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ENERGY-SAVING COORDINATION OF TRAFFIC OF SOME TRAMS DRIVEN BY INDUCTION MOTORS

The paper deals with new software ensuring the ride of some interdependent tram vehicles in accordance with the criterion of the minimum energy consumption. All trams have been driven by vectorially controlled and field oriented three-phase induction motors supplied from the modern inverters. First of all, the influence of light signalling on the coordinated energy-saving traffic of trams has been taken into consideration. In one example there was shown the possible case for three trams ride free from the possibility of collisions. Here the energy savings were the biggest. Every time it is very difficult to ensure the green light for every tram vehicle at the same crossing. There were analysed two variants of disturbances caused by the light signalling: additional short and long tram stop. In the instance of large time lags of the traffic, the ride delay must be liquidated during the run between some succeeding stops.

KEYWORDS: trams, energy-saving traffic, induction motors, light signalling

1. INTRODUCTION

Different techniques of the tram vehicle run can generate large differences within the framework of the values of the electric energy use. It causes great interest for application of better methods of the tram control (both with reference to the vehicle construction 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 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, e.g. [1, 2, 7, 9]. Till now there were realized works relating to the control of only one separate tram vehicle. For the first time, this paper deals with new software ensuring the ride of the set of some interdependent trams according to the

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criterion of the minimum electric energy use; here the influence of light signalling within coordinated energy-saving traffic is taken into account.

Light signalling can also cause traffic disturbances: additional short or long tram stop. In the instance of large time lags of the traffic, the ride delay must be liquidated during the run between some succeeding stops. In this paper, all trams have been driven by vectorially controlled and field oriented three-phase induction motors supplied from the modern inverters.

In practical applications calculations problems relating to energy-saving control of some trams ought to be solved online – in short time. It requires the large power of the computer computation. One possible solution consists in cooperation of the internal tram computer and the modern supercomputer in the same city. The wireless transmission of data is here very useful.

2. MATHEMATICAL MODEL OF TRAM TRAFFIC

The mathematical simulation of the tram ride refers to equations of electrical circuits of driving motors, mechanical parameters of the vehicle and properties of the route of the running tram. Here the mathematical modelling of the tram vehicle with three-phase induction motors is presented. The modern theory [6] for vectorially controlled and field oriented induction motors is used. There are taken into consideration the transformations in which the separation of the magnetizing component of the stator current i_{xS} and the stator component i_{yS} creating the electromagnetic torque is obtained. The control of the rotor magnetic flux and the torque is independent. The coordinate system x, y is connected with the equivalent two-phase induction machine. The axis x is rotating synchronously with the rotor magnetic flux Ψ_W. Equations of the mathematical model of the induction motor in the two-phase system x, y are:

$$D\psi_{xS} = u_x + \omega_k \cdot \psi_{yS} - R_S i_{xS} \tag{1}$$

$$D\psi_{yS} = u_y - \omega_k \cdot \psi_{xS} - R_S i_{yS} \tag{2}$$

$$D\psi_{xW} = (\omega_k - \omega) \cdot \psi_{yW} - R_W i_{xW} \tag{3}$$

$$D\psi_{yW} = -(\omega_k - \omega) \cdot \psi_{xW} - R_W i_{yW} \tag{4}$$

$$D\omega = \frac{p}{J}(T - T_h) \tag{5}$$

$$i_{xS} = \lambda(L_W \psi_{xS} - M\psi_{xW}) \tag{6}$$

$$i_{yS} = \lambda(L_W \psi_{yS} - M\psi_{yW}) \tag{7}$$

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

$$i_{yW} = \lambda(L_S \psi_{yW} - M\psi_{yS}) \tag{9}$$

$$\lambda = \left(L_S L_W - M^2\right)^{-1} \tag{10}$$

$$T = \frac{3}{2} p \frac{M}{L_W} (\Psi_{xW} \cdot i_{yS} - \Psi_{yW} \cdot i_{xS}) \tag{11}$$

where: u_x, u_y are supply voltages; D - the operator of differentiation; ω_k – the angular speed of the coordinate system in relation to the stator; Ψ_{xS}, Ψ_{yS} – linkage fluxes of the stator in the two-phase system x, y; Ψ_{xW}, Ψ_{yW} – linkage fluxes of the rotor; i_{xS}, i_{Ys} – stator currents; i_{xW}, i_{yW} – rotor currents; ω – angular electrical rotor speed; p – the number of pole pairs; J - the moment of inertia; T - the electromagnetic motor torque; T_h - the load torque; R_S, R_W - the stator and rotor resistances; L_S, L_W, M – inductances of the two-phase induction machine.

