Achieved Energy Assessment and Modeling of Railway Transportation Systems with Three Levels Converters

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Abstract**—**This paper emphasizes a number of sustainability-based concepts, such achieved energy and exergy efficiency, related as tools in order to describe, analyse and optimize energy conversion in electric railway transportation systems. For the sustainable railway vehicles, the achieved energy assessment provides a basis for exergy efficiency increasing, reducing both energy losses and environmental damage. Further on, achieved energy and exergy analysis more broadly can help in optimizing designs and modeling decisions. In this goal, the paper describes the mathematical models and structural diagrams of the traction induction motors, useful movement, three levels voltage-source inverter and line-side converter used on the locomotive fed from AC line. The overall structural diagram construction for the principle schemes corresponding to modern locomotives is also presented. At the end are shown the simulated waveforms of the three levels converters and the running diagrams of a high speed train.

Keywords**—** exergy, locomotive, modelling, simulation. traction induction motor, three levels converters.

I. Introduction

THIS paper purpose is to demonstrate, as a study case, that the Sustainable Development must be seen and explained as a process which requires both the traditional development analysis and the further alternatives knowledge [1]. It is taken into account a Railway Transportation Systems, not simply in terms of technico-economical growth, but also as an achievement of the Sustainable Development. In the paper authors' opinion [2], [3], an Electric Railway System should be considered as a component of the Sustainable Development architecture if it meets certain criteria: a strong train operation safety, a high reliability of the electric supply and a great exergy efficiency of the transportation system.

Exergy is a well-established concept in engineering. The exergy of an energy or material quantity measures its usefulness or quality [4]. Although energy cannot be destroyed, exergy can [5]. Energy efficiencies do not always

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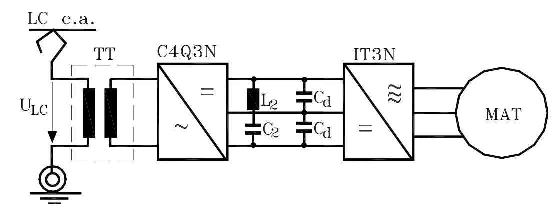
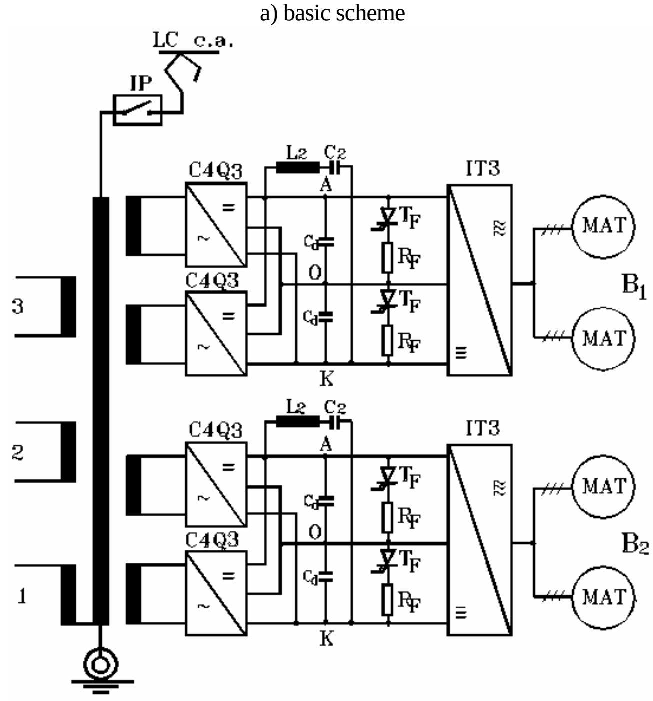


a) basic scheme



b) B_0B_0 locomotive main electric circuits

Fig.1 Basic scheme and main electric circuits used in modern locomotives with three levels converters assess how nearly performance approaches ideality and do not properly describe factors that cause performance to deviate from ideality. Exergy analysis [6] overcomes many of the shortcomings of energy analysis, yielding efficiencies which provide a true measure of approach to ideality and identifying properly the causes, locations and magnitudes of inefficiencies.

This study aims at examining energy and exergy efficiencies in modern locomotives with three levels converters. In this application, the exergy analysis can help improve and optimize the transportation system design and operation.

II. Modelling of Induction Motor

Utilization in the electric traction of the induction motor with squirrel cage it is possibly only in this feeding condition with a three-phase system by voltages of amplitudes and frequency controlled variable. This feeding type it is achieved by means of machine-side converter (CM), usually a voltage-source inverter (IT) with two or three levels (Fig.1,a).

Energy is never destroyed during a process; it changes from one form to another [4]. As a rule, the main electric circuits of modern locomotive (Fig.1) ensure two conversion stages of the electric energy, the first being achieved by line-side converters and the second, by machine-side converters [7], [8], [9]. In the case of AC- line supply, the line-side converter is a four-quadrant converter (C4Q) with two (2N) or three levels (3N), associated to a voltage-source inverter (IT3N), which represents the machine-side converter (Fig.1). The modelling of such line-side converters can use, because exergy analysis is performed in the field of industrial ecology to use energy more efficiently [5]. As far as the model implementation into simulation software is concerned, the switching functions approach presents the advantages of reduced simulation time and good convergence. For three levels converters, the switching functions with three levels f3w [4], [5] are used. For the modelling of different converter

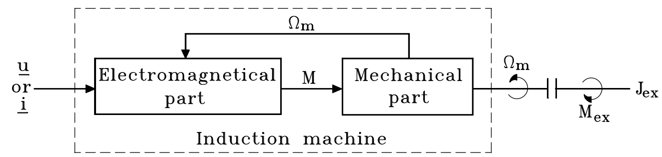


Fig.2 Functional parts of traction induction motor

structures by means of switching functions, it has been considered that the switching devices are ideal, by neglecting the commutation time and forward voltage drop. Such a converter is considered ideal (without losses).

