Exergy Analysis Framework for Underground Transportation Systems

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Abstract**—**The environmental problems are mainly consequences from a too strong belief in traditional engineering and economic growth as the solution. An important human step against ignorance should be to understand that the real world processes involving energy and matter need to be linked to the environmental engineering education, design and operation. Energy systems involving coversion chain processes are highly irreversible and, consequently, they could have low exergy efficiencies. This study aimed at examining an underground railway train 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. Also, because at low speed the mechanical brake can't be avoid, among the environment issues, from viewpoint of exergy efficiency, a special aspect is represented by an abnormal but frequent situation of train operation, concerning the unequal charge of the traction induction motors. In this application there are presented numerical simulations and experimental data related to unequally charged motors regime. The exergy analysis can help improve and optimize the underground transportation system design and operation, but also represents an environmental engineering education example.

Keywords**—**Transportation, Environmental Engineering, Exergy, Induction Motor.

I. Introduction

SCIENTISTS and public authorities around the world are realizing that human actions have to be responsable regarding not only the social and economic matters, but also the environment issues. For the moment, our correct activities must be referred into the frame of Sustainable Development. The vitality and perheps the future survival of the society is strongly depending on the management of physical, environmental and human resources [1]. A dangerously unstable situation is emerging because of people ignorance. The environmental problems are mainly consequences from a too strong belief in traditional engineering and economic growth as the solution. The first human intelligence step against ignorance would be the understanding of concepts such achieved energy, exergy and embodied energy.

Energy is a measure of the ability to do work [2]. Work can involve the movement of a mass by a force that results from a transformation of energy. If there is an energy transformation, this process must involve the dissipation of some energy as losses.

Embodied energy as a concept used in systems ecology seeks to mesure the "true" energy cost of an item, and has extended this to the concept of "true" value.

Exergy is a well-established concept in engineering

Exergy is a measurable value that is decreased during the conversion of useful energy to useless energy. Therefore, exergy measures the actual potential of a system to do work. The exergy consumed to create something, a product or service, is more than the work done to create it. Exergy is the work that can no longer be done elsewhere because the economic good was made. Exergy has been described as a measure of energy quality because of these traits. Energy is never destroyed during a process; it changes from one form to another, but the exergy can be destroyed [3]. The ratio of exergy to energy in a substance can be considered a measure of energy quality. Exergy is useful when measuring the efficiency of an energy conversion process Exergy analysis [4] overcomes many of the shortcomings of energy analysis, yieldind efficiencies which provide a true measure of approach to ideality and identifying properly the causes, locations and magnitudes of inefficiencies.The exergy concept is mostly used within energy optimization studies, where different energy forms occur and in ecological modelling. Exergy is the physical value of a resource than can be compared not only to the economical value, but to the environmental value.

II. Electric Transportation System

On a broader front, an utmost human world priority should

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be the improvement of public 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 effienciency. Costs should reflect value and value is not associated with energy but with exergy and sustainability [5]. This paper aimes at examining an underground railway train viewed as a system [6] where different energy forms occur, so that the successive energy conversion chain to be emphasized and the energy and exergy efficiencies, respectively, to be compared.

This paper purpose is to demonstrate, as a case study, that the Sustainable Development must be seen and explained as a process which requires both the traditional development analyzation and the further alternatives knowledge. It is taken into account an Underground Transportation System, not simply in terms of technico-economical growth, but also as an achievement of the Sustainable Development. In this case study it is understood that the negative effects on efficiency of large exergy destruction and the corresponding longterm environmental degradation can be understood and improved only by an analysis of underground transportation systems operation regimes.

In this application, the exergy analysis can help improve and optimize the transportation system design and operation. Therefore, the first analysis step must emphasize the inter-connection of the electromagnetic part and the mechanical part. On any electric vehicle, the electromagnetic torque developed by the traction electric motors it is transmitted towards the motor wheels [7]. By turning, these wheels are establishing the vehicle translation movement on railway.