The dynamical vehicle state can be described as follows:

$$k_m m \frac{dv}{dt} = F_p - W(v) \tag{12}$$

where m is the tram vehicle mass, k_m – the rotating masses factor, v – the tram speed, F_p – the tractive force, $W(v)$ – the motion resistances. If the electrical machines are in the motoring type of operation the connection between the tractive force F_P and the useful motor torque T_U is given by the formula:

$$F_p = \frac{n_S T_U z \eta_p}{r} \tag{13}$$

where z is the transmission ratio, η_p – the gear efficiency, r – the driving wheel radius, n_S – the number of motors. For calculation of the motion resistances $W(v)$ the Cooper formula [4] is used. The relation between the tram velocity v and the electrical motor speed ω is:

$$v = \frac{\omega \cdot r}{p \cdot z} \tag{14}$$

The electric energy En used by the motors can be obtained by the integration:

$$En = \frac{3}{2} n_S \int_{t1}^{t2} (u_x i_{xS} + u_y i_{yS}) dt \tag{15}$$

The optimization procedure enables determination of the tram traffic algorithm with the minimum electric energy use.

3. ANALYSIS OF COMPUTATION RESULTS

Calculations have been done for three identical trams of the type 105N. The modernization of the tram 105N was realized by application of inverters supplying three-phase induction motors. The rated power and the number of driving motors were the same. Mechanical vehicle parameters were unchanging.

Every tram possesses four identical driving motors of the total power 160 kW. The rated data of the tram vehicle are: the traction network voltage: 600 V (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 speed: 72 km/h.

The nominal data of the driving three-phase induction motor are: the power: 40 kW, the voltage: 380 V, frequency: 60 Hz, the current: 71,7 A, the rotational speed: 1724 rev/min, the efficiency: 90,8%, cosφ: 0,931.

Only the part of simulation results is here given; the results refer to the example when the tram mass m = 22000 kg; it means that the passengers number is equal 80 (in percentage form it is 64% with reference to the rated load).

For the traffic without disturbances (green light at the crossing, Figs. 1–6) the planned ride parameters for the individual trams are the following:
–   the tram I in the segment A between 2 stops: the distance 900 m, ride time 90 s,
–   the tram II in the segment B: the distance 500 m, ride time 50 s,
–   the tram III in the segment C: the distance 950 m, ride time 95 s.

The factor kr informs what part of the energy is recuperated during the vehicle braking. For the tram I and the coefficient value $kr = 0$, Fig. 1 illustrates the ride for the green light at the crossing (no traffic disturbances); the energy use is here minimal: $Enmin$ = 1,039 kWh because of the best choice (the optimization procedure) of the duration of the starting, the running with the constant speed, the coasting and the braking. Figs. 1 – 11 present the values of boundary speeds – diagram points – for consecutive traffic stages. In Fig. 1 there is both the stage of the running with the constant speed and the phase of the coasting.

Fig. 2 presents the vehicle ride (also for the tram I) within the case with the energy recuperation during the tram braking ($kr = 1$) at the minimum energy use equal to $Enmin$ = 0,869 kWh. Here the stage of the tram running with the constant speed is longer than in Fig. 1 concerning the case for the factor $kr = 0$.
In Fig. 1 the energy use is larger by 19,6% than in Fig. 2; the modern power electronics systems make possible realization of the process of the electric energy recuperation and it considerably improves the general vehicle energy balance.

