Stanisław Rawicki
Marcin Nowak
Maciej Różański
Wojciech Wycinka
Politechnika Poznańska

Calculation of energy-saving traffic of tram vehicle with field-oriented control of traction induction motors

The paper deals with the problems of the tram vehicle control according to the criterion of the minimum electric energy consumption. The authors have extended the methodics given in literature and have elaborated the algorithm of the energy-saving tram traffic taking into consideration various ride disturbances. During the running within the framework of the city conditions tram ride parameters change frequently. The mathematical models take into account the field-oriented control of traction three-phase squirrel-cage induction motors. Determination of the run algorithm ensuring the minimization of the electric energy use has been realized by application of the optimization procedure.

1. Introduction

Various techniques of the tram run can cause essential differences between the values of the energy consumption. It generates great interest for application of better methods of the tram vehicle control (both with reference to the vehicle and to the electric drive). The complex allowance for the dynamical conditions of the city traffic, the proper design of the control of the driving motors and elaboration of ride algorithms connected with the time-table create essentials for determination of the energy-saving tram running. The existence of many disturbances within the framework of the tram ride in the city brings about the great computation complexity at formulation of the optimum algorithms ensuring the minimum energy consumption of the tram vehicle.

The scientific work, connected with problems of the optimization strategies applied to the energy saving ride of the tram vehicle, is being realized at Institute of Electrical Engineering and Electronics of Poznań University of Technology (Poland).

The algorithms of the energy saving traffic of tram vehicles, elaborated in literature, are connected only with the ride without the disturbances and can be referred to the separated, straight and horizontal tracks. Except some idealized situations, dynamical changes of city traffic conditions occur. It causes models in literature aren't sufficient for problems of the determination of the tram traffic procedure in accordance with energy use minimization. The authors of this paper have extended the methodics given in literature and have elaborated the algorithm of the energy saving tram traffic allowing for ride perturbations. In this paper the results of investigations connected with the energy-saving traffic of the tram vehicle with the field-oriented control of traction three-phase induction motors have been given.

2. Modelling of tram vehicle traffic

In this chapter it's assumed that the modern tram vehicle possesses three-phase induction driving motors supplied from inverters. For the induction motor, equations of the dynamical mathematical model within the framework of the equivalent diphase system x - y can be written by the following way:

$$u_x = U_m \cos\left[(\omega_1 - \omega_k)\cdot t + \gamma\right] \tag{1}$$

$$u_y = U_m \sin\left[(\omega_1 - \omega_k)\cdot t + \gamma\right] \tag{2}$$

$$D\psi_{xS} = u_x + \omega_k \cdot \psi_{yS} - R_S i_{xS} \tag{3}$$

$$D\psi_{yS} = u_y - \omega_k \cdot \psi_{xS} - R_S i_{yS} \tag{4}$$

$$D\psi_{xW} = (\omega_k - \omega)\cdot \psi_{yW} - R_W i_{xW} \tag{5}$$

$$D\psi_{yW} = -(\omega_k - \omega)\cdot \psi_{xW} - R_W i_{yW} \tag{6}$$

$$D\omega = \frac{p}{J}\left(T - T_h\right) \tag{7}$$

$$i_{xS} = \lambda\left(L_W \psi_{xS} - M\psi_{xW}\right) \tag{8}$$

$$i_{yS} = \lambda\left(L_W \psi_{yS} - M\psi_{yW}\right) \quad (9)$$

$$i_{xW} = \lambda\left(L_S \psi_{xW} - M\psi_{xS}\right) \quad (10)$$

$$i_{yW} = \lambda\left(L_S \psi_{yW} - M\psi_{yS}\right) \quad (11)$$

$$\lambda = \left(L_S L_W - M^2\right)^{-1} \quad (12)$$

$$T = \frac{3}{2} pM(i_{xW} \cdot i_{yS} - i_{yW} \cdot i_{xS}) \quad (13)$$

where D is the operator of differentiation d/dt; u_x, u_y – supply voltages in the system $x - y$ (the maximum value U_m, the pulsation ω_1 and the initial phase angle γ), ω_k – the angular speed of the coordinate system in relation to the induction machine stator; Ψ_{xS}, Ψ_{yS} – linkage magnetic fluxes of the stator winding in the equivalent, diphase coordinate system $x - y$; Ψ_{xW}, Ψ_{yW} – linkage magnetic fluxes of the rotor winding; i_{xS}, i_{yS} – currents of the stator winding; i_{xW}, i_{yW} – currents of the rotor winding; ω – angular electrical speed of the rotor; p – the number of pole pairs; J – the moment of inertia of the rotating system; T – the electromagnetic torque of the motor; T_h – the load torque; R_S, R_W - the resistance of the stator and rotor winding; L_S, L_W, M – inductances of the equivalent, diphase induction machine

