COMPUTATIONAL PROBLEMS OF ELECTRICAL ENGINEERING

Vol. 3, No. 2, 2013

ANALYSIS OF ENERGY CONSUMPTION OF ELECTRIC VEHICLES EQUIPPED WITH A HYBRID ENERGY STORAGE

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Abstract: The paper characterizes currently used vehicles and presents an analysis of fuel consumption of engine cars in the EU in the context of decreasing fuel resources. The article also shows the dependencies describing the resistance forces acting on the vehicle during the drive and the methods for determining the power needed to accelerate and to brake which is possible to recover. In the paper, an analysis of energy consumption of a sample vehicle on two routes of different characteristics is also performed. In the final part of the paper, an analysis of the possibilities of energy recovery during a car drive is presented, and the problems connected with energy storage limitations are discussed on the example of hybrid energy storage.

Key words: electric cars, energy consumption, energy storages, ultracapacitors.

1. Introduction

The increasing mobility of people contributes to the considerable growth in the number of cars and to a growing demand for motor fuel. Also the technology development in the automotive industry leads to the fact that more and more attention is paid to the ecological and economic aspects of the vehicles manufactured. The analyses of those problems are directed towards the improvement of the efficiency of the drive systems designed, as well as with respect to the search of new types of energy and new methods of storing it. Because of this, the present work is dedicated to an analysis of vehicles energy consumption, focusing on the energy that can be recovered. Some basic experiments involving a comparison between the energy demand levels in vehicles without energy recovery capabilities and the energy demand of a vehicle with energy recovery capabilities have been performed. The aim of the tests was analyzing the motion resistance forces, the power needed for acceleration and braking, and then – an analysis of the savings that can be obtained during regenerative braking and determination of the limitations connected with the use of different energy storage devices (including hybrid energy storages). The work also presents an analysis of electric energy storage devices that can meet the expectations of the drivers regarding driving that is dynamic and economical.

2. The demand for fuel in Europe

The total number of cars in the European Union is close to 300 million [1,2] – both in the commercial space and in the private space. The number of cars on the roads has grown considerably over the last few years. For example, the number of passenger cars per 1000 people in Ukraine grew form about 114 in the year 2004 to over 148 in the year 2010 (it is about 30% in 6 years) [2]. In Poland there was a similar situation – about 43% (from 314 cars in 2004 to 451 in the year 2010). In many countries of the European Union, it amounts to about 550 cars per 1000 people, but this increase is not so considerable [1, 2, 3, 4, 5].

Another problem, which is connected with the motor transport, is fuel consumption. This is a very important problem, although a significant reduction in average fuel consumption by motor vehicles (5.8 l/100km on average in EU-27 countries – the lowest in Portugal – 5.1 l/100 km, the highest is Sweden – 6.3 l/100 km [1]), road vehicles in the European Union consume over 260 mega tons of oil equivalent per year [1, 2, 4].

That is why scientists all over the world make more and more frequent attempts at estimating the time for which fuel resources will suffice and the drivers observe their prices which go up systematically with growing concern is a consequence of that. Some of them try to look for a saving by choosing smaller cars. That is why domination of small and compact models over large and luxurious cars can be observed in the car fleet in recent years [1]. Another popular way to obtain savings is purchasing cars designed to burn gas – in 2011, the percentage of newly registered vehicles with a gas installation was 1.0% in EU-27 countries, and only 0.1% in EU-12 countries [1, 2]. However, due to the high cost of the installation, the demand for new cars adjusted to burn LPG has been decreasing recently.

A trendy solution is equipping the vehicle with a different drive system (hybrid vehicles) or replacing an internal combustion engine with an electric one. According to the data from [1], the number of cars with a hybrid drive system in EU-27 countries was 0.7% in 2011, and the number of cars with an electric motor was 0.07%.

3. Vehicle energy consumption

For analyzing energy consumption of a passenger car, it is necessary to consider the forces acting on the vehicle during its motion. The forces depend on a number of factors, the most important of which include the driving force (F_D), the rolling resistance (F_R) and the aerodynamic resistance (F_A) (equation 1) [6]:

$$F = F_D - F_A - F_R \tag{1}$$

The rolling resistance can be estimated on the basis of the following formula:

$$F_R = mgf_{t0}\,(1+Kv^2) \tag{2}$$

where: m is the vehicle mass, g represents the gravitational acceleration, v stands for the vehicle speed, K is the additional rolling resistance coefficient (for asphalt surfaces, the assumed value of this coefficient is $K = 5{*}10^{-5}\ s^2/m^2$), f_{t0} is the rolling resistance coefficient at low speeds.