In the power schemes of motor electric vehicles, the traction induction motor it is the final element from the equipments chain by conversion of energy.

After all, it achieves the electromechanical conversion of energy making thus possibly the movement. Like complex electromechanical system, the induction motor will have decomposed functionally between an electromagnetic part and a mechanical part . Both the M electromagnetic torque and the Ω_m mechanical speed of rotor, they intervene like internal variables, by interaction, between those two functional parts. In the motor vehicle case, the mechanical part of traction induction motor it is coupled (through the transmission intermediation) with the motive axle and can be modelled in the shape of the useful movement or/and the elastic mechanical transmissions [7]. For can be connected, the models must be achieved in accordance to the same principles, indifferently that they describe the phenomenon by electric nature or mechanical nature.

A fixed reference system, related at stator it is taken into account. Hence, the induction motor electromagnetic part will be described by the equations [8]:

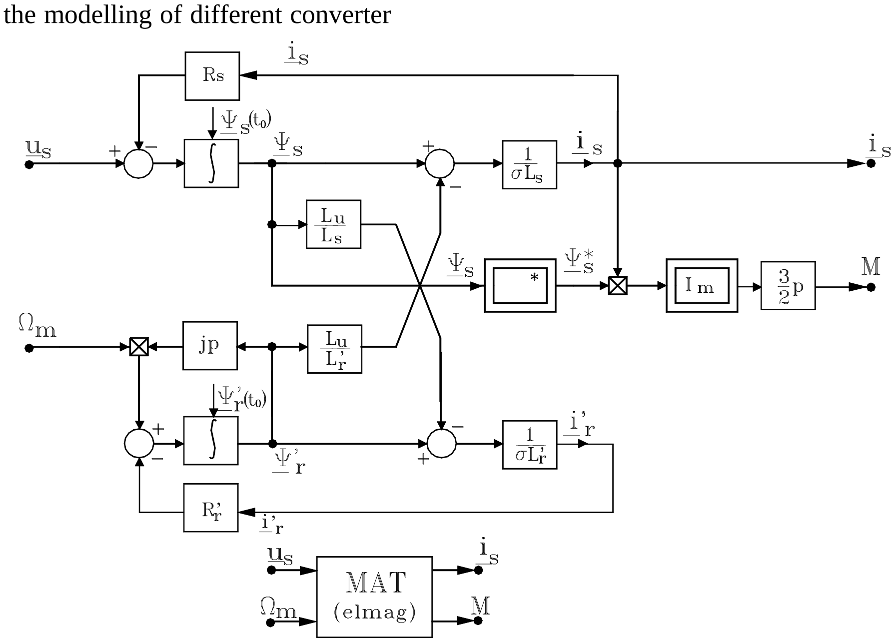


Fig.3 Structural diagram and mask block for electromagnetic part of induction motor

$$\begin{aligned}
&\frac{d\underline{\psi}_s}{dt} = \underline{u}_s - R_s \cdot \underline{i}_s \\
&\frac{d\underline{\psi}'_r}{dt} = j \cdot p \cdot \Omega_m \cdot \underline{\psi}'_r - R'_r \cdot i'_r \\
&\underline{i}_s = \frac{\underline{\psi}_s - \frac{L_u}{L'_r} \cdot \underline{\psi}'_r}{\sigma L_s}; \quad \underline{i}_{r'} = \frac{\underline{\psi}'_r - \frac{L_u}{L_s} \cdot \underline{\psi}_s}{\sigma L_{r'}} \\
&M = \frac{3}{2} \cdot p \cdot \mathrm{Im}\{\underline{i}_s \cdot \underline{\psi}_s^*\}
\end{aligned} \tag{1}$$

where:

$\underline{u}_s$ is the stator voltage vector
$\underline{i}_s$ is the stator current vector
$\underline{i}_r'$ is the rotor current vector
$\underline{\Psi}_s$ is the stator flux vector
$\underline{\Psi}_r'$ is the rotor flux vector
L_u is the magnetizing inductance
L_s is the stator inductance
L_r' is the rotor inductance
p is number of pole pairs
R_s is the stator resistance
R_r' is the rotor resistance and

$\sigma = 1 - \frac{L_u^2}{L_s \cdot L'_r}$ is the motor leakage coefficient.

On basis of equations (1) the structural diagram and the mask block of the induction motor electromagnetic part are represented in Fig.3.

The structural diagram of electromagnetic subsystem can be coupled both with the structural diagram of machine converter through the input variables $\underline{u}_s$ and output variables $\underline{i}_s$ and with the structural diagram of mechanical part through input quantities Ω_m and output quantities M.

III. Modelling of Locomotive Useful Movement

For the dynamic aspect approach of useful movement it is needed of a mathematical model. In this purpose it is considered a motor electric vehicle with mass m[t] and inertia constant ξ having the specific train resistance r[daN/t]. If the movement it had been made under useful torques operation M_2 (identical), developed by those "z" traction motors of motor electric vehicle, then the mathematical model of useful movement it is described by the next equations:

$$\begin{aligned}
&v = \frac{1}{m \cdot \xi} \int (F - R)dt \\
&\Omega_m = \frac{2 \cdot i}{D_r} \cdot v; \quad x = \int v \cdot dt \\
&F = z \cdot \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \\
&R = (r_{ps}(v) \pm i_{de}(x) + r_c(x)) \cdot m \cdot 10
\end{aligned} \tag{2}$$

which they permit the structural diagram construction of useful movement (Fig.4).

For the mask block they have been considered like input quantity the M torque and like output quantity the Ω_m speed, time variable quantities on the useful movement duration.