The control of the induction motor has been realized within the orientation in relation to the rotor linkage flux Ψ_W. For this methodics strategy, the mathematical equations describing the induction machine are being analysed in the coordinate system rotating synchronously with the rotor linkage flux vector. For the perpendicular axis y, the flux component Ψ_{yW} is equal to zero. The independent control of the magnetic rotor flux and the electromagnetic torque (decoupling of the flux control and the induction motor torque control) is here the very advantageous property of the electric drive.

The dynamic run of the tram vehicle can be described by the basic formula:

$$k_W m \frac{dv}{dt} = F_P - W(v) \quad (14)$$

where m is the vehicle mass, k_W is the factor of rotating masses, v denotes the vehicle speed, F_p is the tractive force, $W(v)$ describes the motion resistances. For motoring mode the relation between the force F_P and the useful motor torque T_U is:

$$F_P = \frac{n_M T_U z\eta}{r} \quad (15)$$

where n_M is the number of driving motors, z presents the transmission ratio, η is the gear efficiency, r denotes the radius of the driving wheel. In accordance with the Cooper formula, the motion resistances $W(v)$ depend on the vehicle speed within the trinomial square:

$$W(v) = w(v)m = (p + qv + sv^2)m \quad (16)$$

where $w(v)$ – the unitary motion resistance, p, q, s – the constant factors. In comparison with the electromagnetic torque T, the useful motor torque T_U is smaller by the torque of the mechanical losses.

Mathematical relations describing the tram vehicle traffic contain many nonlinearities, among others as a result of properties of motion resistances. Determination of the run algorithm ensuring the minimization of the electric energy consumption can be realized by application of the numerical method of differential equations solving and use of the optimization procedure. Calculation process must take into consideration many constraints. The important adhesion effect is connected with an existence of a limiting force acting in the wheel circumference.

3. Results of calculations

The computations have been done for the improved version of the tram vehicle 105N. This tram contains the inverters feeding 4 identical driving 3-phase induction motors of the total power 160 kW. The nominal data of the tram vehicle are: the traction network voltage: 600V (DC), total length: 13,5 m, tare mass: 16500 kg, nominal load: 8750 kg, rolling diameter of the wheel: 0,654 m, transmission ratio: 7,16, the maximum permissible speed: 72 km/h. The rated data of the driving induction motor are: the power: 40kW, the voltage: 380V (the stator winding is here star-connected), frequency: 60 Hz, the current: 71,7 A, the speed: 1724 rev/min, the efficiency: 90,8 %, cosφ: 0,931.

Only the small part of calculation results is here presented; these results concern the case when the tram vehicle mass m = 22000 kg. It corresponds with the passengers number equal 80 (64% in relation to the nominal load). In figures shown in this paper, the distance between two neighbouring stops was equal 950m and the traffic time was 95s according to the time-table (the same average speed for different tram rides).

For results presented in Figs. 1-3, the tram ride is realized without disturbances; the vehicle is here fully privileged at the cross-roads within the light signalling (always the green light for the tram). The minimization of the energy use of the tram vehicle is possible on the ground of the suitable traffic control. Determination of the optimum duration of the starting, the runnig with the constant speed, the coasting and the braking is here necessary. Fig. 1 gives the values of boundary speeds (diagram points) for succeeding traffic stages. In this paper, the factor *kr* determines what part of the energy is recuperated during the vehicle braking. For the coefficient value *kr* = 0, Fig. 1 presents the tram ride according to the criterion of minimum energy use.

It was illustrated that the best, optimum control of the tram vehicle has made possible to achieve the energy saving equal even to about 20,5% (at the recuperation factor *kr* = 0 in Fig. 2) and to about 6,9% for the recuperation coefficient *kr* = 1 (Fig. 3).

