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Tram Simulation Model for Energy Balance Analyses

Lukáš Hubka, Petr Školník
Faculty of Mechatronics, Informatics and Interdisciplinary Studies
Technical University of Liberec
Liberec, Czech Republic
{lukas.hubka, petr.skolnik}@tul.cz

***Abstract*—This paper describes a mathematical model of a tramcar which allows to simulate traffic on any tram track and allows to analyze energetic balance on the electrical power link without real energetic data measurement. The described mathematical model could be a useful tool for the design of an energy recovery system for a real tram track. A short description of the tram track model in the city of Liberec is presented together with the mathematical model of the tramcar type T3.PLF that operates on mentioned track. The model simulation results are confronted with data measured during the real tram operation.**

Keywords—tram, model, energetic balance

I. Introduction

The increasing integration of regenerative energetic sources into electrical distribution nets calls for new methods of energetic management and reasonable improvement of system components energetic efficiency. The decentralized solution to store energy is becoming increasingly important for lack of big accumulators in electrical nets. The decentralized solution can be constructed from sources, appliances and energy storages.

One of the interesting methods is the utilization of an appliance as an energy source in predefined operation situation. Such an idea leads to remarkable minimizations of lost in an intelligent electrical net. Electrical drives become a relevant candidate for such a purpose because they are able to recuperate the braking energy back to the net. To take advantage of this concept requires using of modern concept for the energetic flow control and the electrical energy storing.

This paper is focused on the tramcar and the tram trolley net connected with electrical energy storage system. Nowadays all modern trams have to have some system to recuperate the braking energy. The old concept of wasting the braking energy in resistors is only a security solution in the case the recuperation cannot be realized. On the other hand, the utilization of this energy is still an open question because there does not exist the certainty to use this energy effectively. The storage system can be generally oriented directly to the tram as a decentralized mobile solution [1, 2] for the trolley net system or can concentrate all electrical energy flows to centralized solution inside the substation on the primary or on the secondary side of AC/DC converter [3]. Both solutions have pros and cons and different preferable hardware to realize the storage system. The mobile solution should be nowadays focused on capacitors. The centralized solution has more possibilities. In this frame, the flywheel application seems to be one of the attractive realizations [4, 5, 6]. The flywheel electrical accumulation storage fulfills all operation requirements correctly and moreover, the flywheel electrical energy storage is fully ecological. The braking kinetic energy storage based on the flywheel should contribute to the overall efficiency in the electrical energy management and besides other things decrease the oscillation on the primary current during the standard operation. In order to study positive or negative effects of the electrical energy storage based on the flywheel or on capacitors, it is necessary to find the right simulation model.

This paper tries to focus on one possible configuration of the electrical energy storage system and creates a background for the analysis. The simulation is a standard tool to do serious analysis and models of all technological parts have to be defined. This paper focuses on the tram simulation model which should be able to integrate information about the actual track type, the drive regime and trolley supply net situation with an answer to the question of electrical energy flow during time.

At first, the real object is introduced. The real object is represented by the tram and the line. Next, the mathematical model of the tram is presented. The model design is based on the mathematical-physical analysis of the tram and is focused on the electrical energy flows between the tram and the trolley net. The model is designed as a group of submodules and the structure of the model is shown. The developed model was verified by data obtained by measuring in a real operation. After that, the flywheel storage system is introduced and the simulation model is presented. The last part focuses on the simulation results and comparison with the real operation. The possible operation regimes of the storage system are discussed, too.

II. The Tram and The Line Descriptions

The simulation model of the tramcar type T3 is described in this paper. The T3 tram was produced from the beginning of 60's to the end of 90's in the Czechoslovakia. The overall production reaches 14000 pieces and becomes the most produced car in the world.

Every tram carriage has two undercarriages. Every undercarriage contains two driven axles and is driven by the traction electrical motor with serial exciting. There are 2 DC motors, every on 300 V with power 40 kW. Most tramcars went through modernization process and from the resistor control they were rebuilt to the modern transistor (IGBT) control.

