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ENERGETIC MACROSCOPIC REPRESENTATION APPLIED TO AN ELECTRICAL URBAN TRANSPORT SYSTEM

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Abstract: An energetic description of the electric transport urban system ASTRAIK 415T is proposed according to a specific formalism. This is used to simulate the trolleybus system, equipped with a chopper and a direct current series motor. DC series motor is still used for trolleybus and metro, driven by a GTO or IGBT chopper µC-controlled, which allows the implementation of command algorithms. From this synthetically representation a complete model of the electromechanical system was implemented using the Matlab-Simulink simulation environment. A control structure was deduced through model inversion. This will allow the study of the transient phenomena and the implementation of different command laws taking into account the minimum energy losses.

Keywords: urban system transport, transient phenomena, modeling, energetic macroscopic representation.

1. INTRODUCTION

The urban transport still represents a major problem, being generated by the motor vehicles agglomeration, which leads to traffic jam and excessive air pollution. As a consequence, it can be observed a serious development of electrical urban traction system, either for surface (buses, trolleybuses and tramways) or for underground (metro system). These are equipped with different electrical motors: direct current, synchronous and asynchronous.

The electric drive equipment with GTO thyristors and IGBT was used for trolleybuses with direct current motors in Bucharest, Brasov and Timisoara. Currently, only in Bucharest more than 120 “Astra-Ikarus” ASTRAIK-415T trolleybuses are in operation. This equipment assures that the system works with reduced energy consumption in traction mode (economy of 20-35%), depending on the distance between stations and in regenerative braking mode (economy of 5-10%) depending on the braking time and the route characteristics, too.

An electric transport urban system like the ASTRAIK 415T trolleybus has a lot of starting and stopping moments, which consumes a lot of energy through the losses developed in the direct current motor and the direct current converter. Therefore, it is quite important to develop a simulation model to study these transient regimes.

In the first part of this paper, a specific formalism is defined together with the appropriate definitions, to make the study of the electrical urban system easier.

In order to illustrate this formalism, two similar applications are presented in the second part of this paper. The first application, the energetic macro-modeling formalism based on action reaction principle is applied only for the direct current motor and the direct current converter. The second

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application is presenting the transmission system and a real electrical source for the ASTRAIK-415T system.

This second application is implemented in simulation using Matlab-Simulink program. Finally, the results are validated by the experimental values.

2. ENERGETIC MACROSCOPIC REPRESENTATION

The energetic macroscopic representation (EMR) is a specific formalism defined to represent energetic conversions between power structures (Hautier *et al.*, 2000).

The EMR is based on the action-reaction principle. As a matter of fact this formalism is a variant of the informational – causal graph (ICG) formalism developed in France (Hautier and Faucher, 1996). The EMR formalism is more global than the ICG, but sometimes certain important elements used for the system study and analysis are hidden.

In order to better understand the EMR formalism, figure no. 1 presents a mono-machine mono-converter system (Bouscayrol *et al.*, 2000a), which ensures an energy transfer between an electric source (ES) and a mechanical system (MS).

The system was decomposed into four accumulation elements $AE_{1\div4}$ (represented by a rectangle pictogram with an oblique line) and three pure conversion elements (EC, EM, MC). The accumulation elements link the sources with the conversion elements assuring an energy accumulation with possible power loss and the conversion elements assure an energy conversion without power loss or energy accumulation.

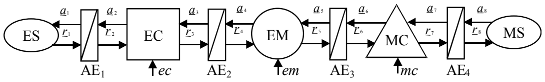

Fig.1. The energetic macroscopic representation for a mono-machine system.

The main conversion elements used in the system are the following:
- EC – the static converter (electrical element) represented by a square pictogram with *ec* the regulating variable;
- EM – the electrical motor (electromechanical conversion element) represented by a circle pictogram with *em* the regulating variable;
- MC – the mechanical converter (mechanical adaptation element) represented by a triangular pictogram with *mc* the regulating variable.

The vectors represent the exchange energetic vectors between different elements of the process based on the action ($\underline{a}_i$) reaction ($\underline{r}_i$) principle.

For the first application, the system (figure no.2) is composed from: the electrical source, the radio parasite filter, the auxiliary services, the direct current converter (with GTO thyristors) and the direct current motor.