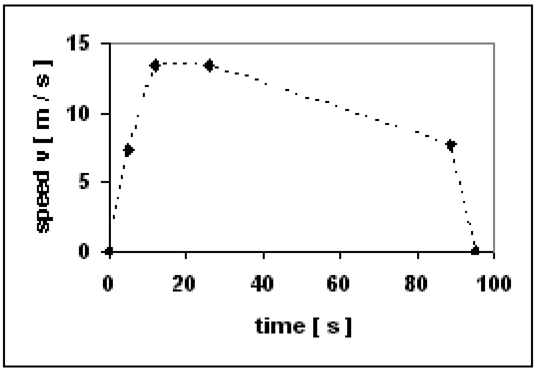

Fig.1. Ride without disturbances; length: 950m, time: 95s, the recuperation factor kr = 0; the minimum energy use: 1,064kWh

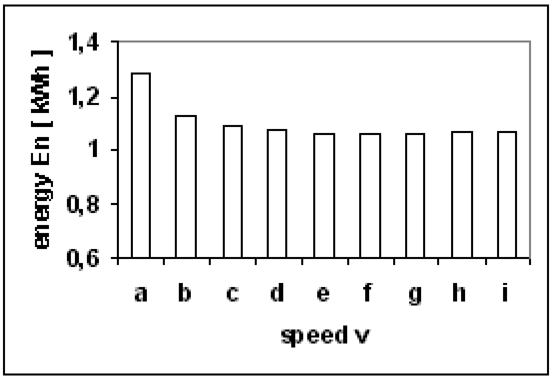

Fig.2. Ride without disturbances; length: 950m, time: 95s, the recuperation factor kr = 0; the total electric energy as a function of the terminal speed (m/s) of the starting: a) 10,97; b) 11,41; c) 11,85; d) 12,29; e) 12,73; f) 13,31; g) 13,70; h) 14,10; i) 14,48

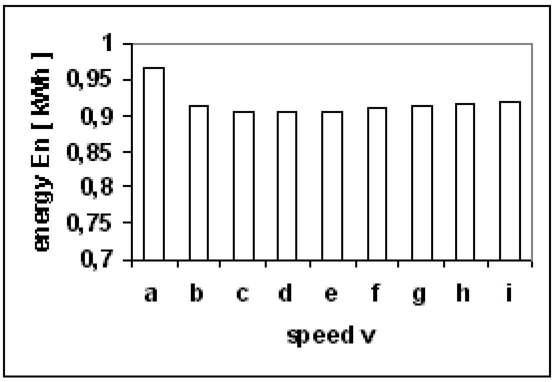

Fig.3. Ride without disturbances; length: 950m, time: 95s, the recuperation factor kr = 1; the total electric energy as a function of the terminal speed (m/s) of the starting: a) 10,97; b) 11,41; c) 11,85; d) 12,26; e) 12,73; f) 13,31; g) 13,70; h) 14,10; i) 14,48

For the given *kr* two cases with the minimum and maximum energy consumption were compared.

At the tram running with the constant speed, the motors load is small in comparison with the rated value of the mechanical motor power. Such load of the three-phase induction squirrel-cage motor causes the small value of power factor cosφ. The reduction of the voltage supplying the motors can be here advantageous. For three different values of the tram speed, Figs. 4-6 present results of calculations of the power factor cosφ for various voltage; the voltage is given in relation to the rated motor voltage.

For the low tram speed: 5m/s (Fig. 4), there were determined the following parameters ensuring the maximum motor efficiency η:

- power factor cosφ: 0,808;
- relative supply voltage: 0,301;
- relative current: 0,201;
- frequency of the supply voltage: 35,9Hz;
- magnetic rotor flux: 0,400Wb;

maximum efficiency η: 0,902.

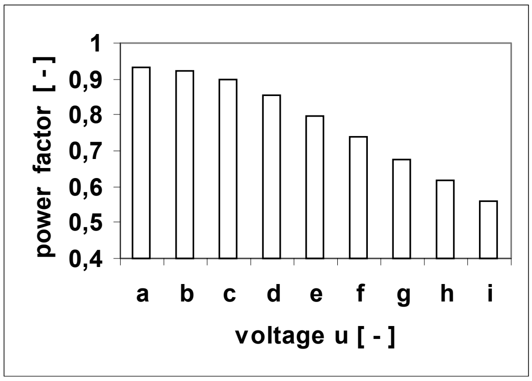

Fig.4. Ride at the constant speed of the small value: 5m/s; the power factor cosφ of the motor as a function of the relative supply voltage equal: a) 0,170; b) 0,204; c) 0,238; d) 0,272; e) 0,306; f) 0,340; g) 0,373; h) 0,407; i) 0,441

At the middle vehicle velocity: 11m/s (Fig. 5), the maximum efficiency has been obtained for parameters:

- power factor cosφ: 0,891;
- relative supply voltage: 0,609;
- relative current: 0,274;
- frequency of the supply voltage: 78,5Hz;
- magnetic rotor flux: 0,371Wb;
- maximum efficiency η: 0,918.