As was mentioned above the main reason for tram model creation is to analyze the installation's possibility of the energy recovery system in Liberec. The main internal city tram track from the station Lidove sady to the station Horni Hanychov was chosen because of its altitude profile (see Fig. 1) with long inclinations and declinations and an intensive workload during a whole day.

The model (description) of the track and its precision are important attributes for the correct behavior of the tram simulation model and for the ability to obtain the correct data for further analysis. Because the elevation of the track at defined time or place is the main part of the track model, it was necessary to have information about the elevation, respectively the altitude, with precision high enough.

The first tram track model was obtained directly from GPS data recorded during the standard travel with the real tram. However, this measurement method was unsuitable because the data are highly imprecise. These inaccuracies are caused by the weak signals from the GPS satellites, which are caused by buildings in high-density urban areas, as well as limitations of the used GPS hardware. These circumstances led to data with high noise altitude. Because of these significant inaccuracies, the final tram track model was corrected using the free available Google Maps JavaScript API [7]. This tool allows the determination of the altitude at a defined position based on the Google maps. The model data, which include more than 800 points, were obtained by this procedure and were used to create a model with an acceptable precision.

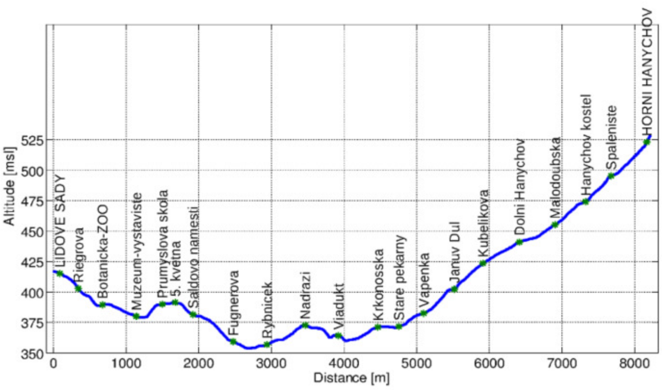

Fig. 1. The altitude profile of the tram track in Liberec.

III. The Tram Simulation Model

A. General Overview

The mathematical model of the tram was assembled to obtain the energy balance data during the operation of one tram or of their group on the defined track without a requirement to measurement or any special experiment in a real traffic system. Experiments with the model could be used for basic analyses of the energy flows in the traction net and obtained data are useful for the electrical storage system sizing.

The inputs for the model are the line voltage, the timetable of the tram or the position of the tram defined in time and the information about actual altitude profile from the track model. The main outputs are the speed or the position of the tram, the consumed power, and the line current. The whole model could be split into two main parts: the mechanical part, and the electrical part. The overall structure of the tram simulation model is in Fig. 2.

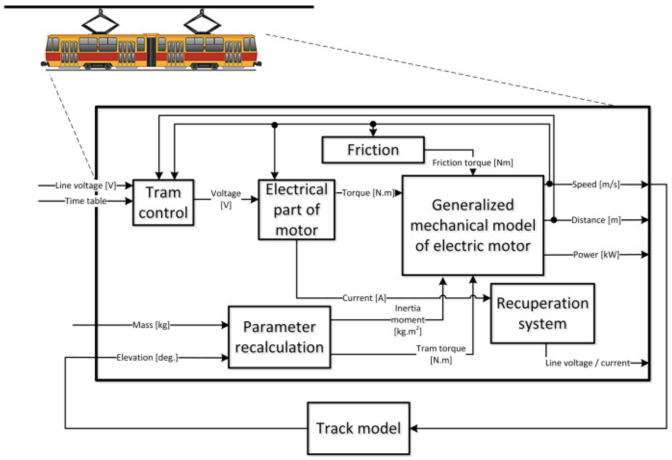

Fig. 2. The structure of the tram model.