By means of this scheme ("coupled" at the structural diagram of electromagnetic part of traction motor) can be simulated the useful movement of any motor electric vehicle as compared with the concrete modality by leadership (or by control) of this. Accordingly they are obtained the running diagrams v(t) and x(t), too. The modification of vehicle mass, of dependences $i_{de}(x)$ or $r_c(x)$, specific to certain vehicle or route, can be easily operated, obtaining an exact mathematical model, which it respects the running concrete conditions.

In the motor wheels diameters inequalities case, the scheme suffers a minor change, the total force F resulting like sum of partial forces developed by each motor partly.

IV. Modelling of the Machine-Side Converter

For the modelling of the machine-side converter, that being the three levels voltage-source inverter, they are used the commutation functions with three levels [8], [9]. From viewpoint of modelling, any static converter it can be approached like a "black box" with input/output characteristics through the commutation functions intermediation. For the different structures modelling of converters by means of commutation they have been considered that the used semiconductor devices they are

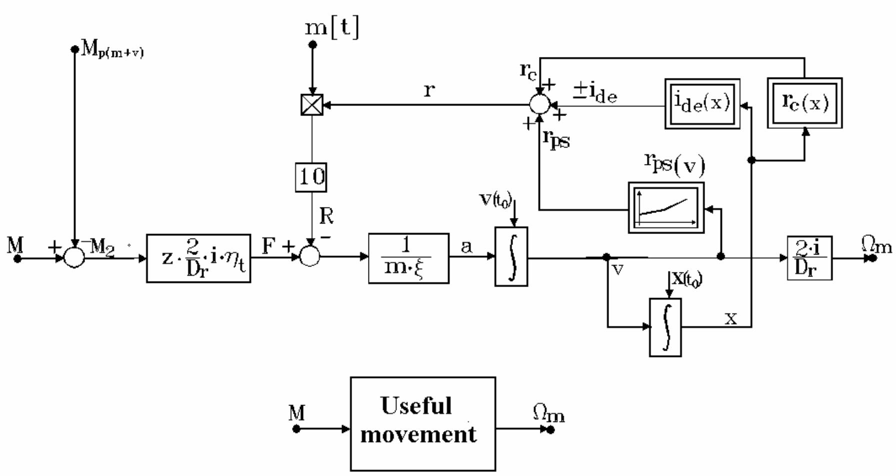


Fig.4 Structural diagram and mask block of useful movement

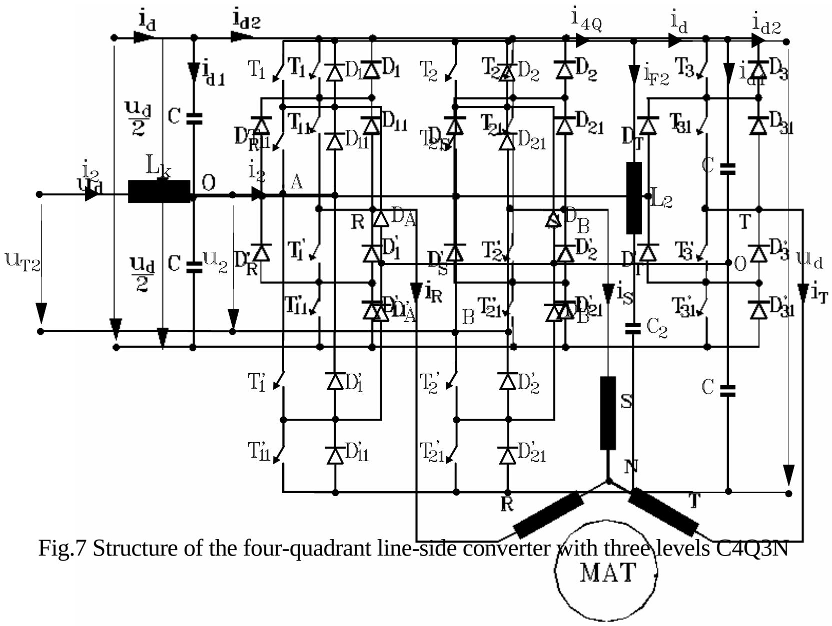


Fig.7 Structure of the four-quadrant line-side converter with three levels C4Q3N

Fig.5 Three-phase voltage-source inverter with three levels (IT3N)

ideally, they are neglected both the commutations times and the voltage drop at conduction in forward direction. Such converter is ideal and it is considered without losses.

For modelling of three-phase voltage-source inverter with three levels (Fig.5) it is considered the ideal case, at which two identical capacitors they divide in equal mode the constant voltage u_d.

For modelling they are used the commutation function with three levels ”f_{3w}”:

$$f_{3w\,R,S,T} = \begin{cases} +1, & T_i, T_{i1}\,(I) \\ 0, & T_{i1}, T_i'\,(I) \\ -1, & T_i', T_{i1}'\,(I) \end{cases} \quad , \quad i=1,2,3 \qquad (3)$$

Analyzing the topology of three-phase voltage-source inverter with three levels (Fig.5) they can be written the equations:

$$\begin{gathered} u_{RO} = \frac{u_d}{2} \cdot f_{3wR}\,; \quad u_{SO} = \frac{u_d}{2} \cdot f_{3wS}\,; \quad u_{TO} = \frac{u_d}{2} \cdot f_{3wT}\,; \\ i_{d2} = i_R \cdot f_{3wR} + i_S \cdot f_{3wS} + i_T \cdot f_{3wT}\,; \\ u_{RN} = u_{RO} - u_{NO}\,; u_{SN} = u_{SO} - u_{NO}\,; u_{TN} = u_{TO} - u_{NO}\,; \\ u_{NO} = \frac{u_{RO} + u_{SO} + u_{TO}}{3}\,; \end{gathered} \qquad (4)$$

On these equations basis, it is obtained the structural diagram of three-phase voltage-source inverter with three levels (Fig.6). This model have comprised in their structure the MAT traction induction motor model, both the electromagnetic part and mechanical part , the link with this making through the voltage ($\underline{u}_s$) and respectively by the stator current ($\underline{i}_s$) space phasors.