The rolling resistance coefficient for low speeds is most frequently determined by performing a drag racing test. Then, the following formula should be used to calculate its value:

$$F_{t0} = v_b^2 / (2gS_t) \tag{3}$$

where v_b stands for the initial speed of the vehicle, S_t – denotes the rolling route of the car.

Usually for passenger cars moving along an asphalt surface, the rolling resistance coefficient for low speeds is assumed to amount to a value between 0,012 and 0,014 [6].

$$F_A = 0.5\,\rho c_x\, A v_r^2 \tag{4}$$

where ρ is the air density (for normal conditions at the temperature of 0°C, and the pressure of 1013 hPa, the dry air density is about 1.29 kg/m^3), c_x is the air resistance coefficient in the longitudinal direction which depends on the shape of the vehicle and equals from 25% to 45%, A is the coefficient of a vehicle front surface area, v_r is the speed of the vehicle relative to the air.

On the basis of the determined air resistance values and for the given value of the instantaneous speed v of the vehicle, and assuming η, as a given level of the drive unit efficiency, it is possible to estimate the driving force, the instantaneous power P and the energy E (equation 5 and 6) needed to cover a given route S over the specified time t (the energy necessary to cover the set moving distance).

$$E = F\,S/\eta \quad \text{or} \quad E = F\,t\,v/\eta \tag{5}$$

$$P = F\,v/\eta \quad \text{or} \quad P = E/t \tag{6}$$

4. Tests and analysis

For verification the presented issues in practice, the analysis of energy consumption of a sample vehicle on two routes of different characteristics was performed. Instantaneous speed values of a Hundai i30 vehicle with the 1400 cc gasoline engine with the capacity of 109 KM (80 kW) and the total mass of about 1250 kg were recorded. An analysis of the drive parameters of the motor vehicle covering two routes – in the city (route 1 – 16 km in 45 min) and on a highway (route 2 – 121 km in 42 min) was performed. For the detailed analysis of the energy consumption, the computer program presentation of the drive has been created. The instantaneous driving speed recorded during the drive is presented in Figures 1a and 1b.

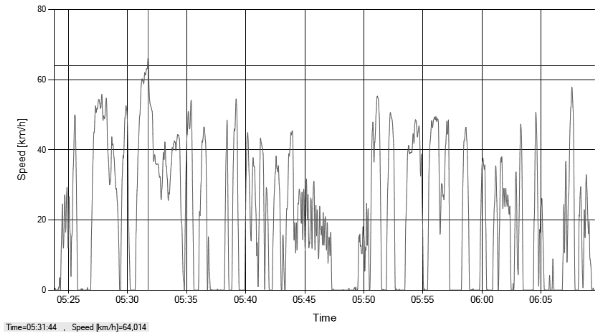

Fig. 1a. Driving speed (route 1).

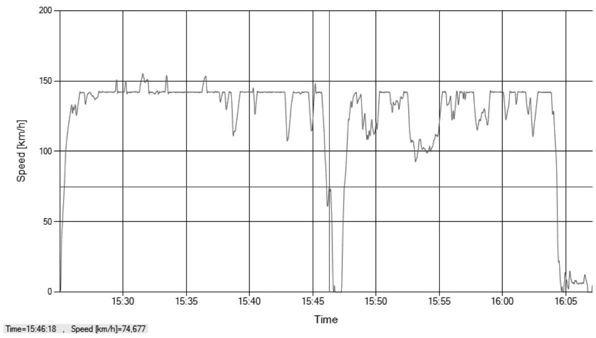

Fig. 1b. Driving speed (route 2).

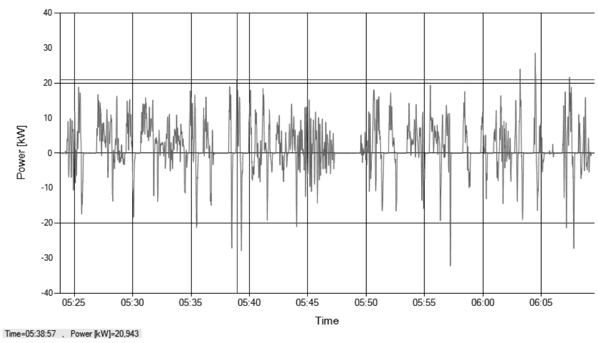

Fig. 2a. Instantaneous power (route 1).