B. Mechanical Part

The mechanical part of the tram model describes its motion dynamic, which depends on a driving torque, the tram mass and the elevation of the tram track. The behavior of the tram is described via following equations

$$J \cdot \dot{\omega}_M = M_M - M_O - M_T \tag{1}$$

$$J = J_M + J_{Tram} \tag{2}$$

$$J_{Tram} = m \cdot p^2 \cdot r^2 \tag{3}$$

$$M_T = m \cdot g \cdot \sin(\beta) \cdot r \cdot p \tag{4}$$

where J is an inertia moment of the whole tram and is given by the summation of an inertia moment of the tram engine J_M and the tramcar body J_{Tram}. The tramcar body inertia moment depends on the gear ratio of the tram transmission p, the mass of tram m and the radius of tram wheel r. The ω_M is the rotation speed of an electrical motor, M_M is a driving torque of the motor and it represents the output of the electrical part of the model. M_O is a friction torque and it is given by a friction of bearings, an air, and a rolling resistance, etc. Finally, M_T is defined as a mechanical moment, which depends on the elevation β of the tram track.

C. Electrical Part

The electrical part of the tram model describes the dynamic behavior of the universal electromotor, which is a source of kinematic energy in the tram T3. The dynamic behavior of the electrical motor is described by following differential equations

$$U = U_i + U_a + U_f \quad (5)$$

$$U_i = L_{af} \cdot \omega_M \cdot I \quad (6)$$

$$U_a = R_a \cdot I + L_{aa} \cdot \dot{I} \quad (7)$$

$$U_f = R_f \cdot I + L_{ff} \cdot \dot{I} \quad (8)$$

$$M = L_{af} \cdot I^2 \quad (9)$$

$$U_T = U_N - R_N \cdot I \quad (10)$$

where U is a supply voltage of the electrical motor and is defined as a summation of the excitation voltage U_f, the armature voltage U_a and the back EMF U_i. I is the excitation or the armature current, R_a is the resistance of the stator, R_f is the resistance of the rotor, L_{aa} is a self-inductance of the stator, L_{ff} is a self-inductance of the rotor and L_{af} is the mutual inductance. The effect of distance from the converter station to the tramcar is defined by (10) equation where U_T is the trolley voltage at the tramcar location, U_N is output voltage from the converter station, R_N is an electrical trolley resistance which is the function of the tram location.

The integral part of the electrical model is a tram control system, too. The tram control system is designed to substitute a tram driver and its main role is to adjust the drive torque by supply voltage changing. The main task of the system is to track the desired position of the tram on the tram track. The desired position can be calculated directly from the timetable and an expected traffic situation.

IV. The Flywheel Storage

A. *The Recuperation on The Line*

The electrical energy storage system has to have some positive effect to integrate into the trolley supply system [8]. At first, a specific real operation test was done on the line [9]. Only one tram equipped with measurement system realized the track on the line. This test brought detailed information about consumption and recuperation (see Fig. 3). The bar graph in Fig. 3 presents an electrical energy balance sequence of consumption and recovery cycles, that was obtain during the tram track passing. There exists a permanent consumption 1.25 kW to cover the traction electric drives cooling, the internal and external lighting, etc. In winter the heating of the salon adds another 12-14 kW.

The measurement gave the result for recuperation. The consumption for one track on the line between end stations is about 3.45 kWh and the recuperated energy for possible storing and reusing is about 0.83 kWh in winter. The recuperation is floating about 18-25 % and there is an assumption that in summer the ratio should be more favorable for the recuperation. The overall consumption and the recuperation ratio are highly dependent on the tram driver style [10].

B. *The Simulation Model*

The simplified simulation model of a flywheel with an electrical drive is described by following equations

$$P_K = M_K \cdot \omega_K \ , \quad (11)$$

$$P_K = U_N \cdot I \cdot \eta(\omega_K), \quad (12)$$

$$J_K \cdot \dot{\omega}_K = M_K \ , \quad (13)$$

where J_K is an inertia moment of the flywheel, ω_K is a rotation speed of the flywheel, M_K is a dry torque and η is an efficiency of the flywheel electrical drive or rather of the flywheel electrical generator which changes electrical energy into mechanical energy of the flywheel or in reverse order and it is function of its rotation speed.