V. Modelling of the Four-Quadrant Line-Side Converter

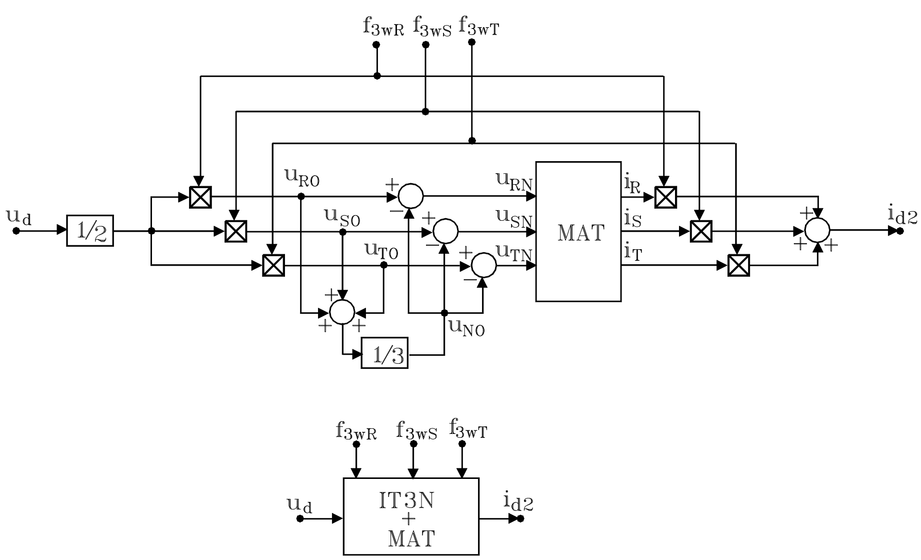


Fig.6 Structural diagram and mask block for three-phase voltage-source inverter with three levels

In order to obtain the mathematical model of the four-quadrant line-side converter with three levels (Fig. 7), the following switching functions are used:

$$f_{3wA}=\begin{cases}+1, & T_1, T_{11}(I)\\ 0, & T_{11}, T_1'(I)\\ -1, & T_1', T_{11}'(I)\end{cases};\quad f_{3wB}=\begin{cases}+1, & T_2, T_{21}(I)\\ 0, & T_{21}, T_2'(I)\\ -1 & T_2', T_{21}'(I)\end{cases} \qquad (5)$$

By means of these functions, the following voltage and current expressions, respectively, can be written:

$$u_{AO}=\frac{u_d}{2}\cdot f_{3wA};\quad u_{BO}=\frac{u_d}{2}\cdot f_{3wB}$$
$$u_2=u_{AB}=u_{AO}-u_{BO}=\frac{u_d}{2}\cdot(f_{3wA}-f_{3wB})=\frac{u_d}{2}\cdot f_{3wAB} \qquad (6)$$

$$i_{4Q}=i_2\cdot f_{3wA}-i_2\cdot f_{3wB}=i_2\cdot(f_{3wA}-f_{3wB})=i_2\cdot f_{3wAB} \qquad (7)$$

With reference to the electric circuit of Fig.7, the following equations can be added to (6) and (7):

$$u_{T2}=L_k\cdot\frac{di_2}{dt}+u_2$$
$$i_{4Q}=i_{F2}+i_d;\quad i_d=i_{d1}+i_{d2}$$
$$u_d=L_2\cdot\frac{di_{F2}}{dt}+\frac{1}{C_2}\cdot\int i_{F2}\,dt \qquad (8)$$
$$i_{d1}=\frac{C}{2}\cdot\frac{du_d}{dt}$$
$$u_2=\frac{u_d}{2}\cdot f_{3wAB};\quad i_{4Q}=i_2\cdot f_{3wAB}$$

Based on the above system of equations, the structural diagram and mask block of the four-quadrant line-side converter with three levels are obtained in Fig.8. The input quantities are:

- u_{T2}, the voltage from the transformer secondary;
- i_{d2}, the input current from the inverter (machine- side converter);
- the switching functions, which allow the four-quadrant operation control of line-side converters, being generated by the traction control system. The DC-link voltage u_d represents the output quantity for the four-quadrant line-side converters and, in the same time, the input quantity for the inverter (machine-side converter) model.

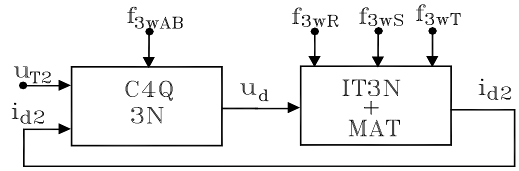


Fig.9 Structural diagrams
of the main electric circuits of Fig.1 a)

VI. Structural Diagrams for AC Locomotives

With the obtained structural diagrams, as well as the mask blocks of other components of the main electric circuit, it is possible to build the structural diagrams for the modern locomotives fed from AC contact line having the main circuit schemes given in Fig.1.

The locomotives with traction induction motors fed from the AC contact line they have obligatory two conversion phases, through the existence of network converter (four quadrant converter). The basic scheme modelling of the traction induction motor feeding (Fig.1., a) it can make easily by means of the mask blocks of the four quadrant converter with three levels („*C4Q3N”*) and of the voltage-source inverter fed traction induction motor („*IT3N+MAT”*) [11]. It is obtained thus the structural diagram (fig.9) having like input variables the u_{T2} (voltage from the transformer secondary) as well as the switching functions of those two converters. The output variables can be considered anything among variables from the mask blocks inside, depending on the studies regime or the possibly connections with other sub-systems.