The motor torque transmitted to the motor wheels is $M_R = i \cdot \eta_t \cdot M_2$, where M_2 is the developed useful torque of the traction motor [7]. At the running radius $r = D_r/2$, to motor torque M_R will correspond a motor force F_o[N] at wheels:

$$Fo = \frac{M_R}{D_r/2} = \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \qquad (1)$$

In slip absence, the peripheral speed v of motor wheels (which are turning with angular speed Ω_0) will be:

$$v = \Omega_0 \cdot \frac{D_r}{2} \qquad (2)$$

It is exactly the vehicle translation movement speed (on railway). With $\Omega_0 = \Omega_m / i$, where Ω_m is angular speed of traction motor rotor and i is mechanical transmission ratio, it results that:

$$v = \frac{D_r \cdot \Omega_m}{2 \cdot i} \qquad (3)$$

The relations (1) and (3) are fundamentals in the electric traction systems design, because allow the establishment of the vehicle characteristics, depending both on the useful torques quantity M_2 and on the angular speed Ω_m. In train running, both under the traction motors action and under the rail resistance influence, the useful translation movement of railway vehicle will be achieved.

III. Induction Machine Operation at Variable Frequency

The electric urban underground trains supplied from a d.c. contact line are equipped with three-phase induction motors (having squirrel cage rotors) and variable voltage and frequency inverters [8]. Since the electric driving systems with static converters and traction induction motors are used, by an appropriate control, with the same electrical machines there can be realized both the operation regime and the electric braking regime of the electric traction vehicles [7],[9].

In the domain of frequencies lower than rated frequency $f_s < f_N$ (in order to ensure a constant level of inductor machine stator flux $\Psi_s = \Psi_{sN}$), at the same time have to be modified the frequency f_s and the supply voltage magnitude U_s, so that the phase voltage effective value U_s will vary with the frequency f_s according to relation $U_s(f_s) = \left| R_s \cdot \underline{I}_s + j \cdot 2\pi \cdot f_s \cdot \underline{\Psi}_{Sn} \right|$. Consequently, the induction machine supplied from a variable frequency and voltage source will operate with full field $\psi_s = \psi_{Sn}$ = ct. in the low frequencies domain $f_s \le f_N$ and with weaker field ($\psi_s < \psi_{Sn}$) in the increased frequencies domain $f_s > f_N$ (when the supply voltage remains constant $U_s = U_N$=ct.).

Taking into account that:

$$U_s = U_s(f_s); \omega_s L_s = \frac{f_s}{f_N} X_s; L_{r'} = \frac{X_{r'}}{\omega_N} \qquad (4)$$

the induction machine electromagnetic torque expression $M = M(f_s, \omega_r)$ will be obtained, for any stator frequency magnitude f_s and rotor pulsation ω_r, respectively:

$$M = \frac{\frac{3p}{\omega_N}(1-\sigma) X_s [U_s(f_s)]^2}{\frac{\omega_N R_{r'}}{\omega_r X_{r'}}\left[R_s^2 + \left(\frac{f_s}{f_N} X_s\right)^2\right] + 2\frac{f_s}{f_N} R_s (1-\sigma) X_s + \frac{\omega_r X_{r'}}{\omega_N R_{r'}}\left[R_s^2 + \left(\frac{f_s}{f_N}\sigma X_s\right)^2\right]} \qquad (5)$$

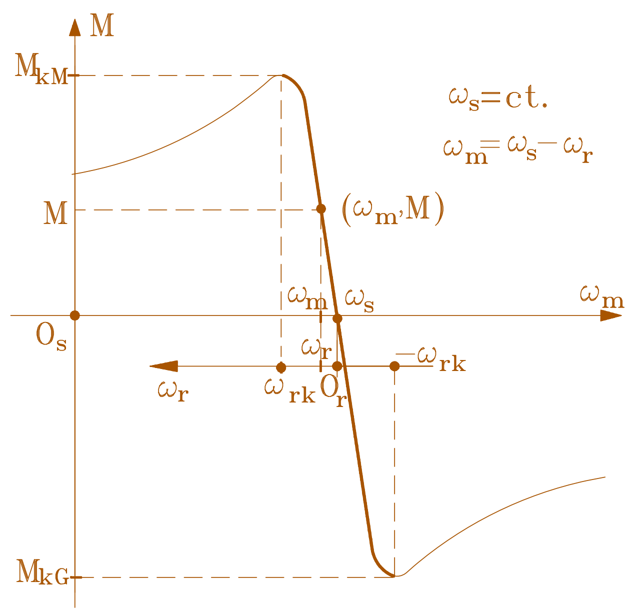

Fig.1 Mechanical characteristic $M = f(\omega_m)$ at ω_s=ct.