For the tram II (500m, 50s), Figs. 3 and 4 present the ride without disturbances and with the minimum energy use. At the factor $kr = 0$ (Fig. 3), $Enmin$ = 0,960 kWh however for the coefficient $kr = 1$: $Enmin$ = 0,644 kWh. For the case shown in Fig. 3, the energy consumption is bigger by 49,1% than in Fig.4. For short distances, energy savings - connected with the effective energy recuperation – are much larger in comparison with the ride at long distances.
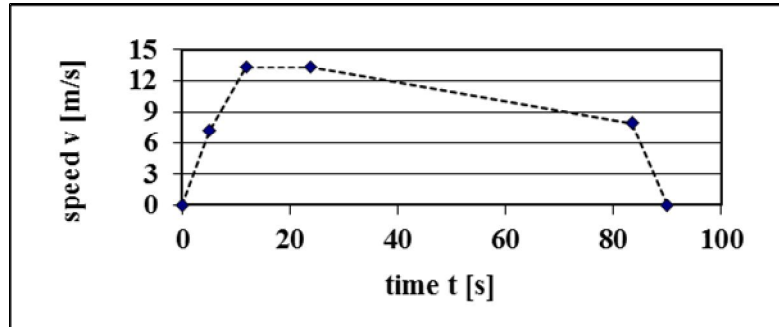
Fig. 1. Tram I; ride without disturbances (green light of the signalling at the crossing)
at the minimum electrical energy consumption $En = 1,039$ kWh; length: 900 m, time: 90 s;
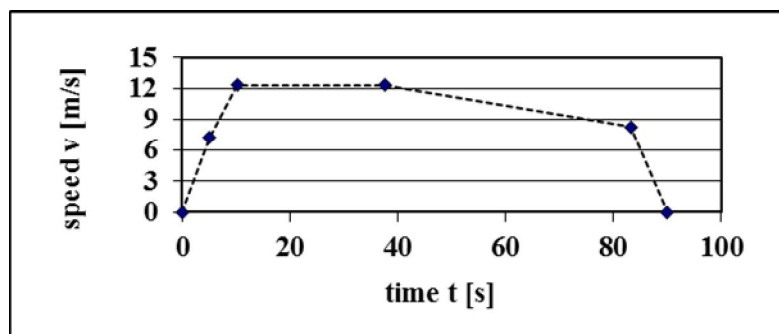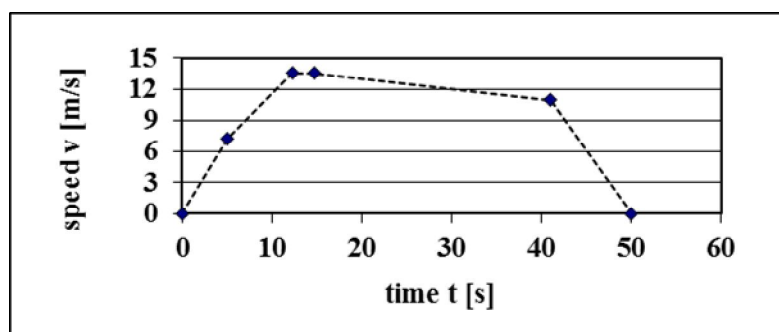the recuperation factor $kr = 0$

Fig. 2. Tram I; ride without disturbances (green light of the signalling at the crossing)
at the minimum electrical energy consumption $En = 0,869$ kWh; length: 900 m, time: 90 s;
the recuperation factor $kr = 1$

Fig. 3. Tram II; ride without traffic disturbances (green light of the signalling at the crossing)
at the minimum electrical energy consumption $En = 0,960$ kWh; length: 500 m, ride time: 50 s;
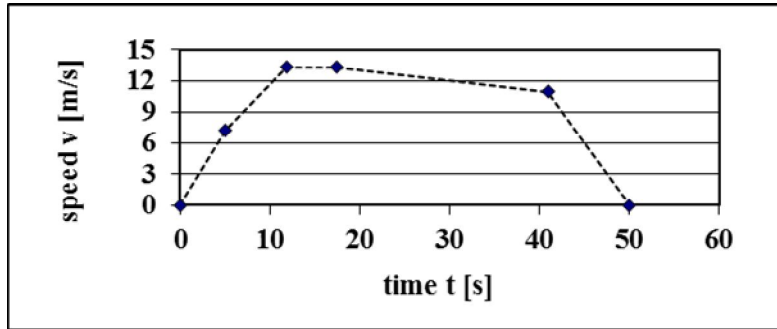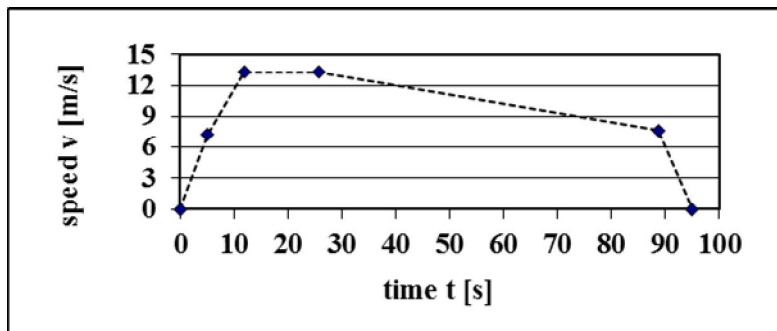the recuperation factor $kr = 0$

