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NEW SOFTWARE FOR ENERGY SAVING CONTROL OF A TRAM VEHICLE

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Abstract
The paper deals with new software ensuring the tram vehicle ride according to the criterion of the minimum energy use. The tram is driven by vectorially controlled and field oriented three-phase induction motors. Traffic disturbances are taken into consideration and a tram ride can contain many cycles consisting of the starting, the running with the constant speed, the coasting and the braking.

Introduction

Nowadays energy saving within the tram traffic is very important. Many new solutions have appeared in this field, e.g. [1], [3 - 7]. Optimization of duration of the typical tram ride stages: the starting, the running with the constant speed, the coasting and the braking can decrease the energy use.

In the city, frequent changes of tram traffic conditions occur. The total and local, planned or unplanned speed limitations, intentional or unexpected stops, changes of the network voltage, changes of a size of the energy recuperation during the braking are typical for the tram city ride. Because of ride perturbations, the run between neighbouring tram stops can contain many cycles consisting of the starting, the running with the constant speed, the coasting and the braking. Sometimes these cycles can possess only some of above ride phases. The author of this paper has elaborated the original algorithms ensuring the minimum energy use taking the different tram traffic disturbances into consideration.

Application of vectorially controlled and field oriented three-phase squirrel-cage induction motors for tram drive ensures diminution of the weight and dimensions; also enlargement of the technical reliability is here important.

In this paper, the mathematical models both for the first part of the starting (constant magnetic flux, increase of the supply voltage at motor terminals) and for the second starting part (the rated motor supply voltage, decrease of the magnetic flux) have been presented. For the tram running with the constant speed, there was given the model ensuring the larger motor efficiency and better power factor. There was also described the optimization strategy giving the minimum energy consumption for the case of traffic disturbances and occurrence of many ride cycles. Exemplary tram ride with unplanned stop and calculation of the algorithm of the tram ride according to the criterion of the minimum energy use have been also presented.

Mathematical model for first part of starting

Vectorially controlled and field oriented three-phase induction motors are supplied from modern inverter systems. After the transformation of the natural three-phase system of the induction machine to the equivalent two-phase system x, y, the separation of the magnetizing component of the stator current I_{xS} (the longitudinal component) and the stator component I_{yS} (the transverse component) creating the electromagnetic torque was obtained. For the substitutional system x, y, the control of the torque and the rotor magnetic flux can be realized by the independent way. Additionally it can be noticed that the axis x is rotating synchronously with the rotor magnetic flux Ψ_W. For the first part of the starting, the longitudinal component of the current I_{xS} and the transverse component I_{yS} can be calculated on the ground of the given value of the rated magnetic flux Ψ_{WN} and the given starting current I_{Rm} (here the maximum current value):

$$I_{xS} = \frac{\Psi_{WN}}{M} \qquad I_{yS} = \sqrt{I_{Rm}^2 - I_{xS}^2} \tag{1}$$

where M is the mutual inductance of the equivalent two-phase system. The field oriented method causes the very simple formula for the current I_{xS} because the rotor current I_{xW} is equal to zero (the current I_{xS} has the magnetizing function). In this phase of the starting, the electromagnetic motor torque T is constant and can be calculated as follows:

$$T = \frac{3}{2} p \frac{M}{L_W} \Psi_{WN} I_{yS} \tag{2}$$

where p is the pole-pair number, L_W – the rotor inductance of the equivalent two-phase system. The tractive force F_p is:

$$F_p = \frac{n_S(T - T_m) z \eta_p}{r} \tag{3}$$

where n_S is the number of motors, T_m – the torque connected with the motor mechanical losses, z – transmission ratio, η_p – the gear efficiency, r – the driving wheel radius.

The electrical angular slip speed ω_r (difference between the synchronous speed ω_1 and rotor speed ω) is the following:

$$\omega_r = \frac{2R_W T}{3p\Psi_{WN}^2} \tag{4}$$

where R_W is the rotor resistance.