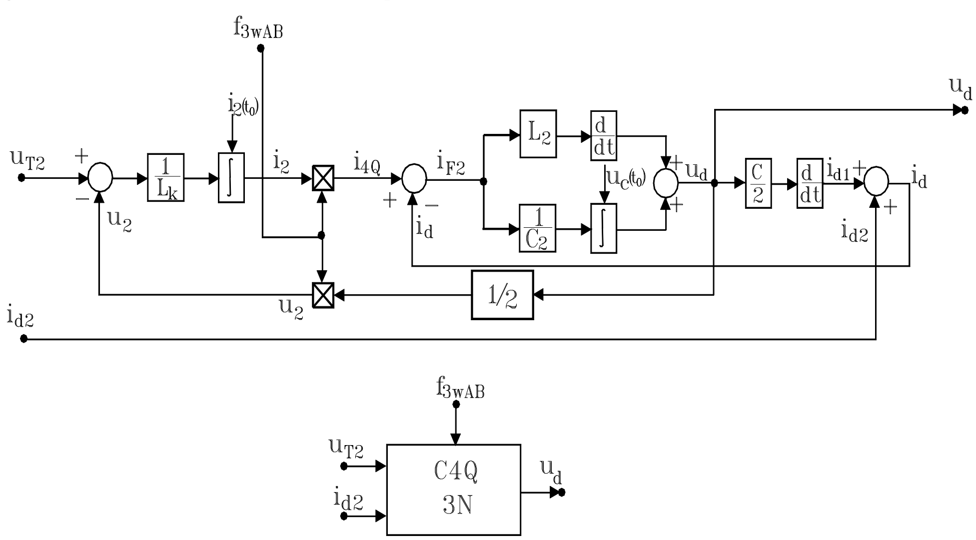


Fig.8 Structural diagram and mask block of the four-quadrant line-side converter with three levels

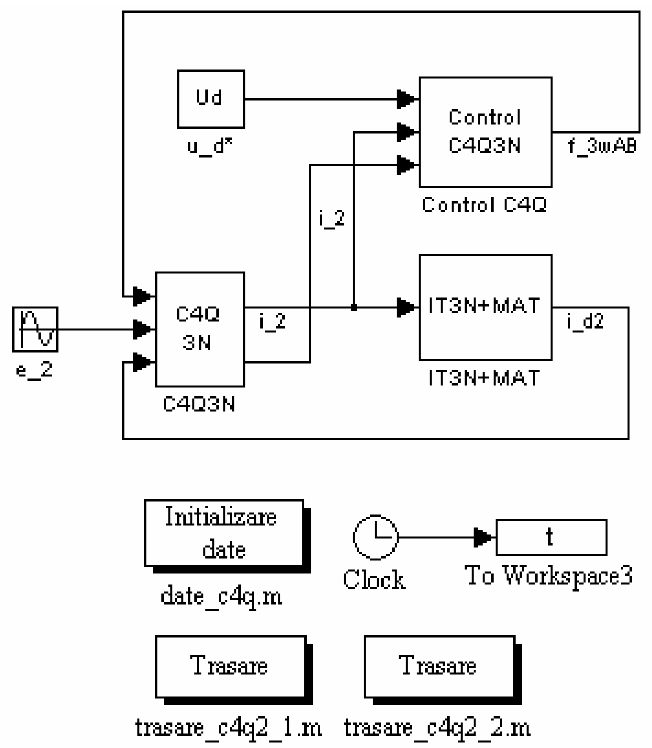


Fig.11 SIMULINK model
of the main electric circuits of Fig.1 a)

For the structural diagram construction of the entire main circuit, corresponding to a high-speed train (Fig.10), the previous diagram it is multiplied of four time (the total numbers of motors) and they are written the proportionality relations what they describe the traction transformer working. For the identification of the blocks and of the quantities corresponding to those four traction secondary they have been used superior indexes. Like input and output variables they have been considered those which interact with the contact line, the u_{LC} voltage and the i_{LC} current absorbed by the train. For obtainment of this from behind, given the previous cases, it was necessary the utilization, from the four quadrant converters inside, of the $i_2^{(i)}, i = 1,4$ currents from the traction transformers secondary.

