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ENERGY CONSUMPTION IN THE MOTION OF THE VEHICLE WITH ELECTRIC PROPULSION

Piotr Tarkowski, Ewa Siemionek

Lublin University of Technology, Faculty of Mechanical Engineering
20-618 Lublin, Nadbystrzycka 36 Str.
e-mail: p.tarkowski@pollub.pl, e.siemionek@pollub.pl

Summary. In the article, energy balance of the wheeled vehicle is discussed. Also, detailed analysis of factors determining energy consumption of the motion is provided. It comprises basic phases of the motion, as well as different cases when the vehicle realizes a complex speed profile. The conception of carrying out energy balance of the vehicle with electric propulsion was used for a car model with the electric motor of direct current and for a two-wheeled vehicle with the triphase asynchronous motor placed in the front wheel.

Key words: energy consumption, electric vehicle, energy balance, electric propulsion.

INTRODUCTION

The subject of energy analysis of the wheeled vehicle motion are factors determining the total expense of energy, as well as the demand for electric energy drawn from the battery. The starting point of the analysis is energy balance of the vehicle moving according to the determined speed profile. The main element of the balance is energy consumption of the motion which reflects the demand for energy on propelled wheels necessary for the realization of the assumed speed profile – it is the basic quantity determining the uptake of electric energy from the battery.

If the motion of the vehicle with electric propulsion is analysed as the result of particular energy transformations, one should take into consideration the way of delivering energy necessary for its realization, which can consist in:

- delivering energy from the engine through the power transmission system to the propelled wheels,
- using disposable kinetic energy (obtained earlier in the phase of acceleration) for overcoming resistance in retarded motion,
- using potential energy of the vehicle for overcoming resistance to motion while driving down the slope.

The following cases of the motion can be distinguished depending on the way it is forced by particular longitudinal forces:

- motion forced exclusively by the action of driving force; it includes acceleration and driving at constant speed,

- motion on the sloping road forced by the component of gravity force (G·sinα),
- retarded motion caused by the shortage of driving force, i.e. when $F_N<F_{OP}$, coasting ($F_N = 0$),
- braking with the use of brakes causing the dissipation of kinetic energy [Siłka 1995,1997,2002].

ENERGY BALANCE OF THE CAR

In energy balance of the electric wheeled vehicle (covering a particular road section), the total energy delivered to the motor in the form of electric energy taken from E_{El} battery is the sum of: energy on propelled wheels (i.e. energy consumption of the motion) balancing resistance to motion, energy losses in the motor and in the system of propulsion transmission, and also energy consumed by the engine while idling, e.g. during braking or at stops. Thus:

$$E_{EL}= E + \Delta E_S + \Delta E_{Pe} +\Delta Ej, \tag{1}$$

where: E - energy consumption of the motion, ΔE_S - losses which occurred during the processing of energy in the motor, ΔE_{Pe} - losses which occurred during the transmission of energy from the motor to the propelled wheels, ΔEj - energy delivered to the motor while idling, i.e. without the transmission of propulsion to the wheels .

Energy consumption of the motion is the amount of propelling energy delivered to the wheels exclusively in the phases of propulsion; because while driving with the disconnected wheel propulsion, resistance to motion is overcome at the expense of kinetic energy acquired during acceleration. It follows that the drive forced by torque transmitted from the motor to the wheels is considered the basic condition of the wheeled vehicle motion; therefore energy consumption of the motion is an important energy parameter.

Energy consumption of the motion is the amount of energy used to overcome: rolling resistance E_t , air resistance E_p, grade resistance E_w, and also energy used to increase kinetic energy of the vehicle E_K:

$$E = E_t + E_p + E_w + E_K . \tag{2}$$

Contrary to rolling resistance and air resistance, which are always present, grade resistance appears periodically. Energy used to overcome this resistance is equal to the gain in potential energy of the vehicle and may be partially recovered while descending the slope; at the same time the battery is recharged.

While covering a longer section of the road with variable speed, when the speed profile consists of a series of modules (including acceleration, fixed motion and braking), energy consumption of the motion is determined by the sum:

$$E = \sum \int_0^{L_N} (F_{OP})_N\, ds + \sum E_K . \tag{3}$$

Kinetic energy and potential energy of the vehicle are acquired exclusively at the expense of energy delivered from the electric motor to the wheels, during acceleration and overcoming the slope, respectively. In retarded motion, depending on the type of forcing, resistance is overcome partly or wholly at the expense of kinetic energy. In the case of commonly used friction brakes, the process of braking consists in the dissipation of considerable amount of kinetic energy, which as a result of friction changes into heat discharged into the environment. At the same time, the remaining part of this energy is used to overcome resistance to motion on the braking path. Substituting equation (2) to energy balance equation (1) leads to:

$$E_{EL} = E_t + E_p + E_w + E_K + \Delta E_S + \Delta E_{Pe} + \Delta Ej. \quad (4)$$