For further studies, the analysis of the demand for power and energy consumption by the vehicle was performed on the basis of the equations shown in chapter 3. The following vehicle parameters were assumed during the calculations: a rolling resistance coefficient for low speeds f_{t0}=0.014, a coefficient of the vehicle front surface area A=2, an air resistance coefficient c_x = 30%.

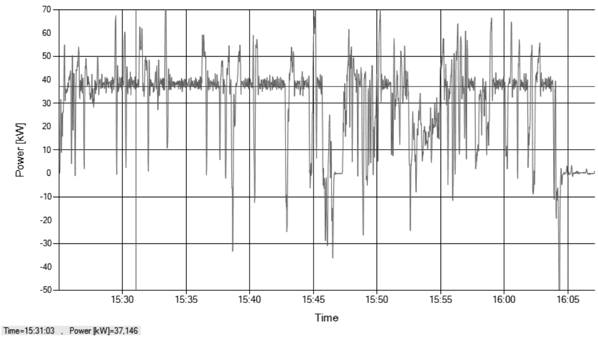

Fig. 2b. Instantaneous power (route 2).

The results obtained while calculating the energy demand were assumed as positive values, and the recovered energy values were assumed as negative values. The calculation of instantaneous power demand for driving is presented in Figures 2a and 2b.

The energy consumed by the tested vehicle is presented in Figures 3a and 3b (as curve "1"). Moreover, on the basis of the motion resistance forces, the energy that could be recovered through electro-dynamic braking (Fig. 3a and Fig. 3b, curve "2") and their sum – that is the energy that would be consumed by the vehicle if it could recover the energy (Fig. 3a and Fig. 3b, curve "3") were calculated.

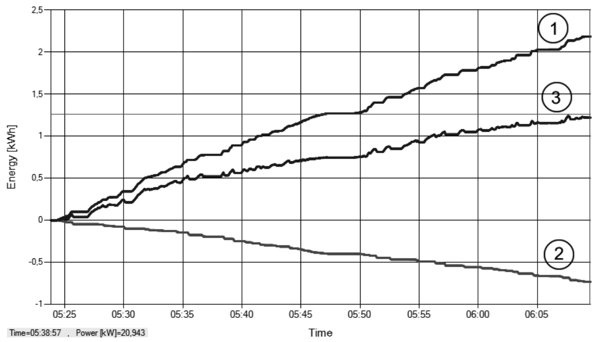

Fig. 3a. Energy balance (route 1).

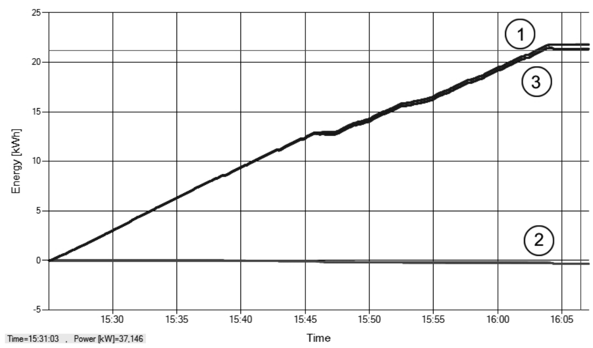

Fig. 3b. Energy balance (route 2).

The calculations of energy consumption by the vehicle was verified by the comparison to the demand for E95 gasoline during the drive. The assumed average efficiency of the internal combustion engine equals 27% [4], but the fuel calorific value is of 43 MJ/kg [4] at the density of 750 kg/m3 (at the temperature of about 15°C). In the case of the city route, the fuel demand calculated was 1.4 l, and in the case of the highway, the demand was 11.0 l. The above results were slightly different from the real ones, which had the value of 1.5 l in the first case and 9.4 l in the highway route.

As the next considerations regarding the analysis of vehicle energy, the capacity of the electric energy source that allows the vehicle to pass about an 80 km long route has been tested. Moreover, the ability of electrical systems to transmit appropriate power in dynamic states (during vehicle acceleration), as well as in the case of energy recovery (during electro-dynamic braking), has been analysed. While analysing, it was assumed that the vehicle would use a battery with a voltage of 84 V, constructed of seven chains (42 lead-acid cells). In such a case, using an energy storage intended for traction operation – for deep discharge – is sufficient.