VII. SIMULINK MODEL

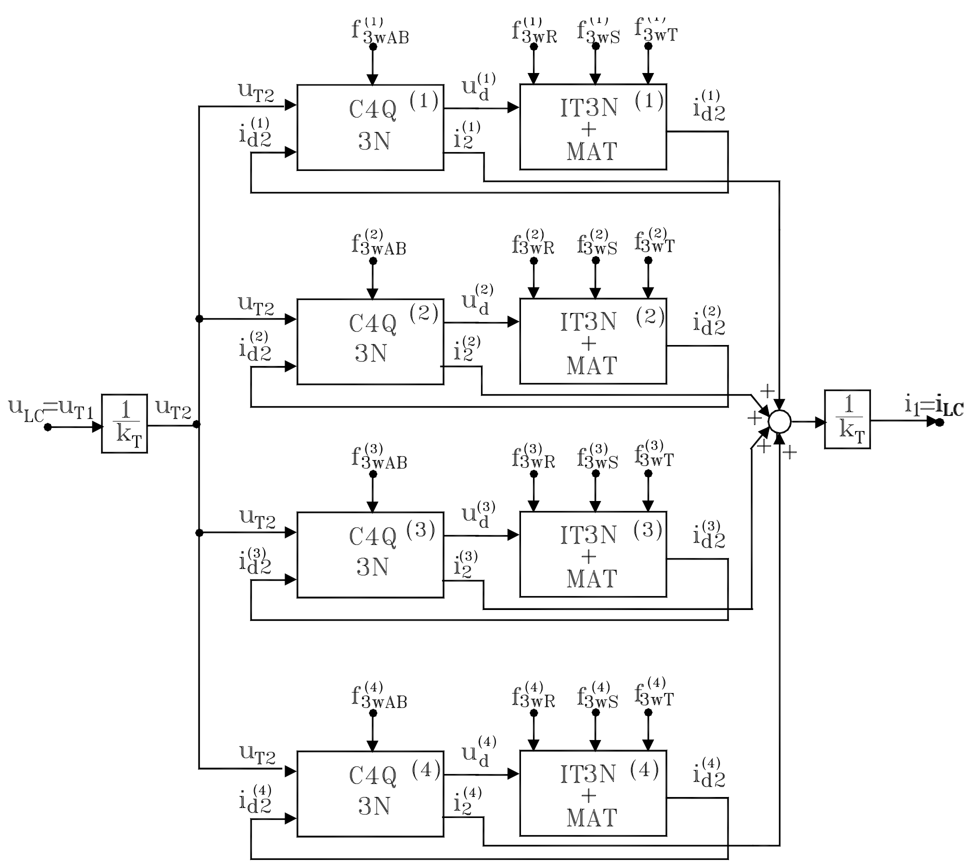


Fig.10 Structural diagrams of the main electric circuits (B_0B_0 locomotive)

Based on the presented structural diagram (fig.9), its SIMULINK model has been achieved, as shown in Fig.11. They are obtained the identical SIMULINK model from viewpoint topology with associated structural diagram.

For example, the SIMULINK model of traction induction motors contains two blocks corresponding to:

- the electromagnetic part of traction induction motor (fig.12,a) (based on the structural diagram from fig.3) and
- the useful movement (fig.12,b) (based on the structural diagram from fig.4)