For the high tram speed 17m/s (Fig. 6), the maximum efficiency η was ensured at the following data:

- power factor cosφ: 0,918;
- relative supply voltage: 0,965;
- relative current: 0,373;
- frequency of the supply voltage: 121,1Hz;
- magnetic rotor flux: 0,380Wb;
- maximum efficiency η: 0,918.

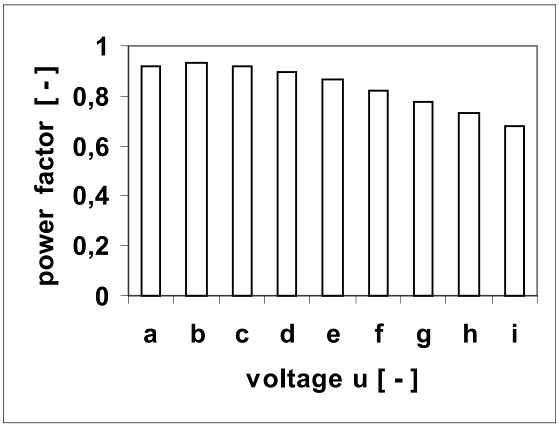

Fig.5. Ride at the constant speed of the middle value: 11m/s; the power factor cosφ of the motor as a function of the relative supply voltage equal: a) 0,373; b) 0,447; c) 0,521; d) 0,595; e) 0,670; f) 0,774; g) 0,818; h) 0,892; i) 0,996

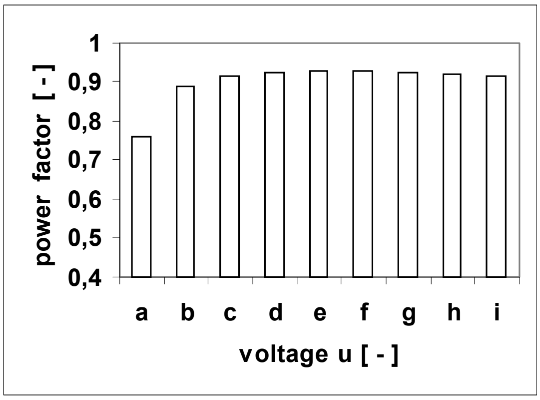

Fig.6. Ride at the constant speed of the high value: 17 m/s; the power factor cosφ of the motor as a function of the relative supply voltage equal: a) 0,543; b) 0,600; c) 0,657; d) 0,714; e) 0,772; f) 0,829; g) 0,886; h) 0,944; i) 1,000

In Figs. 7-9, the ride distance was also equal 950m and the traffic time was 95s in accordance with the time-table. At the beginning of the route, there was arc of the radius 50m and the length 78,5m. Additionally, for the initial length equal 78,5m the obligatory speed limitation to the value 25km/h occured. It is known that the ride of the traction vehicle along arc causes increase of the motion resistances *W*(*v*); in literature there is information about the motion resistances for arcs. To obtain the same ride time: 95s in comparison with the case illustrated in Figs. 1-3, the tram run in the second route part (straight and horizontal, without speed limitation) must be realized with the greater speed and the enlargement of the energy consumption can be here expected.

For the recuperation coefficient *kr* = 0 (no recovery of the energy during the braking of the tram vehicle), the total (for the distance 950m) consumption of the energy in Fig. 7 is 8,9% greater in comparison with the case presented in Fig. 1.