Energy consumption of the motion, according to equation 2, is the sum of energy expenditure for overcoming resistance to motion and also for overcoming inertial force during acceleration. After the equivalence of work and energy has been taken into consideration, either component of energy consumption of the motion can be expressed as the product of force and distance:

$$E_t = mg \int_0^{L_N} f_t ds = \overline{F}_t L_N, \quad (5)$$

$$E_p = K \int_0^{L_N} v^2 ds = \overline{F}_p L_N, \quad (6)$$

$$E_W = mg \int_0^{L_{NW}} \sin\alpha ds = \overline{F}_W L_{NW}, \quad (7)$$

$$E_K = m\delta \int_0^{L_A} a ds = \overline{F}_b L_A, \quad (8)$$

where: a - acceleration, ds - path differential , f_t - rolling resistance coefficient, E_t, E_p, E_W - energy used to overcome resistance to the motion of rolling, air and grade, respectively, E_K - kinetic energy, - rolling, air and grade resistance, respectively, - force of inertia, $K=c_x A\varepsilon$ - air resistance coefficient, L_A - length of path in the acceleration phase, L_N - total length of path in the propelling phase, *Lnw* - length of path covered in overcoming the slope, m - vehicle mass, v - vehicle speed, a - angle of longitudinal path inclination, δ - coefficient of rotating masses.

In the most general case, the driving cycle consists of several modules with the speed profile as shown in Figure 1. Points u and p denote the beginning of the deceleration phase and braking phase, respectively (with the engine disconnected from the propulsion system); point k denotes the end of a given module and the beginning of the next.

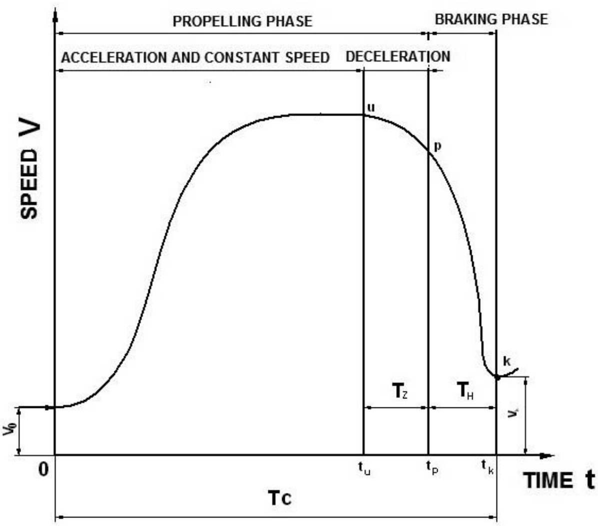

Fig. 1. Speed profile of a single module [Siłka 1998]

Where:
$0 \div t_u$ acceleration phase + phase of driving at constant speed, subscript N,
$t_u \div t_p$ - deceleration phase, subscript Z,
$tp \div tk$ - braking phase, subscript H (where $t_k = Tc$).

If these denotations are used, energy consumption in the motion of a single module equals:

$$E_i = mgf_t(L_N + L_z)_l + K(\vartheta_N L_N + \vartheta_z L_z)_i + -m/2(v^2_p - v_0^2), \tag{9}$$

where: f_t-rolling resistance coefficient, K - air resistance coefficient, L_z - path of deceleration phase, m - vehicle mass, ϑ_N-mean square value of speed in the propelling phase, ϑz - mean square value of speed in the deceleration phase.

The speed profile of a wheeled vehicle covering an adequately long section of the path consists of a bigger or smaller number of modules, depending on external factors, including features of the path and conditions of the motion. In such a case, energy consumption of the motion is the sum of energy consumptions of particular modules [Madej 2004, Prochowski 2005,Siłka 1998].

EXPERIMENTAL STUDIES

In order to verify experimentally relationships between the parameters of speed profile and energy consumption per unit, road tests of the electric car model and the two-wheeled vehicle with electric propulsion were conducted in the Department of Motor Vehicles at the Technical University of Lublin. The tests comprised multiple drives of vehicles in real traffic conditions, according to various complex speed profiles, with a simultaneous registration of kinematic parameters of the motion and measurements of energy consumed by batteries.

During acceleration, due to the action of the forcing signal U on the electric vehicle, the flow of electric current with intensity I was initiated. The intensity of this process and the obtained final value of angular velocity ω of the engine shaft (Fig. 2) depended on the value of applied voltage U, as well as on external and internal resistance to motion M_m. In the course of the experiment, the following values were recorded: voltage on battery terminals, angular velocity ω of the engine shaft and the intensity of current I flowing in the electric circuit. The second controlling value, which is torque M_m, was not measured directly during the tests . It was determined from dependences (10) and (11).

$$M_m = F_t r + M_{STR}, \tag{10}$$

$$F_t = mgf_t, \tag{11}$$

where: Ft-rolling resistance, r - radius of the circle, M_{STR} - moment of internal losses in the power transmission system, m - total mass of the vehicle, g-gravitational acceleration , ft - rolling resistance coefficient [Grzegożek 2003, Merkisz 2007, Orzełowski 1995, Śmieszek 2000].