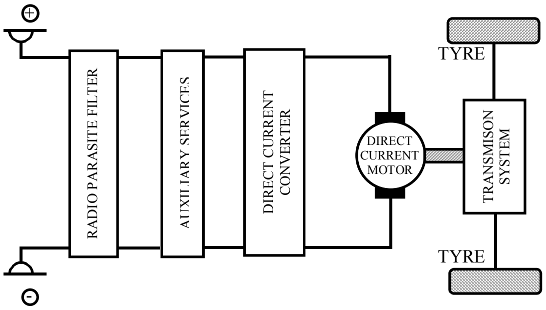

Fig.2. Synoptic of the ASTRAIK 415T trolleybus

The electrical source ES is a constant source, which provides the choppers with a DC voltage u_{DC}. A chopper is an EC, which imposes modulated voltage u_{ch} to the machine from the voltage source. It yields also the current in the source i_{ch} through the modulating function (Vulturescu *et al.*, 2001):

$$(1)\quad \begin{cases} u_{ch} = f_H \cdot u_{DC} \\ i_{ch} = f_H \cdot i \end{cases} .$$

The machine is decomposed into an electromechanical conversion element EM and two adaptations ones. Indeed, the rotor winding yields an energy accumulation (L inductance, R resistance): so its current i is a state variable. Moreover, the speed of the motor Ω is obtained by a mechanical accumulation (J inertia, f viscous coefficient).

$$(2)\quad \begin{array}{l} L\dfrac{d}{dt}i = -Ri + u_{ch} - e \\ J\dfrac{d}{dt}\Omega = -f\Omega + c - c_r \end{array} .$$

The classical internal electromechanical relations define the EM converter ($k\phi$ flux constant, e electromechanical force and c electromagnetic torque).

$$(3)\quad \begin{cases} e = k\phi \cdot \Omega \\ c = k\phi \cdot i \end{cases} .$$

The mechanical source is associated with the vehicle environment. It yields a resistive force to the motion F_{res}. The mechanical conversion of the vehicle is constituted by an accumulation element.

Determination of the studied process command law is meant to impose the desired trajectory through a regulating variable (in our case the chopper modulating function f_H). Using the inversion rules to determine the command law for an energetic macroscopic representation gives the maximum control structure (MCS). In the first step, it is assumed firstly that all variables are measurable and all perturbations are rejected directly with specific operations outside controllers. In a second step, simplifications and estimations of non-measurable variables are realized.

A conversion element can be directly inverted because it owns non-causal relations, but an accumulation element cannot be directly inverted because the energy accumulation yields a causal relation and is required an indirect inversion through a controller.

The EMR and the afferent MCS for the first application are presented in figure no. 3, where ES is the 750Vcc electrical network, VTC is the chopper, ME is the direct current series excitation motor and MS is the mechanical source. Control blocks of the MCS are depicted with rhombus pictograms. Continuous lines indicate variables used in inversion operations and dashed lines indicate perturbation rejections.

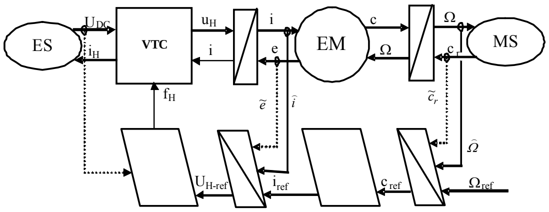

Fig.3. The energetic macroscopic representation and maximum control structure of the engine and VTC from ASTRAIK-415T system

The MCS presents two command loops with the following controller relations:

- for current loop:

$$(4)\ u_{H-ref} = C_i(i_{ref} - \hat{i}) + \tilde{e}\,;$$

- for speed loop:

$$(5)\ c_{ref} = C_v(\Omega_{ref} - \hat{\Omega}) + \tilde{c}_r\,;$$

where $\hat{i}$ and $\hat{\Omega}$ are process estimated variables and $\tilde{e}$ and $\tilde{c}_r$ are process measurable variables. In fact we have two IP (integral-proportional) correctors C_i and C_v.

The other two blocks from the MCS representation are based on the following relations:

$$(6)\ m_{ref} = \frac{u_{H-ref}}{u_{DC}}$$

$$(7)\ i_{ref} = \frac{1}{k\phi} c_{ref}$$

where u_{DC} is the measurable d.c. tension.

In the second application (figure no.2), if is taken in consideration the transmission ration $i=10.673$ from the tyre and the direct current engine introducing a new bloc in the simulation, the EMR and the MCS of the studied system is shown in figure no. 4. This new block is based on the following two relations:

- relation between the traction force F *[kgf]* and the motor torque C *[kgf*m]*:

$$(8)\ F = \frac{i \cdot \eta_n}{R_d} C = \frac{10{,}763 \cdot 0{,}9}{0{,}47} C = 20{,}44 \cdot C;\ K_{CF} = 20.44$$

- relation between the driving speed v*[m/s]* and engine angular velocity Ω*[rad/s]*:

$$(9)\ v = \frac{R_d}{i \cdot 60} \Omega = 0.043668\Omega \text{ or } \Omega = 22.9 \cdot v;\ K_{Wv} = 22.9$$

As, in practice, the alimentation tension can vary with *±15%* compared to the *750 Vcc* ideal tension, the ES block was changed to reflect this.