V. Simulation Experiments

A. *Model Verification*

The described model of the tram was verified with fitted parameters. Some parameter values of the mathematical model were obtained from the technical documentation of the tram and the track. Parameters that could not be obtained from the technical documentation were obtained by a sequential structure optimization of the model and its parameters according to the measured data. The verification experiment was based on the measured data, which were obtained during the test run on the tram track in Liberec. The result from the verification experiment is shown in Fig. 4. It can be seen that the simulation model achieves a relatively good match with data from the real measurements.

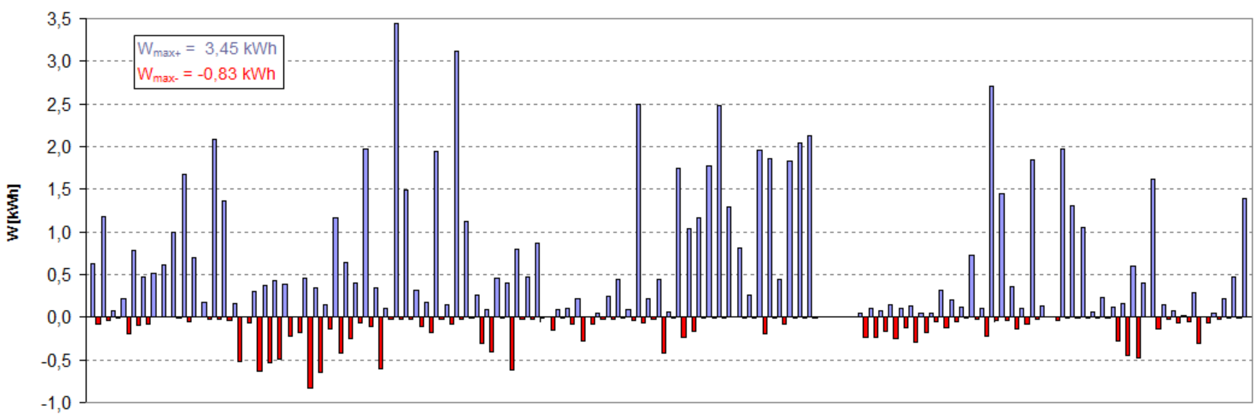

Fig. 3. The electrical energy balance for acceleration and deceleration of the tram, the heating is included.