Typical motion equation is given in the classical literature [2].

Between the electrical angular speed ω of motors and the tram velocity v there is the following relation:

$$\omega = c \cdot v \qquad c = \frac{p \cdot z}{r} \tag{5}$$

The longitudinal component U_x and the transverse component U_y of the supply voltage can be calculated as a function of the vehicle speed v:

$$U_x = \Psi_{WN}\left[\frac{R_S}{M} - \frac{(c \cdot v + \omega_r)\cdot \omega_r}{R_W \cdot M \cdot \lambda}\right] \tag{6}$$

$$U_y = \Psi_{WN}\left[(c \cdot v + \omega_r)\cdot \frac{L_S}{M} + \frac{R_S \cdot L_W \cdot \omega_r}{R_W \cdot M}\right] \tag{7}$$

$$\lambda = (L_S \cdot L_W - M^2)^{-1} \tag{8}$$

where R_S is the stator resistance, L_S - the stator inductance of the equivalent two-phase system.

Additionally the core loss ΔP_{Fe} is included and the input active power P_1 of the motor can be calculated as follows:

$$P_1 = \frac{3}{2}(U_x \cdot I_{xS} + U_y \cdot I_{yS}) + \Delta P_{Fe} \tag{9}$$

For optimization of the tram energy use, the input motor energy must be determined by integration of the active power P_1. The core loss ΔP_{Fe} consists of the hysteresis loss ΔP_{Feh} and the eddy-current loss ΔP_{Few}. For induction motors it is assumed that the main magnetic circuit is linear and two components of the core loss are the following:

$$\Delta P_{Feh} = \Delta P_{FehN} \cdot \frac{\omega_1}{\omega_{1N}} \cdot \left(\frac{I_{xS}}{I_{\mu SN}}\right)^2 \tag{10}$$

$$\Delta P_{Few} = \Delta P_{FewN} \cdot \left(\frac{\omega_1}{\omega_{1N}}\right)^2 \cdot \left(\frac{I_{xS}}{I_{\mu SN}}\right)^2 \tag{11}$$

where ΔP_{FehN} , ΔP_{FewN} are suitably the rated hysteresis loss and the rated eddy-current loss; $I_{\mu SN}$ is the maximum value of the magnetizing stator current at the nominal motor operation. In the first part of the starting, the magnetizing component of the current I_{xS} is equal the nominal value $I_{\mu SN}$ and the formulae become simplified:

$$\Delta P_{Feh} = \Delta P_{FehN} \cdot \frac{\omega_1}{\omega_{1N}} \tag{12}$$

$$\Delta P_{Few} = \Delta P_{FewN} \cdot \left(\frac{\omega_1}{\omega_{1N}}\right)^2 \tag{13}$$

Initially it is necessary to calculate the last tram speed V_k when the increasing supply voltage is nominal (U_N). For the nominal maximum voltage U_{mN} there are the formulae:

$$U_{mN} = \sqrt{U_{xN}^2 + U_{yN}^2} \qquad U_{mN} = \sqrt{2} \cdot U_N \tag{14}$$

The value of the last speed can be found by solving the equation with one unknown V_k:

$$U_{mN} = \Psi_{WN}\sqrt{[f_1(V_k)]^2 + [f_2(V_k)]^2} \tag{15}$$

where

$$f_1(V_k) = \frac{R_S}{M} - \frac{(c \cdot V_k + \omega_r)\cdot \omega_r}{R_W \cdot M \cdot \lambda} \qquad 16)$$

$$f_2(V_k) = (c \cdot V_k + \omega_r)\cdot \frac{L_S}{M} + \frac{R_S \cdot L_W \cdot \omega_r}{R_W \cdot M} \tag{17}$$