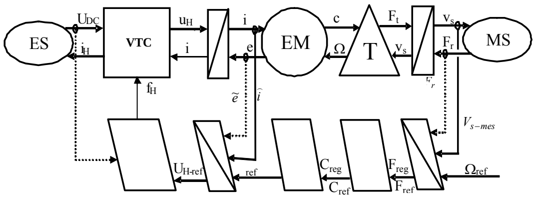

Fig.4. The energetic macroscopic representation and maximum control structure of the entire ASTRAIK system.

The new block introduced in the MCS is based on the following relation:

$$(10)\ C_{ref} = \frac{1}{K_{CF}} F_{reg}$$

where F_{reg} is equal to F_{ref} the force obtained by the precedent IP regulating block.

3. SIMULATION RESULTS

The simulation structure obtained from the REM and SMC of the entire ASTRAIK-415T system (second application) is presented in figure no.5.

To verify these structures the measurement data made on a ASTRAIK–415T trolley was taken into consideration. In the simulation it was introduced, like input variables, the supply voltage of the ES and the reference speed trajectory shown in figure no. 6 (the simulation time is equal to 40 ms and the fixed step size of 5ms).

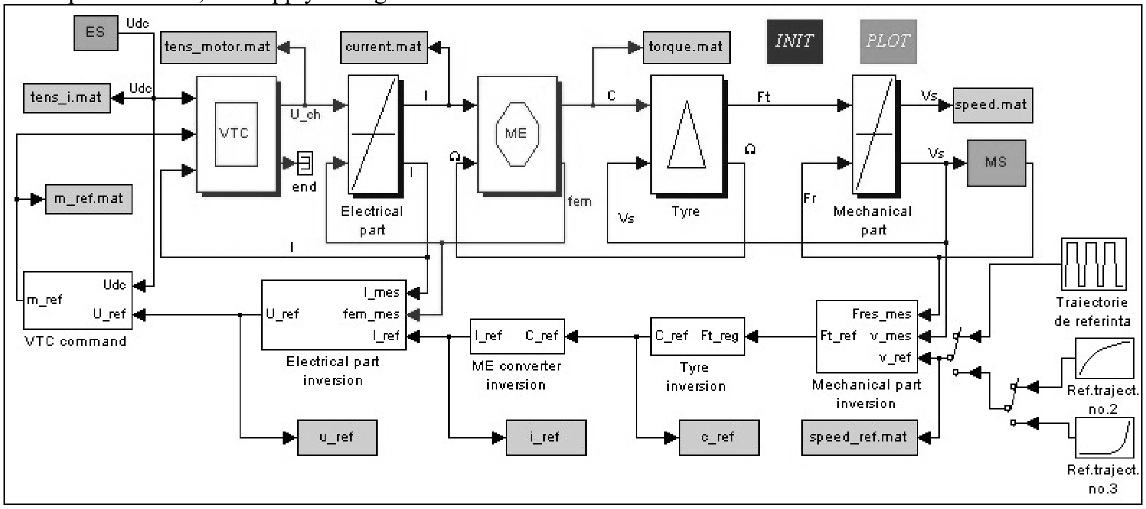

Fig.5. Matlab - Simulink simulation blocks

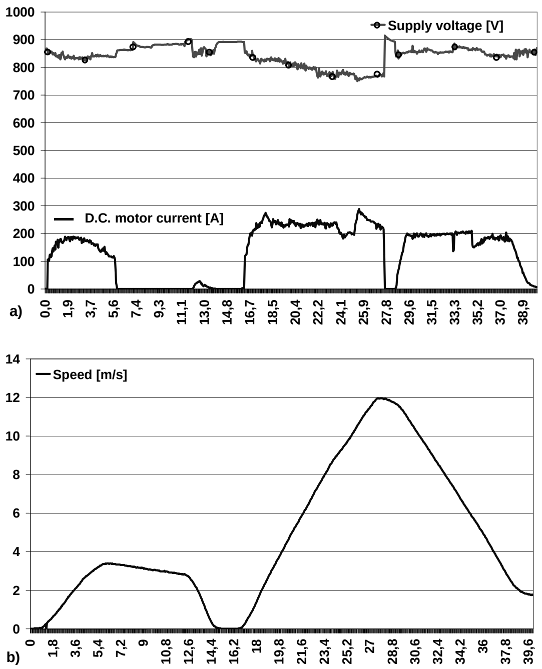

Fig.6. Measured date from ASTRAIK-415T trolley a) supply voltage [V] and d.c. motor current [A] depending on time [s]; b) reference trajectory speed [m/s] depending on time [s].