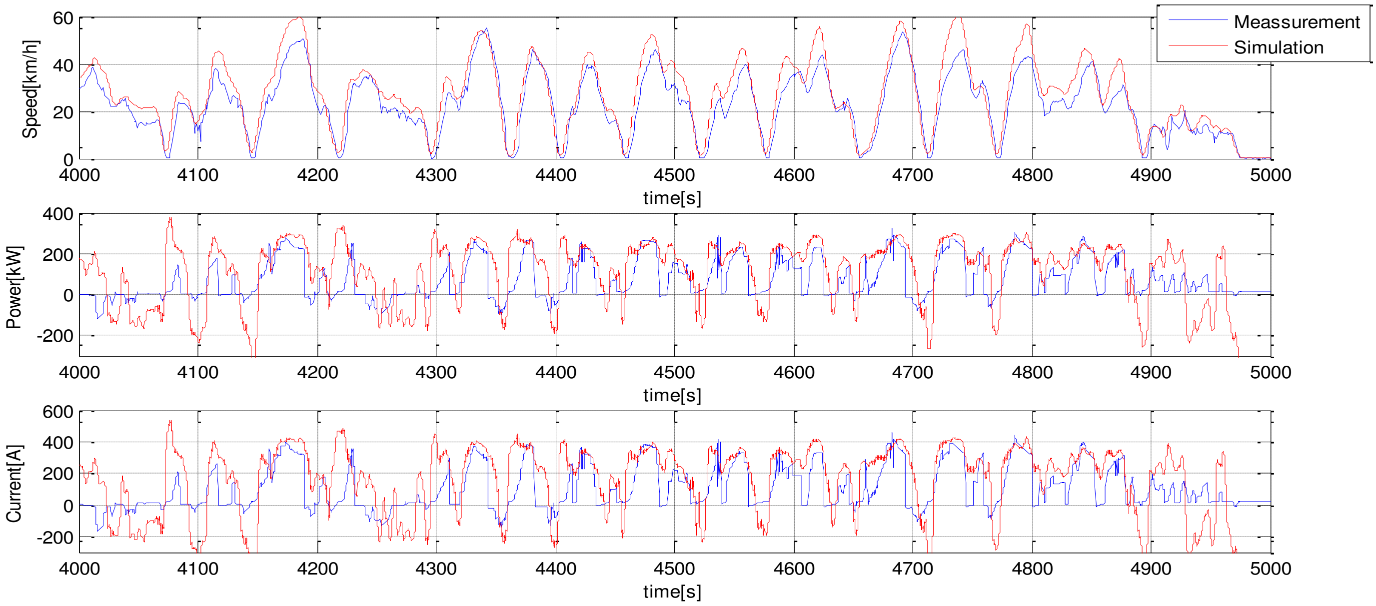

Fig. 4. Model verification.

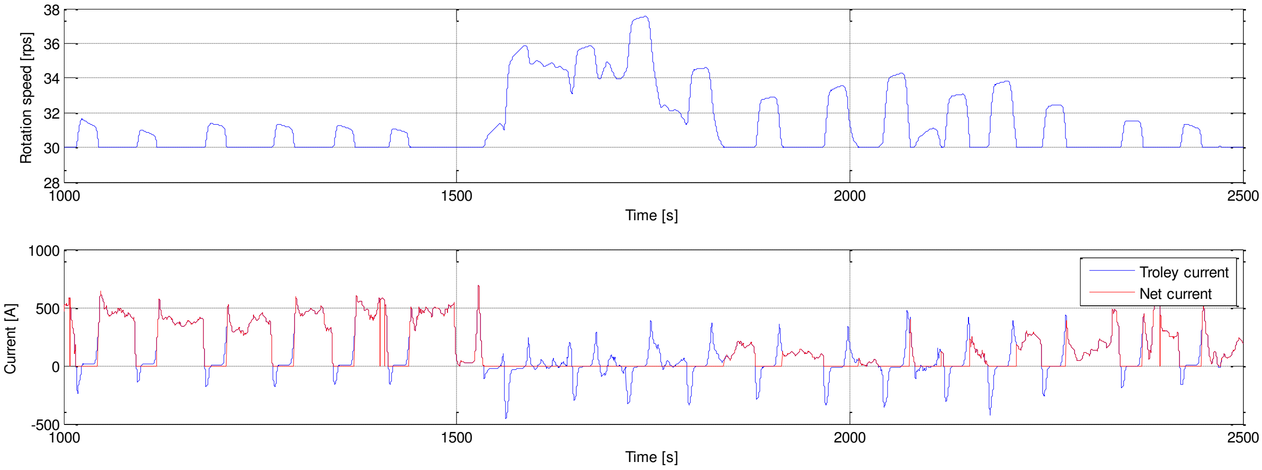

Fig. 5. Simulation experiment for the storage mode of the recovery system.

B. Recovery System Simulations

The whole model which consists of the tramcar model, the tram track model and the flywheel storage system model was used for testing and analyzing of different approaches to the recovery system utilization. Before designing the storage system, the question about the optimal operation regime and maximization of benefits has to be answered. The storage system has only one chance to store the energy – during tram braking, but many different options to support the trolley line with the stored energy. Mainly two powerful strategies were simulated and analyzed.