Equations describing second starting part

In the second part of the starting, the voltage supplying the traction motors has the constant value equal to the rated voltage U_N. In general, enlargement of the vehicle speed during the starting is realized by increase of the frequency of inverter systems. The forced, constant value of the voltage and simultaneous increase of the frequency cause process of weakening of the magnetic flux of the traction induction motor. It is assumed that the control systems maintain here the given large effective value I_R of the starting motor current. For the vehicle speed v, and suitably for the electrical angular slip speed ω_r, the following equation with one unknown ω_r ought to be solved:

$$\left(\frac{U_{mN}}{I_{Rm}}\right)^2 = M^2 \frac{[g_1(\omega_r)]^2 + [g_2(\omega_r)]^2}{g_3(\omega_r)} \tag{18}$$

where
$$g_1(\omega_r) = \left[\frac{R_S}{M} - \frac{K \cdot (c \cdot v + \omega_r) \cdot \omega_r}{L_W \cdot \lambda}\right]^2 \tag{19}$$

$$g_2(\omega_r) = \left[R_S \cdot K \cdot \omega_r + \frac{L_S \cdot (c \cdot v + \omega_r)}{M}\right]^2 \tag{20}$$

$$g_3(\omega_r) = 1 + M^2 \cdot K^2 \cdot \omega_r^2 \qquad K = \frac{L_W}{M \cdot R_W} \tag{21}$$

After determination of the angular slip speed ω_r, the magnetic rotor flux is calculated:

$$\Psi_W = \frac{M \cdot I_{Rm}}{\sqrt{1 + M^2 \cdot K^2 \cdot \omega_r^2}} \tag{22}$$

With the aim of calculation of the tractive vehicle force F_p, at first the value of the electromagnetic torque T and the useful motor torque T_U must be calculated:

$$T = \frac{3p}{2R_W} \cdot \Psi_W^2 \cdot \omega_r \qquad T_U = T - T_m \tag{23}$$

$$F_p = \frac{n_S T_U z \eta_p}{r} \tag{24}$$

The components of the stator current: I_{xS}, I_{yS} and the components of the supply voltages: U_x, U_y can be determined in the following manner:

$$I_{yS} = \frac{L_W \cdot \omega_r \cdot \Psi_W}{R_W \cdot M} \qquad I_{xS} = \sqrt{I_{Rm}^2 - I_{yS}^2} \tag{25}$$

$$\omega = \frac{p \cdot z}{r} \cdot v \qquad \omega_1 = \omega + \omega_r \tag{26}$$

$$U_x = R_S \cdot I_{xS} - \frac{\omega_1 . I_{yS}}{L_W \cdot \lambda} \tag{27}$$

$$U_y = R_S \cdot I_{yS} + \omega_1 \cdot L_S \cdot I_{xS} \tag{28}$$

In the second part of the vehicle starting, the magnetic rotor flux is changing and also the magnetizing component of the stator current I_{xS} is modifying. These relations are taken into account at calculation of input active power P_1 of the motor and additionally the complementary iron loss is included:

$$P_1 = \frac{3}{2}(U_x \cdot I_{xS} + U_y \cdot I_{yS}) + \Delta P_{Fe} \tag{29}$$

$$\Delta P_{Fe} = \Delta P_{Feh} + \Delta P_{Few} \tag{30}$$

$$\Delta P_{Feh} = \Delta P_{FehN} \cdot \frac{\omega_1}{\omega_{1N}} \cdot \left(\frac{I_{xS}}{I_{\mu SN}}\right)^2 \tag{31}$$

$$\Delta P_{Few} = \Delta P_{FewN} \cdot \left(\frac{\omega_1}{\omega_{1N}}\right)^2 \cdot \left(\frac{I_{xS}}{I_{\mu SN}}\right)^2 \tag{32}$$

Motor equations at constant tram speed in a steady state

During the tram running with the constant speed, driving motors operate in the steady state and under small load. For induction motors diminution of the voltage can cause the greater value of the power factor cosφ and larger motor efficiency η. For this stage of tram ride there are completely different run conditions in comparison with the first and second part of the starting. Within the starting the tractive force F_p is considerably larger than motion resistances *W (v)* and the vehicle speed is quickly increasing. During the running with the constant speed, the tractive force F_p and the motion resistances *W(v)* are the same. For these conditions theoretically there are many variants for values of the supply voltage, the frequency and the magnetic flux with the identical tractive force for the same tram speed *v*. Within the optimization, the best parameters of the supply system ought to be chosen to ensure the maximum of the motor efficiency.