Fig. 4. Tram II; ride without traffic disturbances (green light of the signalling at the crossing) at the minimum electrical energy consumption $En = 0{,}644$ kWh; length: 500 m, ride time: 50 s; the recuperation factor $kr = 1$

Fig. 5. Tram III; ride without traffic disturbances (green light of the signalling at the crossing) at the minimum electrical energy consumption $En = 1{,}064$ kWh; length: 950 m, ride time: 95 s; the recuperation factor $kr = 0$
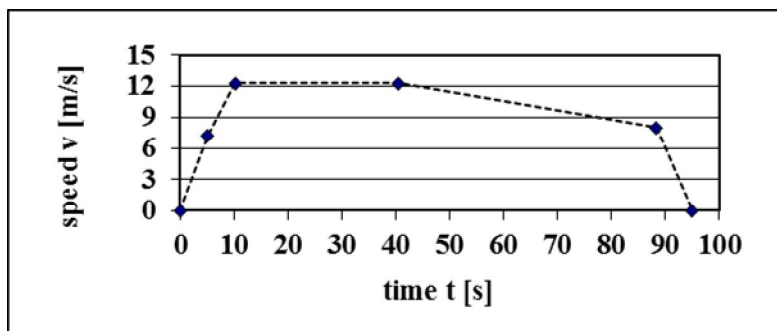

Fig. 6. Tram III; ride without disturbances (green light at the crossing) at the minimum energy use $En = 0{,}903$ kWh; length: 950 m, time: 95 s; the recuperation factor $kr = 1$

Figs. 5 and 6 are connected with the tram III (950 m, 95 s). Minimized energy use is here equal: at $kr = 0$ in Fig. 5: *Enmin* = 1,064 kWh and for $kr = 1$: *Enmin* = 0,903 kWh. It means that in Fig.5 the energy use is larger by 17,8% than in Fig.6; here advantage caused by energy recuperation is the smallest.

At the segment A (900 m, 90 s), Figs. 7, 8 show the computation results in the case when it was not possible to ensure the green light for the tram I during riding at the cross-roads. The traffic disturbance (red light of the signalling) has appeared and the tram I first reduced considerably the speed and then stopped a short time (1 s). At the beginning, the tram was running in accordance to the primary algorithm of minmization of the energy use. After time 7,71 s the driver has noticed yellow light of the signalling and he decided to make first the tram coasting and then the vehicle braking. The tram has stopped after 210 m from the starting point (this part is here called: section I). After 30 s (counting right from the route beginning) the tram began the ride within the section II of the length 690 m. To liquidate the delay, ride time for the section II was equal to 60s and here the new algorithm of the subsequent run has been elaborated taking minimum energy use into consideration.

In Fig. 7 ($kr = 0$) the energy use is *Enmin* = 1,856 kWh (78,6% more than in Fig. 1 with fluent traffic) and in Fig. 8 ($kr = 1$) *Enmin* = 1,236 kWh (42,2% more compared with Fig. 2). In comparison with Figs. 1 and 2, the energy consumption is larger because the unplanned short stop forces the additional, renewed starting and the speed in the section II must be bigger to liquidate delay.
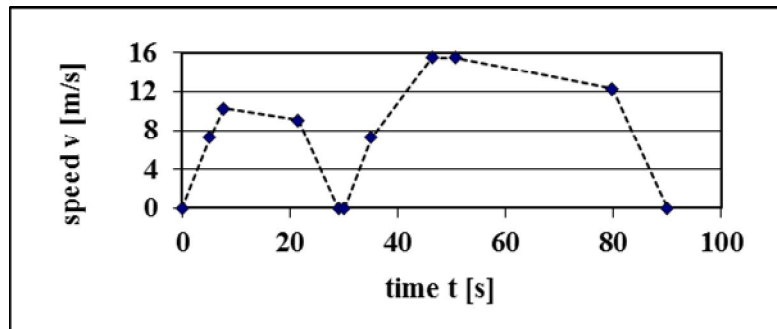

Fig. 7. Tram I; ride with traffic disturbance caused by the red light of the signalling
and the unplanned short tram stop of 1s after the distance 210m at the minimum energy use
En = 1,856 kWh; length: 900 m, time: 90 s; the recuperation factor $kr = 0$