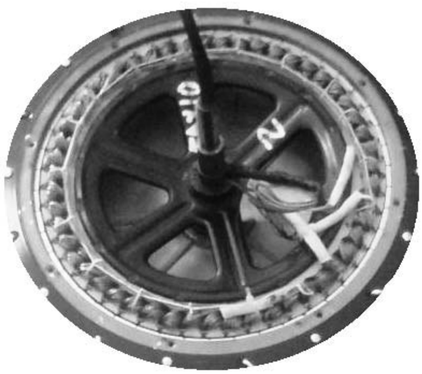

Fig. 2. View of the electric engine of the two-wheeled vehicle

In the course of conducted tests, besides direct measurements of voltage U, current intensity I and angular velocity ω of the engine shaft, a number of additional steps were carried out. These steps were necessary to determine chosen structural parameters of the tested object, to verify proper operation of the measuring system, as well as to enable carrying out the process of estimation of some values occurring in dependences (10) and (11). Therefore, the studies which were carried out were divided into the following stages:

1. Preliminary studies. Within the range of these studies there were: the measurement of vehicle mass, determining parameters characterizing batteries used in tests, determining design parameters of vehicles, such as gears and rolling radius of wheels, and checking proper functioning of the measuring system.
2. The study of acceleration process and steady motion. These studies were carried out for different supply voltages and for different total masses of vehicles.
3. The coasting test. These tests consisted in accelerating vehicles with different total masses, and then determining motion retardation occurring during their free coasting.

For the purpose of registering data derived from measurements, a set consisting of the portable Notebook computer and the USB Basic data acquisition card (8ch, 14-Bit) from National

Instruments were used. The system was connected to the tested vehicle by means of electric wires. The view of the tested two-wheeled vehicle is shown in Figure 3.

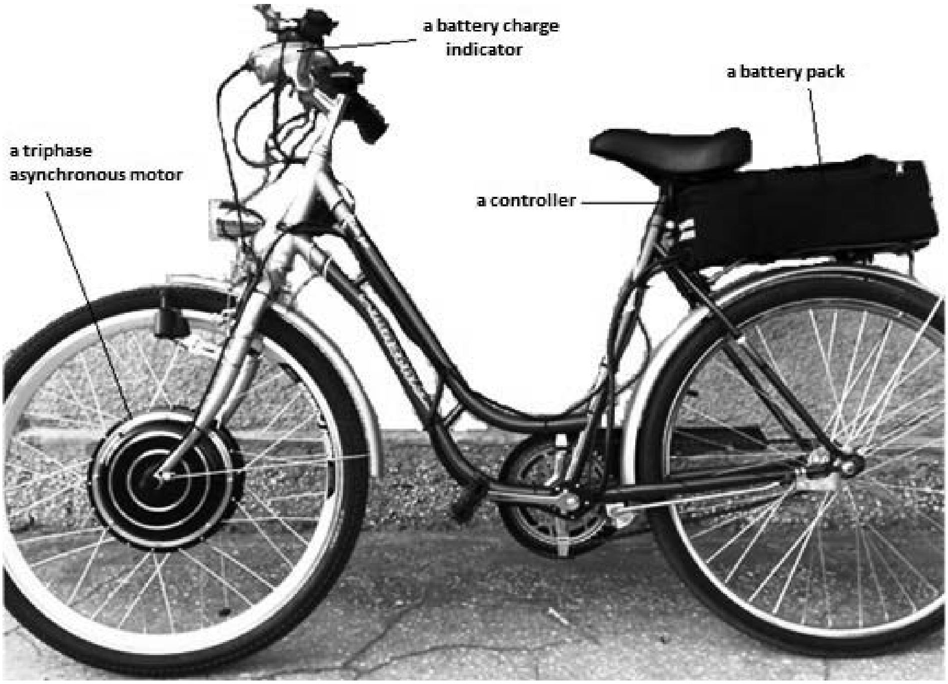

Fig. 3. View of the two-wheeled vehicle with electric power transmission system

CONCLUSIONS

In conclusion, it can be stated that the studies which were carried out make it possible to determine energy consumption associated with the motion of the electric vehicle.

On the basis of carried out registration of supply voltage and current consumed by the motor and the control system, it is possible to determine the power drawn from the fully charged battery and the maximum range of the drive. In further research, procedures enabling the full use of properties of electric motors and electrochemical batteries in the realization of the motion with a complex speed profile will be worked out .

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ENERGOCHŁONNOŚĆ RUCHU POJAZDU Z NAPĘDEM ELEKTRYCZNYM

Streszczenie. W artykule rozważono bilans energetyczny pojazdu kołowego oraz podano szczegółową analizę czynników decydujących o energochłonności ruchu, obejmującą podstawowe fazy ruchu oraz różne przypadki realizacji przez pojazd złożonego profilu prędkości. Koncepcję przeprowadzenia bilansu energetycznego pojazdu z napędem elektrycznym przeprowadzono dla modelu samochodu z silnikiem elektrycznym prądu stałego oraz pojazdu jednośladowego z trójfazowym silnikiem asynchronicznym umieszczonym w przednim kole.

Słowa kluczowe: energochłonność, pojazd elektryczny, bilans energetyczny, napęd elektryczny.