For the speed *v* motion resistances *W(v)* are given in literature, e.g. [2]. The force F_p and resistances *W(v)* are the same and useful torque T_U and electromagnetic torque T are:

$$T_U = \frac{F_p \cdot r}{n_S \cdot z \cdot \eta_p} \qquad T = T_U + T_m \tag{33}$$

For the system of field oriented control, succeeding values of the rotor flux Ψ_W are assumed; with the help of the optimization process, the frequency and the value of the supply voltage can be found according to the criterion of the motor efficiency maximum. For the given flux Ψ_W and the vehicle speed v, the following quantities are calculated: the slip speed $ů_r$, the electrical angular motor speed $ů$ and the electrical synchronous speed $ů_1$. Next the components of the stator currents: I_{xS}, I_{yS} are determined by the formulae:

$$\omega_r = \frac{T}{K_3 \cdot \Psi_W^2} \qquad K_3 = \frac{3p}{2R_W} \tag{34}$$

$$\omega = \frac{v \cdot p \cdot z}{r} \qquad \omega_1 = \omega + \omega_r \qquad I_{xS} = \frac{\Psi_W}{M} \tag{35}$$

$$I_{yS} = K_2 \cdot \omega_r \cdot \Psi_W \qquad K_2 = \frac{L_W}{R_W M} \tag{36}$$

The components of the supply voltages: U_x, U_y are:

$$U_x = \frac{R_S \cdot \Psi_W}{M} - \frac{K_2 \cdot \omega_r \cdot \omega_1 \cdot \Psi_W}{L_W \cdot \lambda} \tag{37}$$

$$U_y = R_S \cdot K_2 \cdot \omega_r \cdot \Psi_W + \frac{\omega_1 \cdot L_S \cdot \Psi_W}{M} \tag{38}$$

The input active power P_1 of the induction motor, the output mechanical useful power P_2 and the motor efficiency η are:

$$P_1 = \frac{3}{2}(U_x \cdot I_{xS} + U_y \cdot I_{yS}) + \Delta P_{Fe} \tag{39}$$

$$\Delta P_{Fe} = \Delta P_{Feh} + \Delta P_{Few} \tag{40}$$

$$\Delta P_{Feh} = \Delta P_{FehN} \cdot \frac{\omega_1}{\omega_{1N}} \cdot \left(\frac{I_{xS}}{I_{\mu SN}}\right)^2 \tag{41}$$

$$\Delta P_{Few} = \Delta P_{FewN} \cdot \left(\frac{\omega_1}{\omega_{1N}}\right)^2 \cdot \left(\frac{I_{xS}}{I_{\mu SN}}\right)^2 \tag{42}$$

$$P_2 = \frac{\omega \cdot T_U}{p} \qquad \eta = \frac{P_2}{P_1} \cdot 100\% \tag{43}$$

Tram ride at traffic disturbances

A generalized variant of the tram vehicle ride between two neighbouring stops takes into account the possibility of many traffic disturbances which can be both unexpected and planned. As a result of perturbations, the tram ride can contain many cycles consisting of the starting, the running with the constant speed, the coasting and the braking. Some cycles can have only some of above ride phases. Because of traffic disturbances, the algorithm of the energy saving control must be constantly updated. Application of the computer makes possible forecasting of the subsequent energy saving vehicle run. Sometimes liquidation of the tram delay in relation to the time-table requires the quicker vehicle ride for next traffic segments.