The simulation results are presented in figure no.8. It can be observed that the output variable: the d.c. motor current has the same form and value, which means that the simulation model is accurate.

For the following simulation a different real ON-OFF cycle determined by measurements on the 70's Bucharest trolley line was taken into consideration: a duty cycle with t_l=64s and a cycle period of T=108s.

The cycle parameters, described in figure no. 7 are the following:

- v_{pal} - the desire speed, corresponding to the traffic necessity; for this application the speed is equal to 36 km/h (which means 10 m/s);

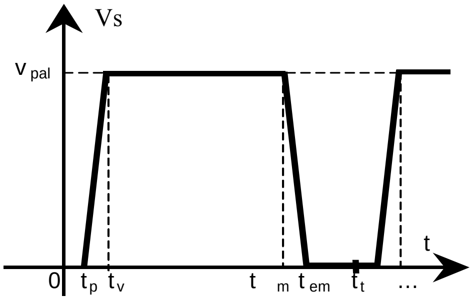

Fig.7. ON-OFF simulation cycle parameters

- t_p - the starting moment (for this application was taken equal to the axes origin);
- t_v - the moment when the trolleybus speed is equal to v_{pal}, obtained with the following relation:

$$(11)\quad t_v = t_p + dpa_1$$

where $dpa_1 = \frac{v_{pal}}{a_{max}}$ represents the acceleration period chosen for the passengers comfort, with a_{max} – maximum admission acceleration of $1,78\ m/s^2$;

- t_{em} - the total drive time (including the acceleration and deceleration period). The deceleration period is given by:

$$(12)\ dpa_2 = \frac{V_{pal}}{d_{max}}$$

where d_{max} represents the maximum admission deceleration of $2{,}75 m/s^2$ chosen for the passengers comfort.

- t_t - represents the cycle period.

The results of the MATLAB-SIMULINK simulation, corresponding to a reference speed (a ramp trajectory) of 36 km/h (10m/s) and considering the full capacity (the maximum weight) of the trolley are presented in figure no. 9. It can be observed that the traction system variables (speed and current – shown by asterisks) are the same with the imposed reference variable (speed and current) of the command system.

The most consuming period from the ON-OFF cycle is the starting and breaking moments.

By calculating the energy consumed in the starting period using three different command strategies, the results are:

i) a ramp signal - $9.78*10^5 J$;
ii) an exponential signal - $14.14*10^5 J$;
iii) a parabolic signal - $8.07*10^5 J$;

It was noticed that the third one is having the minimum power losses.

Also, if the trolley is empty (without passengers), the energy consumed in the starting period, using the third strategy, decreases with 62% (at $5.007*10^5$ J) compared with full charge trolley.

In this simulation can also be observed that in the regenerative braking period, the d.c. motor current is negative.