For the tram III, Figs. 9 – 11 present the case connected with the large traffic disturbance. In the segment C of 950 m (Fig. 9), there was the unplanned long stop of 40s caused by the red light after 300m counting from the vehicle start (the section I of the segment C).
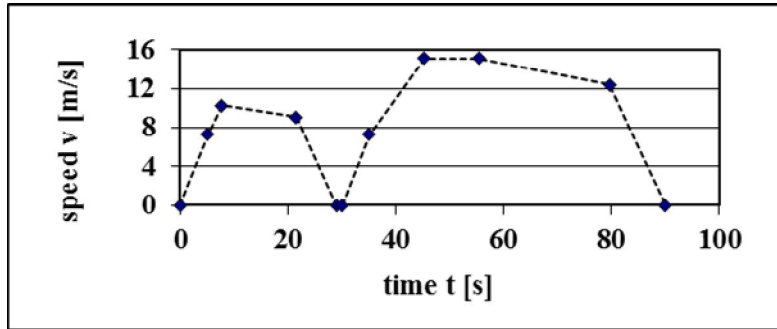
Fig. 8. Tram I; ride with traffic disturbance caused by the red light of the signalling
and the unplanned short tram stop of 1s after the distance 210 m at the minimum energy use
$En = 1,236$ kWh; length: 900 m, time: 90 s; the recuperation factor $kr = 1$

Because of the limited place, only the variant for the recuperation factor $kr = 1$ is here shown. As a result of the large traffic delay, the forecasting of the subsequent energy-saving run must deal with some succeeding ride segments. After the special computation analysis, it was found the compromise: the delay will be liquidated within the quicker ride in three next segments: D, E and F. The segments D and F are the same: the distance 850 m, ride time 85 s planned for the traffic without perturbations. The segment E has the length 650 m and the normal ride time is here 65 s.

After optimization the best common ride time: 70,05 s (instead of 85 s) has been determined for identical segments D and F. For each segment D, F, the quicker run with the speed 12,13 m/s (instead of planned 10m/s) makes possible diminution of the delay by 14,95 s. In Fig. 10 the minimized electrical energy use is equal $Enmin = 1,104$ kWh (by 32,1% more than at tram III ride without disturbances).
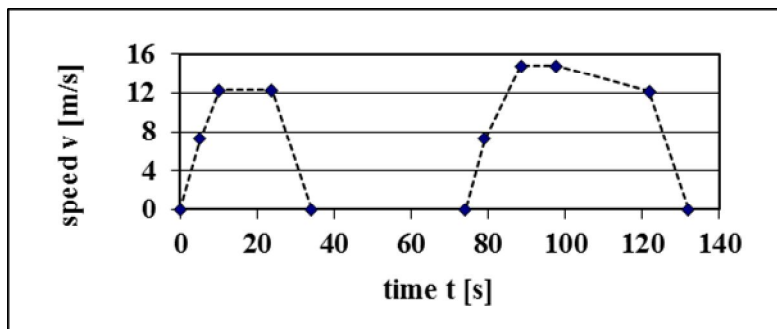

Fig. 9. Tram III; ride with traffic disturbance caused by the red light of the signalling
and the unplanned long tram stop of 40s after the distance 300m at the minimum energy use
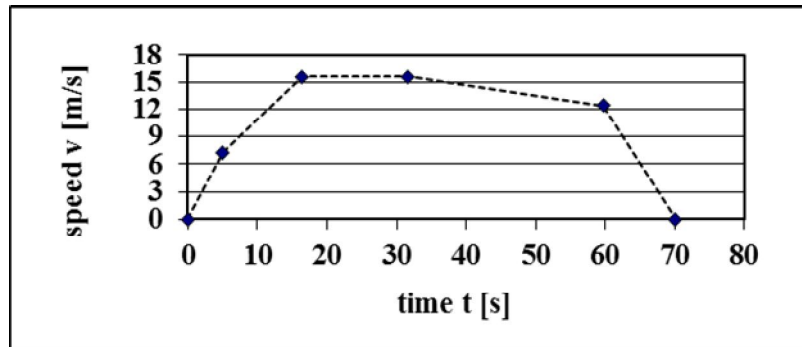$En = 1,367$ kWh; length: 950 m; the recuperation factor $kr = 1$