Within problems of the minimum energy use, the author of this paper has elaborated generalization of the optimization procedure by taking any number K of different parts of the segment into account. Individual parts between tram stops have numbers: 1, 2, …, j,…, K. For the part with the number j, by $ns(j)$ there is denoted the number of start ups, the number of runs with the constant speed has the notation $ncs(j)$, $nc(j)$ is the number of coasting phases, $nb(j)$ – the number of braking stages. $T(j)$ is the ride time in the part j (without time connected with unexpected internal stop), $L(j)$ – the length of this part. The following relations are fulfilled:

$$\sum_{i=1}^{ns(1)} Ts_i + \sum_{i=1}^{ncs(1)} Tcs_i + \sum_{i=1}^{nc(1)} Tc_i + \sum_{i=1}^{nb(1)} Tb_i = T(1) \tag{44}$$

$$\sum_{i=1}^{ns(1)} Ls_i + \sum_{i=1}^{ncs(1)} Lcs_i + \sum_{i=1}^{nc(1)} Lc_i + \sum_{i=1}^{nb(1)} Lb_i = L(1) \tag{45}$$

$$\sum_{i=1}^{ns(2)} Ts_i + \sum_{i=1}^{ncs(2)} Tcs_i + \sum_{i=1}^{nc(2)} Tc_i + \sum_{i=1}^{nb(2)} Tb_i = T(2) \tag{46}$$

$$\sum_{i=1}^{ns(2)} Ls_i + \sum_{i=1}^{ncs(2)} Lcs_i + \sum_{i=1}^{nc(2)} Lc_i + \sum_{i=1}^{nb(2)} Lb_i = L(2) \tag{47}$$

$$\sum_{i=1}^{ns(j)} Ts_i + \sum_{i=1}^{ncs(j)} Tcs_i + \sum_{i=1}^{nc(j)} Tc_i + \sum_{i=1}^{nb(j)} Tb_i = T(j) \tag{48}$$

$$\sum_{i=1}^{ns(j)} Ls_i + \sum_{i=1}^{ncs(j)} Lcs_i + \sum_{i=1}^{nc(j)} Lc_i + \sum_{i=1}^{nb(j)} Lb_i = L(j) \tag{49}$$

$$\sum_{i=1}^{ns(K)} Ts_i + \sum_{i=1}^{ncs(K)} Tcs_i + \sum_{i=1}^{nc(K)} Tc_i + \sum_{i=1}^{nb(K)} Tb_i = T(K) \tag{50}$$

$$\sum_{i=1}^{ns(K)} Ls_i + \sum_{i=1}^{ncs(K)} Lcs_i + \sum_{i=1}^{nc(K)} Lc_i + \sum_{i=1}^{nb(K)} Lb_i = L(K) \tag{51}$$

$$Ts_i \geq 0 \qquad Ls_i \geq 0 \qquad Tcs_i \geq 0 \qquad Lcs_i \geq 0 \tag{52}$$

$$Tc_i \geq 0 \qquad Lc_i \geq 0 \qquad Tb_i \geq 0 \qquad Lb_i \geq 0 \tag{53}$$

$$T(1) + T(2) + \cdots + T(j) + \cdots + T(K) = T \tag{54}$$

$$L(1) + L(2) + \cdots + L(j) + \cdots + L(K) = L \tag{55}$$

where T is the total ride time in the segment consisting of K component parts (without time connected with unplanned internal stops), L is the total segment length.

Examples of simulation results

Exemplary calculations have been done for the modernized tram of the type 105N. Vehicle modernization was connected with application of inverters supplying vectorially controlled and field oriented three-phase squirrel-cage induction motors. The tram has four identical driving electrical motors of the total power 160 kW.

The nominal tram vehicle data are the following:

the voltage of the traction DC network: 600 V, total vehicle length: 13.5 m, tare tram mass: 16500 kg, nominal load: 8750 kg, rolling diameter of the wheel: 0.654 m, transmission ratio: 7.16, the maximum allowed speed: 72km/h.

The rated data of the driving 3-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,ó.8%, cosφ: 0.931.

