнение с конвенционален автомобил с ДВГ със същия размер, което води до по-малко замърсяване на околната среда. ДВГ в комбинация с ЕД и блок за съхранение на енергия (батерия Б) осигуряват разширен обхват за ХА и намаляват замърсяването. ХА служи като компромис за проблема със замърсяването на околната среда и ограничената способност на днешното чисто електрическо превозно средство. Консумацията на електроенергия и регенерирането на батериите са един от основните фактори за оценка и подобряване на енергийната ефективност. Консумацията на електрическа енергия от ХА е свързана с разреждането на батерията по време на работа и управление на електродвигателите, а рекуперацията е свързана със зареждането на батерията по време на рекуперативно спиране. Консумацията на електроенергия и регенерацията на батерията могат да бъдат измерени и оценени с помощта на специално оборудване. Физическото им измерване дава точните резултати, които са от съществено значение за правилните заключения. Тази статия разглежда методика за определяне на консумацията и рекуперацията на електроенергия на хибридни автомобили.*