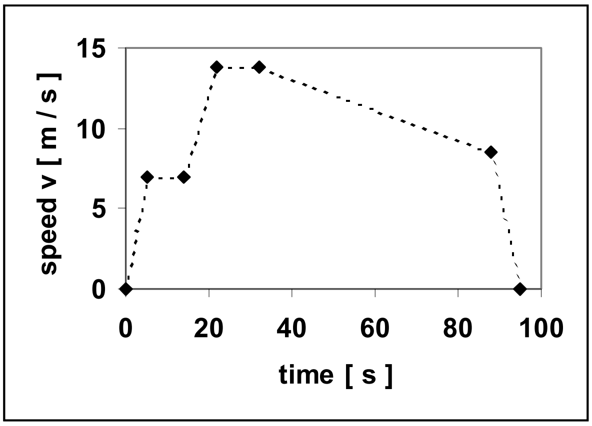

Fig.7. Ride along arc and at the speed limitation to 25km/h at the beginning of the tram route; the recuperation coefficient kr = 0; for the second ride part without limitations the minimum electrical energy consumption: 0,837kWh

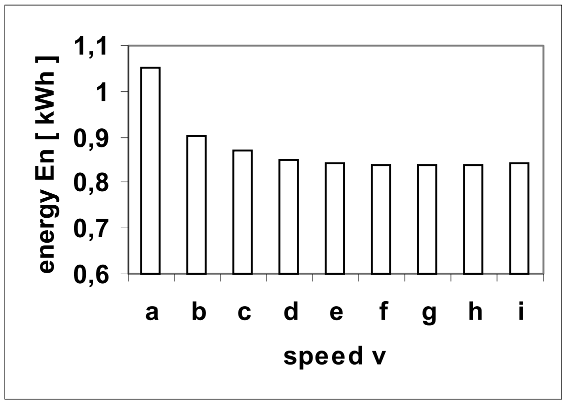

Fig.8. The second ride part without limitations; the recuperation factor kr = 0; the total electric energy as a function of the terminal speed (m/s) of the starting: a) 11,55; b) 11,92; c) 12,28; d) 12,65; e) 13,01; f) 13,38; g) 13,74; h) 14,19; i) 14,64

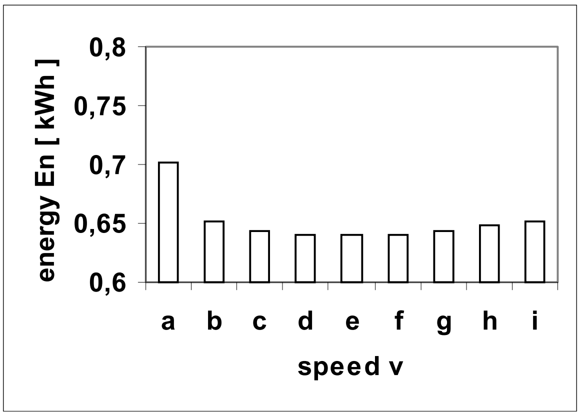

Fig.9. The second ride part without limitations; the recuperation factor kr = 1; the total electric energy as a function of the terminal speed (m/s) of the starting: a) 11,55; b) 11,92; c) 12,28; d) 12,80; e) 13,01; f) 13,38; g) 13,74; h) 14,19; i) 14,64

Similarly for the recuperation factor *kr* = 1 (maximum recovery of the energy during the tram vehicle braking), the total consumption of the electrical energy in Fig.9 is 6,5% greater than for the case presented in Fig. 3.

Figs. 10-12 are connected with the case when during the tram ride the unexpected, additional braking was necessary. Moreover untypical situation forced the slow vehicle running with the speed 25km/h during the distance of 40m. After disappearance of the traffic disturbances, the quicker tram ride is necessary with intent to attain the liquidation of the traffic delay in comparison with the time-table. The additional starting after the velocity reduction enlarges also the energy use.

For the initial part of the ride in Fig. 10, the time function of the velocity is identical in comparison with the traffic without disturbances because it is assumed here that the tram ride is at the start realized according to the criterion of the minimum energy use and the necessity of the additional vehicle stop appeared as the traffic perturbation.

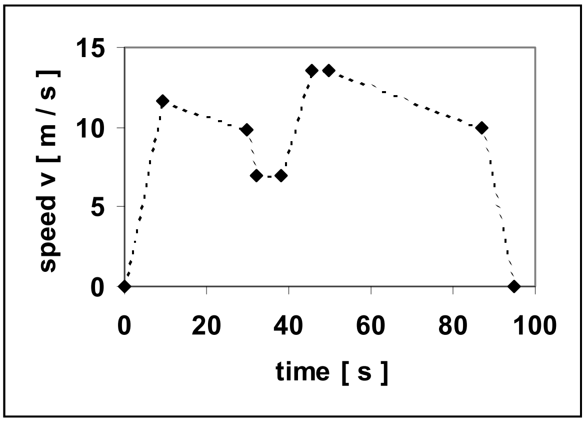

Fig.10. Ride with the forced, additional braking and short speed limitation to 25km/h; the recuperation factor kr = 0; for the second ride part without limitations the minimum energy consumption equal to 0,837kWh