Because of the limited place, only the chosen examples of simulation results are given in this paper. For all examples, the distance L between two succeeding tram stops is equal to 950 m and the total traffic time T_t is 95 s (the average speed is 10 m/s). The shown results deal with the example when the tram mass is 22000 kg; it means that the passengers number is equal 80 (64% in relation to the nominal tram load).

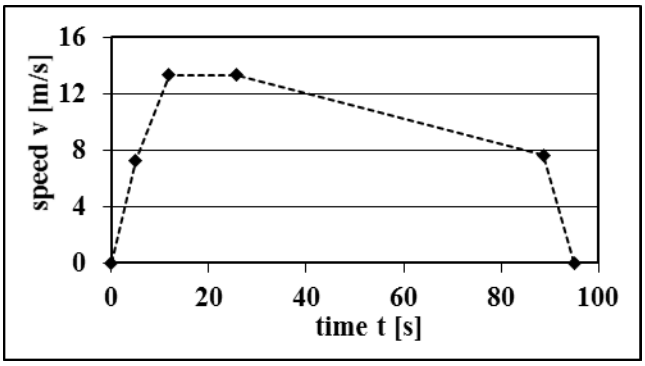

Fig. 1 – Tram ride without traffic disturbances at minimum energy use En = 1.064 kWh; the recuperation factor kr = 0

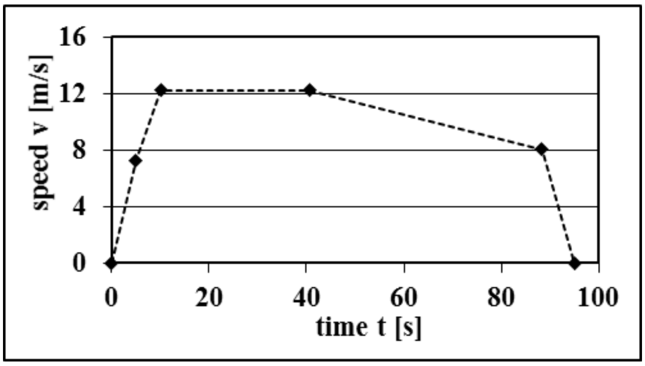

Fig. 2 – Tram ride without traffic disturbances at minimum energy use En = 0.903 kWh; the recuperation factor kr = 1

Fig. 1, 2 refer to the tram ride without traffic disturbances. For further analysis of the tram run with traffic perturbations, valuation of influence of ride disturbances on the energy use will be possible. The factor kr informs what energy part is recuperated during the vehicle braking.

For the case when energy recuperation doesn't exist (kr = 0), Fig. 1 illustrates the vehicle ride with the minimum energy use equal $Enmin$ = 1.064 kWh; this figure shows values of boundary velocities (diagram points) for the succeeding ride phases. The optimization process has realized minimization of the energy use by the best determination of the duration of the starting, the running with the constant speed, the coasting and the braking. The graph in Fig. 1 possesses the phase of the run with the constant speed and the coasting.

For the variant when energy recuperation occurs during braking and the factor kr = 1, Fig. 2 presents the tram ride realized in the best possible manner (the minimum energy use $Enmin$ = 0.903 kWh). It is the interesting property that here the phase with the vehicle running with the constant velocity is longer than in Fig. 1 relating to the case for the coefficient kr = 0.

Fig. 3, 4 present the example when traffic unexpected perturbations occur. Disturbances have forced the tram driver to be under the necessity to make an additional, internal stop of the vehicle. This unplanned stop has divided the ride into two parts (two cycles containing the starting with the initial speed equal to zero and the braking finishing at the velocity v = 0). The unexpected stop of 5s followed after the distance of 300 m. In Fig. 3 the recuperation factor kr =0 however in Fig. 4 full recuperation exists and kr = 1.