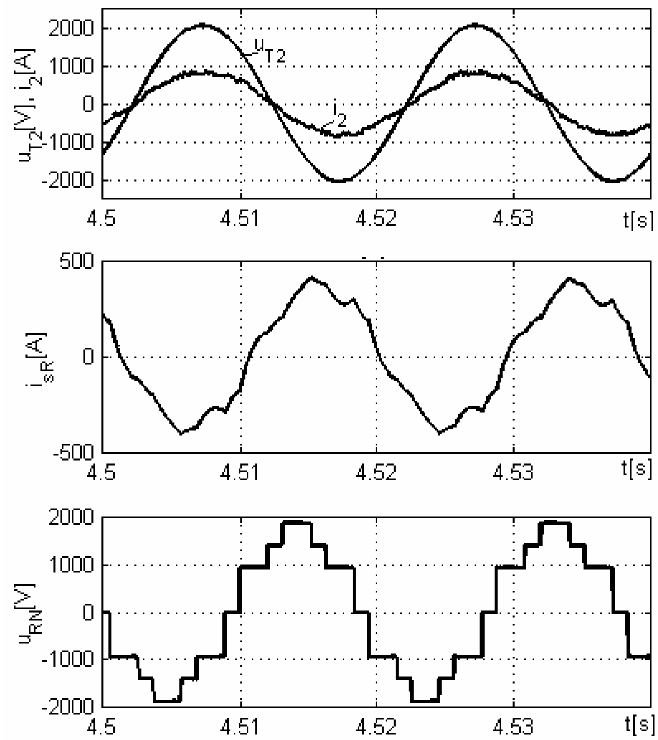


Fig.14 Waveforms of simulated system quantities

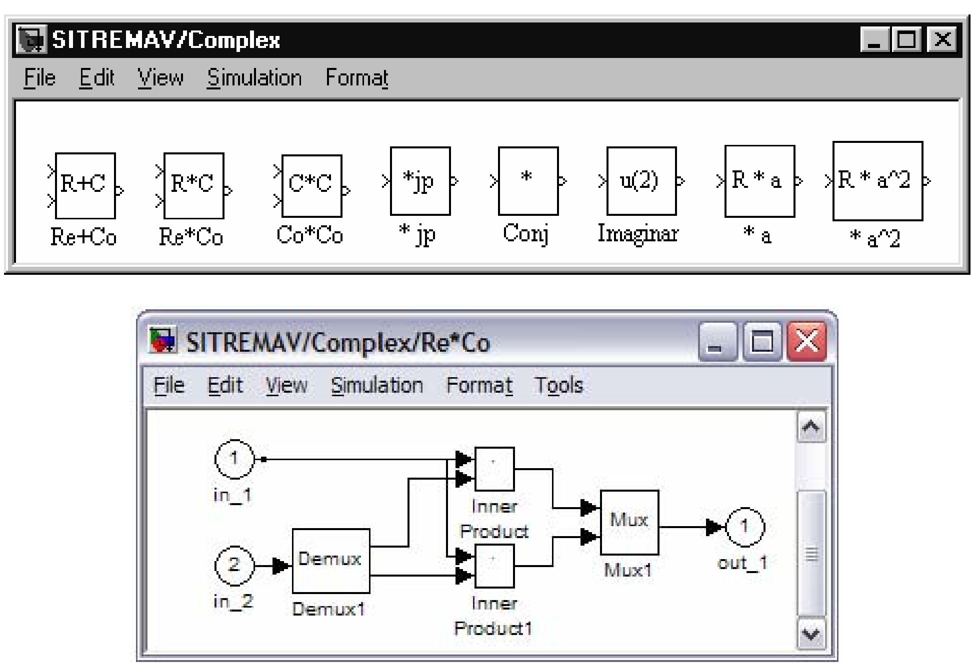
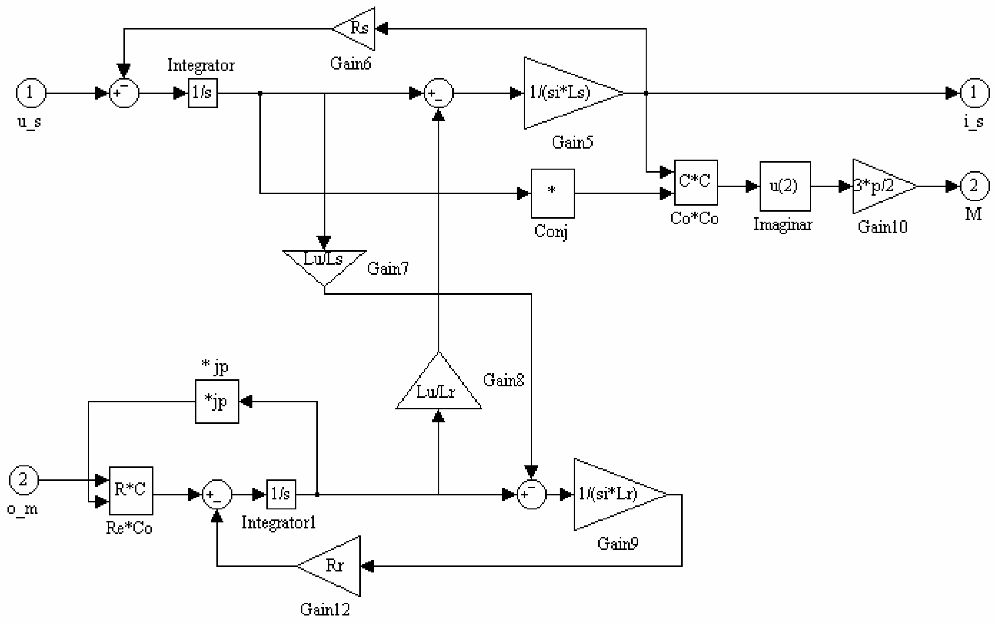
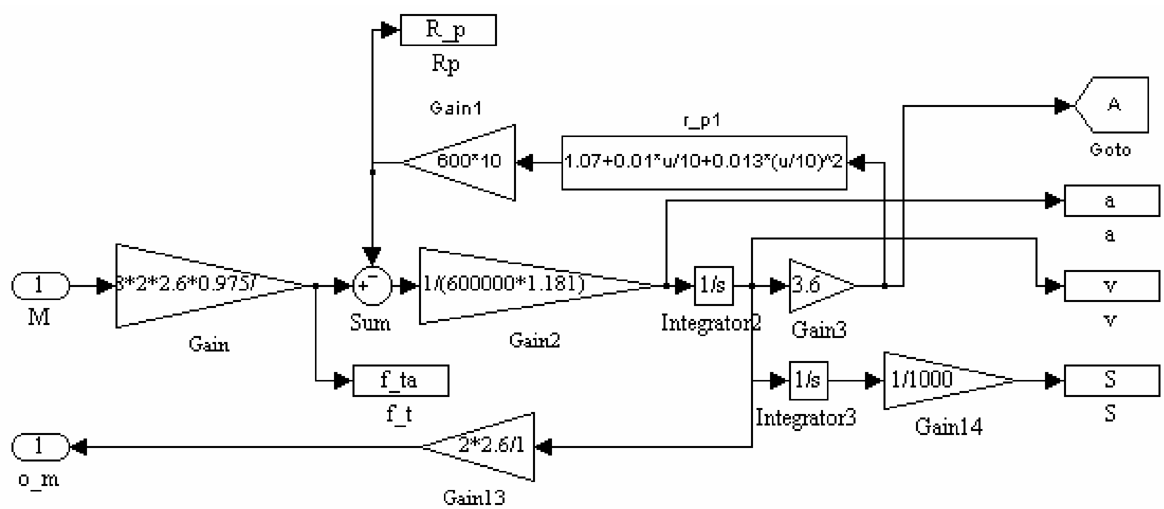


Fig.13 Complex calculus library



a)



b)

Fig.12 SIMULINK models
a) for electromagnetic part of traction induction motor; b) for useful movement

For the implementation facility in SIMULINK of the electromagnetic part of traction induction motor it has been created a library of complex calculus blocks (fig.13) obtaining thus a topology much simplified given the case of decomposition of those two axles of used reference system.

Using the SIMULINK model from Fig.11, the operation of a four-quadrant line-side converter together with a voltage-source inverter with two levels and a traction induction motor has been simulated (fig. 14).

Another example of the useful movement model it constitutes it the running diagrams drawing, which they illustrate the dynamic aspect of the dynamic aspect of the electric vehicle [12].

The running diagrams of the electric train they are drawn on the traction and braking characteristics basis and of the conditions imposed of route.

For the running diagrams drawing corresponding to a route of the ETR500 it is used a SIMULINK model based on the useful movement model (fig.15).

In the blocks „$F_t(v)$" and "$F_f(v)$" they are implemented the traction and braking characteristics of the ETR 500. The model is based on the useful movement model, at which the