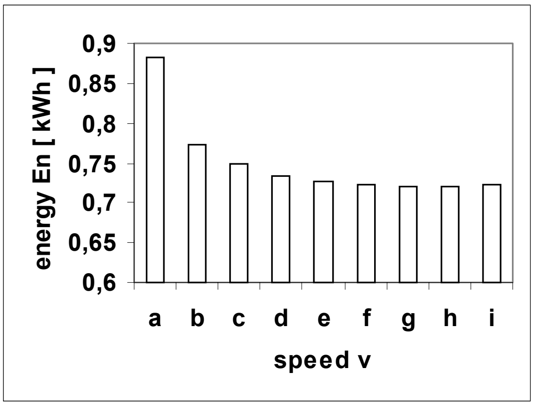

Fig.11. The second ride part without limitations (the case in Fig.10); the factor kr = 0; the total electric energy as a function of the terminal speed (m/s) of the starting: a) 11,93; b) 12,18; c) 12,42; d) 12,67; e) 12,91; f) 13,16; g) 13,40; h) 13,53; i) 13,89

For the case when the recovery during the braking doesn't exist (the recuperation coefficient *kr* = 0), the total (for the whole distance 950m) consumption of the energy in Fig. 10 is 34% greater in comparison with the case presented in Fig. 1. If the value of the recuperation factor is equal to 1 this energy enlargement is smaller and equal 15,1%.

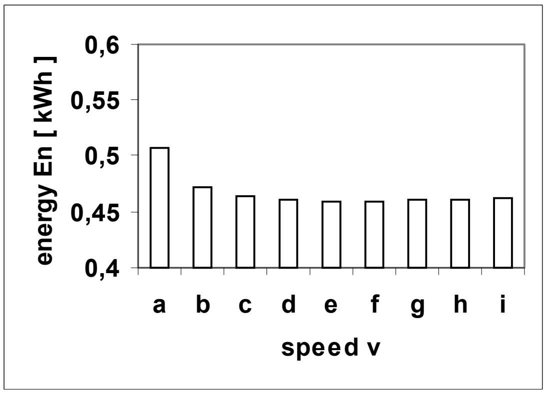

Fig.12. The second ride part without limitations (the case in Fig.10); the factor kr = 1; the total electric energy as a function of the terminal speed (m/s) of the starting: a) 11,93; b) 12,18; c) 12,42; d) 12,67; e) 12,91; f) 13,05; g) 13,40; h) 13,53; i) 13,89

4. Conclusions

- Elaborated in literature algorithms of the energy saving traffic of tram vehicles are connected only with the ride without disturbances and can be referred to separated tracks. Except some situations, usually frequent and dynamical changes of city traffic conditions occur.
- The following tram traffic perturbations are of great importance for algorithm of the energy saving tram ride: influence of light signalling, changes of the network voltage, speed limitations, unexpected stops.
- The presented simulation models (described here scientifically) allowing for the traffic disturbances enable saving even about 20% electric energy consumed by tram vehicles. The models take into consideration the field-oriented control of traction three-phase induction motors.

Literatura

[1] Frąckowiak J., Method of calculation of energy saving traffic of tram vehicle driven by three-phase induction motors. Doctor's thesis, Poznan University of Technology, Poland, 1995.

[2] Kacprzak J., Automatics and control of electric traction vehicles. WKiŁ, Warsaw, 1981.

[3] Krzysztoszek K., Control of traction vehicle taking into consideration voltage drops in traction network. Doctor's thesis, Warsaw University of Technology, Poland, 1998.

[4] Pniewska B., Follow-up control of traction vehicle at given time-table. Doctor's thesis, Warsaw University of Technology, Poland, 1995.

[5] Rawicki S., Energy Saving Control of Tram Motors Taking Light Signalling and City Disturbances into Account. Proceedings of International Conference EPE-PEMC, Poznan, Poland, 2008.

[6] Zielińska M., Rationalization of energy use in city traffic of electric rail traction vehicles. Doctor's thesis, Poznan University of Technology, Poland, 1993.