Fig. 10. Tram III; ride in the same segments: D and F (850 m) at liquidation of the large traffic delay caused by the unplanned long tram stop of 40 s in the segment C; the minimum energy use $En = 1,104$ kWh; the recuperation factor $kr = 1$
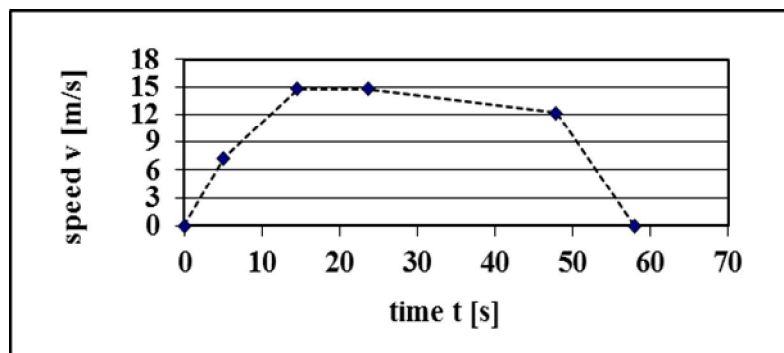

Fig. 11. Tram III; ride in the segment E (650 m) at liquidation of the large traffic delay caused by the unplanned long tram stop of 40 s in the segment C; the minimum energy use $En = 0,865$ kWh; the recuperation factor $kr = 1$

Advantageous ride time: 57,95s (instead of 65s) was found for the segment E. The quicker ride (speed 11,22m/s instead of 10m/s) makes possible delay reduction by 7,05 s. In Fig. 11 minimal energy use is $Enmin = 0,865$ kWh (increase by 32,3%).

At the recuperation factor $kr = 1$ and for the whole route (segments C, D, E and F), the minimized electrical energy use is $Enmin = 4,440$ kWh (35,0% more in comparison with the fluent ride without any traffic disturbances – green light in the crossing).

The results of the additional calculations realized by the authors inform that at the factor $kr = 0$ this energy is much bigger: $Enmin = 6,389$ kWh (more by 57,9%).

4. CONCLUSIONS

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 running with the constant speed, the coasting and the braking is here necessary. The elaborated algorithms of the tram ride at minimum energy consumption make possible to save about 20% energy in comparison with the ride basing only on subjective decisions of a driver. The above possibilities are very attractive for designers because the best computer software can ensure energy savings within the framework of the tram traffic.

Scientific works relating to the control of only one separate tram vehicle are not sufficient in practice. New software ensuring the ride of the set of some interdependent trams according to the criterion of the minimum electric energy use are of great importance. Here light signalling within coordinated energy-saving traffic ought to be taken into account. Light signalling can cause traffic disturbances: additional short or long tram stops. At large time lags of the traffic, the ride delay must be liquidated during the run between some succeeding stops.

In practical applications calculations problems relating to energy-saving control of some trams ought to be solved online – in short time. It requires the large power of the computer computation. One possible solution consists in cooperation of the internal tram computer and the modern supercomputer in the same city. The wireless transmission of data is here very useful.

Because of many cars, Polish streets often are crowded. Within next research, by optimum way authors will try to coordinate light signalling at crossings both for trams and cars taking reduction of the energy use into consideration.

REFERENCES

[1]   Frąckowiak J., Method of calculation of energy-saving ride of tram vehicle driven by three-phase induction motors, Doctor's thesis, Poznan University of Technology, Poznan, 1995.
[2]   Glia R.S., Investigation of the influence of disturbances of the traffic of tram vehicles with series direct current motors on the forecasting of the subsequent energy saving run, Doctor's thesis, Poznan University of Technology, Poznan, 2005.
[3]   Halangau A.M., A new solution for the optimization of urban public transport consumption, 11th Intern. Conference: Modern Electric Traction, Warsaw, Poland 2013, p. 1-6.
[4]   Kacprzak J., Koczara W., Fundamentals of electric traction vehicle drive, Publishing House of Communications, Warsaw, 1990 (in Polish).

[5]   Lewandowski M., Analysis of electromechanical phenomena in rail traction vehicle taking into consideration changes of adhesion of driving wheels, Publishing House of Warsaw University of Technology, Electrical Engineering, No. 139, Warsaw, 2009 (in Polish).

[6]   Orłowska-Kowalska T., Sensorless driving systems with induction motors, Publishing House of Wroclaw University of Technology, Electrical Engineering, No. 48, Wroclaw, 2003 (in Polish).

[7]   Rawicki S., Semi-automatic control of tram vehicle with intent to attain minimum electric energy use, Przegląd Elektrotechniczny (Electrical Review), No. 7, 2009, p. 159-162.

[8]   Szeląg A., Problems of analysis and design of electric direct-current traction system applying modelling and simulation techniques, Publishing House of Warsaw University of Technology, Electrical Engineering, No. 123, Warsaw, 2002.

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