The first storage system operation strategy uses the recovery system to store the actual excess energy and uses it to support the trolley line as soon as it is possible. The energy storage system works as a short time storing and supporting electrical device. The result of this experiment is presented in Fig. 5. In the case of convenient conditions (descending part of the line, more trams on the line, etc.) this strategy can lower the current peaks on the trolley during acceleration and in the supply net, too. The minimal speed of flywheel was set to 30 rps to hold the optimal efficiency level of the electrical energy storage system. The simulation brought the information about utilization of the recovery system and electrical power consumed from the supply electric net in a situation when the energy recovery system is used in a storage mode.

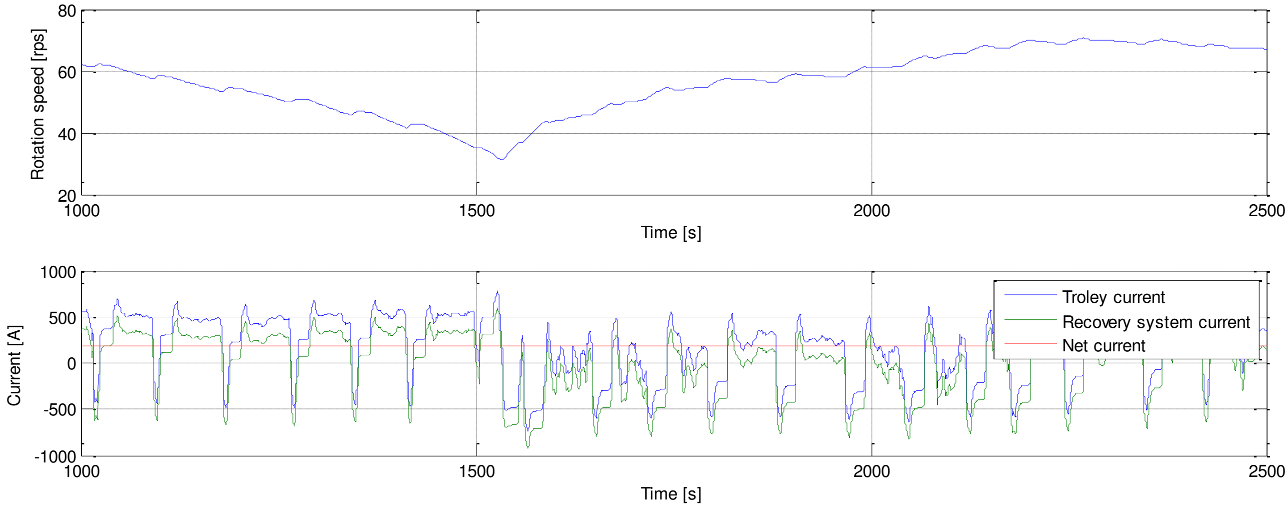

Fig. 6. Simulation experiment for the filter mode of the recovery system.

The second operation strategy discussed in this article uses the recovery system as a power filter for the supply electrical net. It means that the recovery system tries to reduce the oscillation on the electrical primary side. The current or the power peaks on the supply electrical net could have the effect of increasing electrical power price for the organization; on the other hand, the oscillation in the net generally is not welcomed by the net operator. In this case, the storage system operation regime is completely different from the first one. The efficiency is more dependent on the right setting of the storage system to be able to operate in the optimal range. Generally, this configuration leads into the cutting off current peaks in the trolley net and filling of holes in primary net during the time where any appliance is presented on the trolley. This type of the storage system utilization also needs a different electrical configuration to allow direct feed of the storage system from the primary net, which is in the first case unnecessary. The result of this experiment is presented in Fig. 6. The simulation brought the information about utilization of the recovery system and electrical power consumed from the supply electric net. It can be seen that the power consumed from the network is constant, but the right setting is very tough and the best option consists of an adaptation on the current level and a prediction of the consumption combination.

VI. Conclusion

The tram seems to be the right target to search for energy saving. Both analysis and simulations give results where the total amount of recuperated energy to store and reuse is interesting. The concept of the flywheel as electrical energy storage system is applicable to this system, but the economic benefits have to be discussed. The flywheel mass should be good to press the current peaks in the application where the flywheel mass is an advantage, for example, in the wind power plant production stabilization.

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