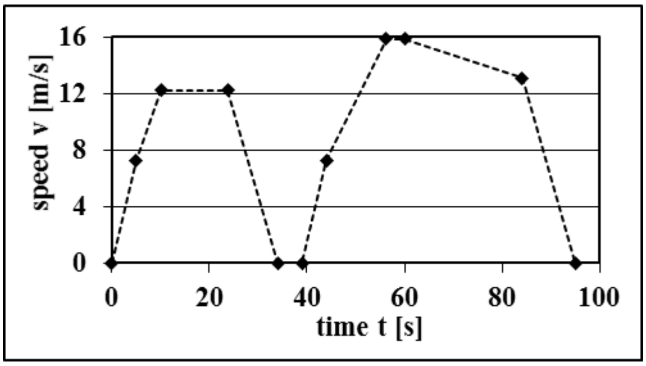

Fig. 3 – Tram ride with unplanned internal stop of 5 s at minimum energy use En = 2.280 kWh; the recuperation factor kr = 0

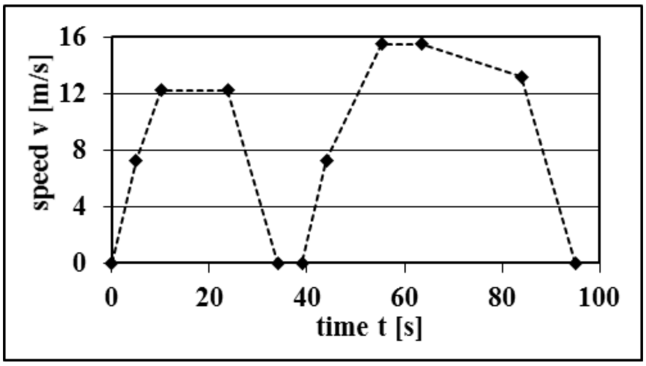

Fig. 4 – Tram ride with unplanned internal stop of 5 s at minimum energy use En = 1.435 kWh; the recuperation factor kr = 1

At the beginning the tram ride was realized in accordance with the algorithm of the energy saving traffic free from disturbances. After time 10.17 s and the distance 70.11 m (the tram was still in the starting phase), the driver has noticed a certain perturbation (e.g. it could be influence of light signalling) and first he has decided the tram running with the constant speed v = 12.26 m/s during 13.65 s. Afterwards – in keeping with driver's decision – there was vehicle braking and the stop of 5 s in the point 300 m from the start. Owing to the quicker ride in the second segment part (within the second run cycle), the liquidation of tram delay was possible already in the end of this segment. It required the quicker run and caused enlargement of energy use. The ride in the first cycle (part I) is the same in Fig. 3 and 4 because here the run manner was fully realized by the driver (in the dangerous run part his decisions were not aided by a vehicle computer).

In the part I of the segment, parameters of particular ride phases are the following:

a) starting:
- covered distance: s = 70.11 m,
- ride time: t = 10.17 s,
- initial speed of the stage: v = 0 m/s,
- terminal speed of the stage: v = 12.26 m/s,
- consumed electrical energy En = 0.752 kWh;

b) running with the constant speed:
- covered distance: s = 167.3 m,
- ride time: t = 13.65 s,
- initial speed of the stage: v = 12.26 m/s,
- terminal speed of the stage: v = 12.26 m/s,
- consumed electrical energy En = 0.145 kWh;

c) braking:
- covered distance: s = 62.61 m,
- ride time: t = 10.18 s,
- initial speed of the stage: v = 12.26 m/s,
- terminal speed of the stage: v = 0 m/s,
- recuperated electrical energy: En = 0 (for kr = 0) and En = 0.395 kWh (for kr = 1).