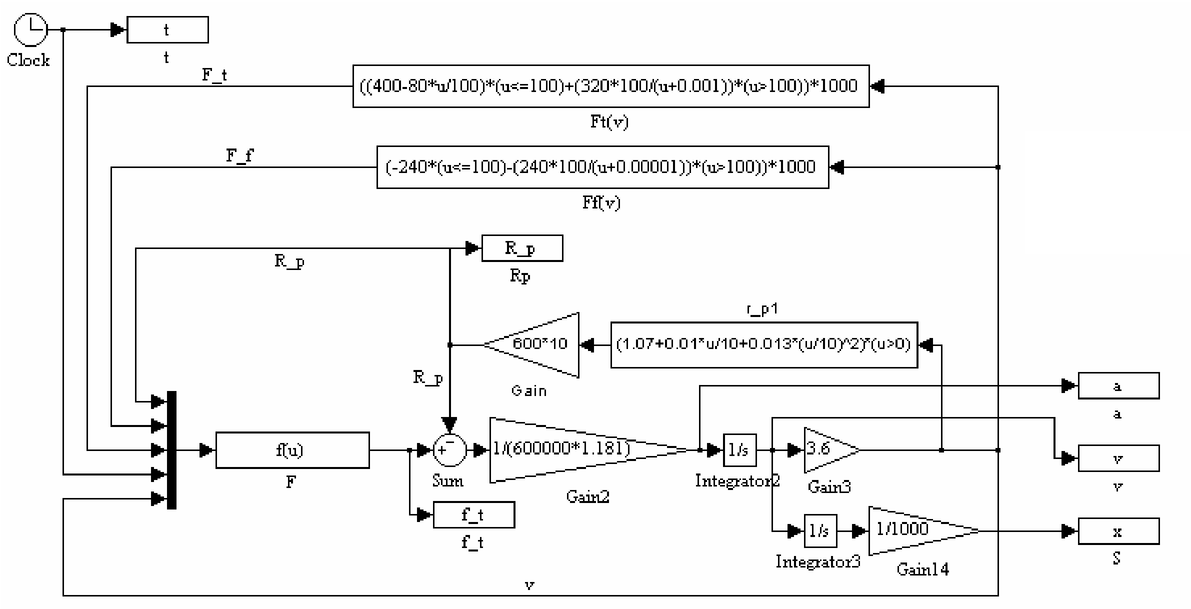


Fig.15 SIMULINK model used for running diagrams drawing

main input variable it is supplied of the block „F”,”which it models the useful movement phases:

- starting phase,
- running at constant speed phase,
- coasting phase and
- braking phase.

By means of this SIMULINK model (fig.15) they have been drawn the running diagrams corresponding to a test route of the high-speed train, on its route has been reached the speed of 44,44 m/s (160 km/h) and respectively of 83,33 m/s (300 km/h). They have been drawn the variations of the force, of the train resistance, of the acceleration, of the speed and of the distance (fig.16).

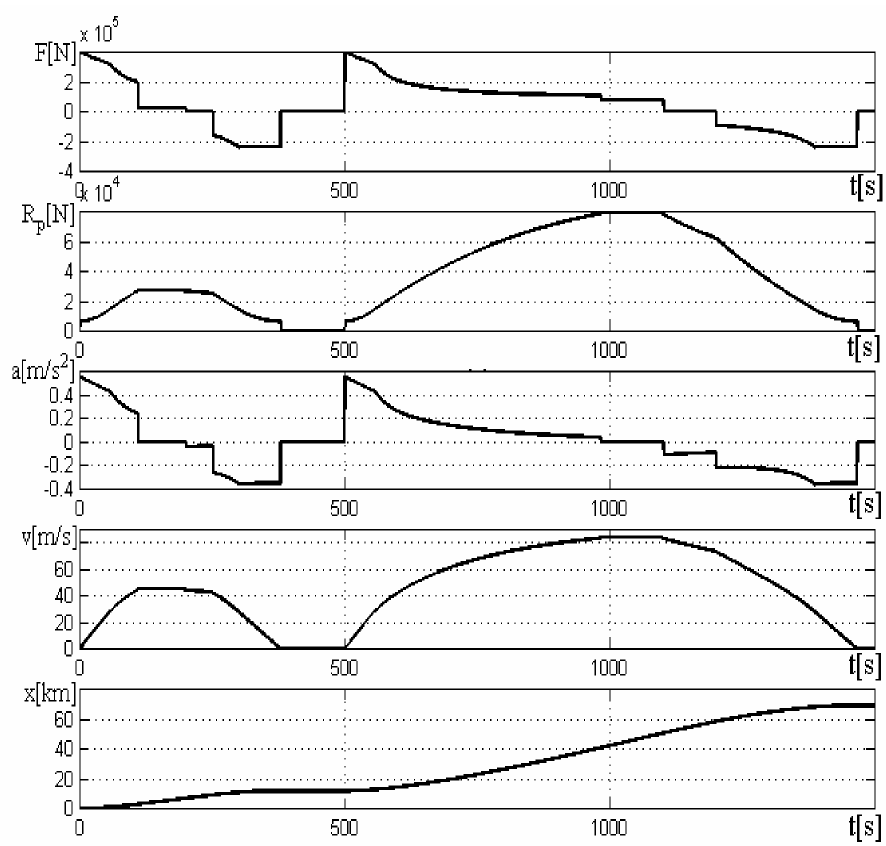


Fig.16 Running diagrams of high speed train

VIII. CONCLUSIONS

For the moment, our correct activities must be referred into the frame of Sustainable Development. An utmost priority is the improvement of railway transportation systems. The merit of an electric transportation system is based not only on technical performance, safety, energy efficiency, societal and economic acceptance and but also on environmental impact and exergy efficiencies. Costs should reflect value and value is not associated with energy but with exergy and sustainability. This paper aimed at examining an electric railway locomotive viewed as a system where different energy forms occur, so that the successive energy conversion chain is emphasized and the energy and exergy efficiencies, respectively, are compared.

Consequently, from the exergetical viewpoint, the imposed specific features of the utilization in electric traction of equipments used in modern locomotives fed from AC contact line must be studied by means of the simulation. In this context it is necessarily a mathematical modelling consorted of the structural diagrams obtainment what permit the immediate implementation within the framework of a simulation soft like MATLAB- SIMULINK. With the obtained structural diagrams, as well as the mask blocks of other components of the main electric circuit, it is possible to build the structural diagrams for the locomotives with traction induction motors fed from AC contact. It is observed the facile modality by achievement of the structural diagram corresponding to a complex circuit from viewpoint topology. Otherwise, it is achieved a construction on four levels, easy to study modified and implemented in a simulation soft like MATLAB-SIMULINK. It is possibly, for a high exergy efficiency, the integration of this diagram in to another more complex, how it would be that which it is studied the interaction between the traction substation and motor electric vehicles, too.

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