For the purposes of covering the distance of 80 km at the average speed of 40 km/h, (the car) must overcome the motion resistance forces at the level of 235 N. It means that the dement power is about 2,6 kW, but the energy level is equal to about 5,2 kWh. Such a value of electric energy is equivalent to the energy stored in a battery with the capacity of 70 Ah, including the Peukert effect. However, during rapid acceleration, the power exceeded the value of tens of kW. On such occasions, the batteries used would not be sufficient due to the fact that this would require a current input at the level of more than 200 A – in the example of route 1, and 500 A – in the example of route 2. This would increase the Peukert effect – accelerating the battery discharge process – and exceed the capacity of the energy sources suggested. It means it would be harmful to them (considerably shortening their service life), causing their fast destruction and the need for more frequent replacements. A similar situation would occur during rapid braking.

It is important to make sure that the battery will not be discharged too deep. The analysis of instantaneous current values showed that in the case of the drive at the speed presented in Figure 1a, it would be necessary to use batteries with the capacity of about 160 Ah, but at the speed presented in Figure 1b – of about 300 Ah. Currents of high values discharge electrochemical energy sources (like in the example of route 2) disproportionally faster and they lead to faster battery destruction – especially in popular lead-acid batteries. That is why the creators of electric vehicles more and more often decide to use different batteries, e.g. lithium-ion batteries or lithium-polymer batteries. Apart from higher operational voltage (about 4.2 V per cell), they are characterized by higher energy density (up to 180 Wh/kg) and longer service life (up to 2 thousands cycles) [7, 8].

Independently from the type of the electrochemical energy source used, currents of high values have a negative influence on their work. For this reason, it is very important to use an additional energy storage – which allows currents of high values such as ultracapacitors (in dynamic states) to be transferred. They are characterized by a much greater ability to emit energy – the power density values of ultracapacitors are many times higher than the power density of batteries – and they are many times more efficient during charging and discharging, regardless of the temperature [7,8,9]. Their disadvantage is their low ability to store energy in comparison to the batteries discussed earlier. For that reason, at the current level of knowledge, they cannot be used as a main energy source in electric vehicles. They can be used, when they are used as an additional energy buffer, especially in dynamic drive states (rapid acceleration and braking) - then currents of high values, which are the most disruptive for batteries, are limited [8].

5. Final remarks and conclusion

The studies show that computer calculation methods allow an analysis of energy consumption of motor vehicles to be performed. Based on the analysis of the situation of the car market and fuel, it can be stated that in the near future there will be an increase in the demand for electric cars.

One of the significant advantages of electric vehicles is their ability to recover energy. The amount of recovered energy varies depending on the characteristics of driving. In the analyzed cases, very different results have been obtained - in the case of driving through an urban area, there achieved about 30% energy recovery, while driving almost at a constant speed energy recovery has been achieved at the level of 2%.

The determined energy storage capacity, designed to overcome the 100 km stretch of road while driving with the characteristics shown in Figures 1a and 1b differed significantly: 160 Ah in the first case and 300 Ah in the second case. These differences are mainly due to different motion resistance (dependent on speed) that characterize the discussed examples.

The second factor influencing the differentiation of the designated energy storage capacity is disproportionate, to the current, reducing energy in electrochemical energy storages. It is the result of the Peukert effect. It shows that in the near future electric vehicles will be dedicated to driving over short distances at relatively low speed (e.g. in a city traffic).

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АНАЛІЗ ЕНЕРГОСПОЖИВАННЯ ЕЛЕКТРИЧНИХ АВТОМОБІЛІВ, ОБЛАДНАНИХ ГІБРИДНИМ НАКОПИЧУВАЧЕМ ЕНЕРГІЇ

Лєшек Каспшик

Охарактеризовано сучасні транспортні засоби і подано аналіз споживання палива автомобілями, обладнаними двигунами внутрішнього згорання у Європейському союзі в контексті вичерпування паливних ресурсів. Стаття наводить залежності, які описують сили опору, що діють на транспортний засіб під час його руху, а також розглядає методи для визначення потужності необхідної для прискорення і гальмування. Проаналізовано енергоспоживання автомобіля в умовах двох доріг з різними характеристиками. У завершальній частині статті подано аналіз можливості відновлення енергії під час руху автомобіля. Крім того, на прикладі гібридного нагромаджувача енергії обговорено проблеми, пов'язані з обмеженнями енергонагромадження.

Leszek Kasprzyk – Professor at Poznan University of Technology, Poland, The Institute of Electrical Engineering and Electronics since 2000. In 2008, he defended the doctoral thesis in the area of electrical engineering. For 6 years he has been a deputy director of the Institute. He is a member of the Organizing Committee of the scientific conference on Computing Applied in Electrical Engineering, member of the Polish Society of Theoretical and Applied Electrical, and co-organizer of the Research Night in Poznan, Poland.