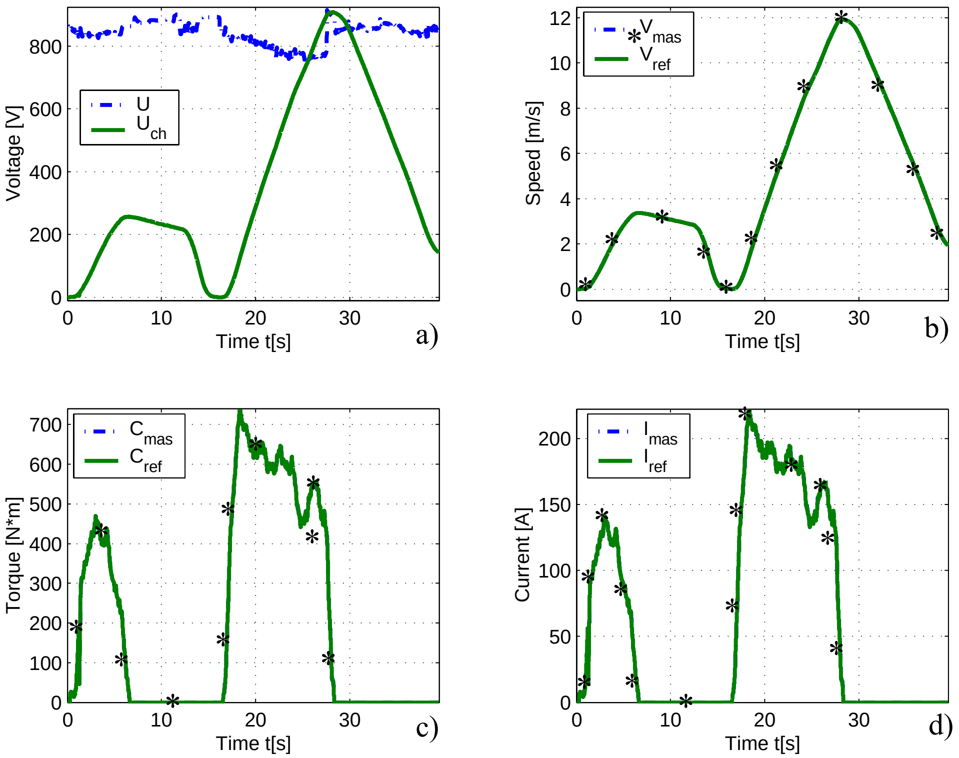

Fig.8. Verifying the proposed structures:
a) the supply voltage and the converter voltage;
b) the reference and measured trolley speed;
c) the reference and measured motor torque;
d) the reference and measured motor current.

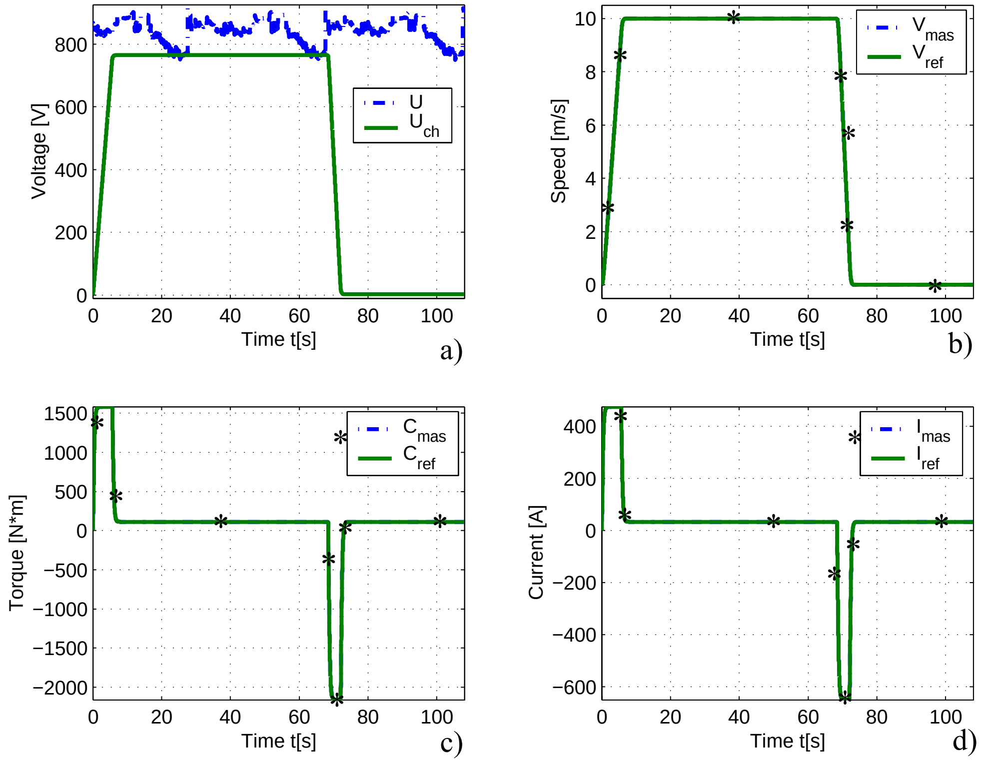

Fig.9. Simulation results of a ramp trajectory reference speed

4. CONCLUSIONS

This paper shows a specific formalism based on energetic conversion and action–reaction principle used to model the ASTRAIK-415T system.

In this way, it was realized a complex simulation model for both the process and the control law, which can be used to study the transient phenomena and the implementation of different command laws.

The simulation results of the ASTRAIK-415T trolley representation were validated by the measured values (Gheorghe, 2000) (see the comparison between figure 6a - figure 8a, 8d, and between figure 6b – figure 8b).

After that, there were simulated three types of command strategies: ramp, exponential and parabolic. The result was that the parabolic strategy is more economic than the others, the energy consumes for the starting interval is $8.07*10^5$ J ($V_s=0\div V_{pal}$).

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