On the other hand for the part II in Fig. 3, 4, algorithms of the ride in agreement with the requirement of minimum energy use are different. After optimization procedure for the factor kr = 0 (Fig. 3), the total electrical energy consumption for whole segment (the sum of parts I and II) is equal $Enmin$ = 2.280 kWh. In the part II in Fig. 3, parameters of the individual ride stages are:

a) starting:
- covered distance: s = 170.5 m,
- ride time: t = 17.22 s,
- initial speed of the stage: v = 0 m/s,
- terminal speed of the stage: v = 15.86 m/s,
- consumed electrical energy En = 1.318 kWh;

b) running with the constant speed:
- covered distance: s = 60.08 m,
- ride time: t = 3.79 s,
- initial speed of the stage: v = 15.86 m/s,
- terminal speed of the stage: v = 15.86 m/s,
- consumed electrical energy En = 0.065 kWh;

c) coasting:
- covered distance: s = 347.2 m,
- ride time: t = 24.05 s,
- initial speed of the stage: v = 15.86 m/s,
- terminal speed of the stage: v = 13.09 m/s;

d) braking:
- covered distance: s = 72.29 m,
- ride time: t = 10.95 s,
- initial speed of the stage: v = 13.09 m/s,
- terminal speed of the stage: v = 0 m/s,
- recuperated electrical energy: En = 0 (kr = 0).

After energy minimization process for the recuperation factor kr = 1 (Fig. 4), the total energy use for whole segment (part I and part II) is equal $Enmin$ = 1.435 kWh. In the part II in Fig. 4, parameters of the particular ride phases are:

a) starting:
- covered distance: s = 156.6 m,
- ride time: t = 16.34 s,
- initial speed of the stage: v = 0 m/s,
- terminal speed of the stage: v = 15.52 m/s,
- consumed electrical energy En = 1.252 kWh;

b) running with the constant speed:
- covered distance: s = 128.0 m,
- ride time: t = 8.25 s,
- initial speed of the stage: v = 15.52 m/s,
- terminal speed of the stage: v = 15.52 m/s,
- consumed electrical energy En = 0.135 kWh;

c) coasting:
- covered distance: s = 291.9 m,
- ride time: t = 20.38 s,
- initial speed of the stage: v = 15.52 m/s,
- terminal speed of the stage: v = 13.18 m/s;

d) braking:
- covered distance: s = 73.48 m,
- ride time: t = 11.04 s,
- initial speed of the stage: v = 13.18 m/s,
- terminal speed of the stage: v = 0 m/s,
- recuperated electrical energy: En = 0.455 kWh (kr = 1).

In Fig. 3, 4 the unplanned internal stop of 5s forces the repeated energy-consuming vehicle starting. Additionally, in order to attain liquidation of traffic delay, the ride with the quicker speed is necessary and it causes the greater energy use. At the factor kr = 0 for the case with unplanned stay (Fig. 3), the energy consumption is greater by 114.3% in comparison with the tram ride without disturbances (Fig. 1). If the energy recuperation (kr = 1) during braking exists (Fig.4) the energy use is by 58.9% greater than for the traffic without perturbations (Fig. 2). Diminution of the energy use is here possible if a part of time lag will be liquided within the ride in the next segment.

Conclusions

For vectorially controlled and field oriented three-phase induction motors supplied from modern inverter systems, the author has elaborated new software determining the vehicle tram ride with the minimum energy use.

Within the new possibilities, traffic disturbances can be taken into account, e.g. the total and local, planned or unplanned speed limitations, intentional or unexpected stops, changes of a size of the energy recuperation during the vehicle braking.

The optimization of duration of the typical tram ride stages: the starting, the running with the constant speed, the coasting and the braking can decrease the energy consumption.

For traction three-phase squirrel-cage induction motors, it is interesting that the algorithm of energy saving tram traffic possesses both the phase of the vehicle running with the constant speed and the stage of the coasting.

Because of traffic perturbations, the tram ride can contain many cycles consisting of the starting, the running with the constant speed, the coasting and the braking. Some cycles can have only some of the above ride phases. The algorithm of the energy saving control must be constantly updated. Application of a computer makes possible forecasting of the subsequent energy saving ride with minimum energy use.

Elaborated algorithms of the tram ride at minimum energy use make possible to save about 20% energy in comparison with the ride basing only on subjective decisions of a driver.

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