where: $\omega_s = \omega_r + \omega_m\, ;\, \omega_m = p \cdot \Omega_m\, ;$

$$X_s = X_{s\sigma} + X_u\, ;\, X_{r'} = X_{r'\sigma} + X_u\, ;$$

$$\sigma = 1 - \frac{X_u^2}{X_s \cdot X_{r'}}$$

Consequently, for any constant value of frequency f_s=ct. (when either $\omega_s = 2\pi f_s$=ct.) the voltage U_s will be also constant $U_s(f_s)$=ct. and the torque curve (or induction machine mechanical characteristic $M=f(\omega_m)$ will maintain the classic shape of Fig.1. It must be noticed the relation between angular speed (in el.rad.) ω_m, stator pulsation ω_s and rotor pulsation ω_r:

$$\omega_m = \omega_s - \omega_r = p \cdot \Omega_m = p \cdot 2\pi n/60$$

In Fig.1, corresponding to synchronism point $\omega_m = \omega_s$ (at frequency f_s) it is marked the origin O_r (on axis ω_r) from which it is measured (in opposite sense to ω_m) the rotor pulsation magnitude ω_r.

A. *Operation at low frequency*

Operation at stator decreased frequencies, lower than rated frequency, is corresponding to induction machine supply with three-phase symmetrical voltages by frequency $f_s \leq f_N$, with effective value of phase voltage $U_s \leq U_N$ depending on frequency magnitude as it had shown as before.

In steady-state regime, the induction machine operation at U_s/f_s=ct.$=U_N/f_N$ can be followed by replacing in relation (5) the stator voltage U_s with linear dependence expression $U_s=U_s(f_s)= U_N \cdot f_s/f_N$:

$$M = \frac{\frac{3p}{\omega_N}(1-\sigma)X_s\left(\frac{f_s}{f_N}U_N\right)^2}{\frac{\omega_N R_{r'}}{\omega_r X_{r'}}\left[R_s^2 + \left(\frac{f_s}{f_N}X_s\right)^2\right] + 2\frac{f_s}{f_N}R_s(1-\sigma)X_s + \frac{\omega_r X_{r'}}{\omega_N R_{r'}}\left[R_s^2 + \left(\frac{f_s}{f_N}\sigma X_s\right)^2\right]} \qquad (6)$$

For any stator frequency constant value f_s=ct., with $f_s \leq f_N$, the electromagnetic torque expression (5) can be represented as depending on rotor pulsation magnitude ω_r, by curve $M=f(\omega_r)$. Moreover, if the substitution $\omega_r = \omega_s - \omega_m$ it is made, with ω_m depending on rotor speed n according to $\omega_m = 2\pi pn/60$, then for any constant frequency $f_s < f_N$ the mechanical characteristic $M=f(n)$ of induction machine supplied with variable voltage $U_s = U_N \cdot f_s/f_N$ can be obtained.

From the exergetic viewpoint it is important to emphasize an important drawback of operation at U_s/f_s=ct., which concerns the sudden decrease of maximum torque M_k in motor regime when the stator frequency f_s is reducing under 20 Hz (generally, under f_N/3 Hz). The physical explanation for this dropping of maximum torque M_k is based on the motor flux decreasing at low frequencies, when the stator voltage $U_s = U_N \cdot f_s/f_N$ is already reduced while the voltage drop on the stator resistance $R_s \cdot I_s$ remains almost invariable as magnitude at all frequencies $f_s \leq f_N$. As consequence, in the operation regime with U_s/f_s=ct., at low frequencies the induction motor performances will be strongly affected, because of severe flux decreasing which will produce an intolerable loss of induction motor torque capability.

Consequently, it must be noticed that from the exergetic issues, the emodied energy is unsatisfactory.

This situation can be avoided only by the forced increasing of the terminals voltage U_s. Consequently, this voltage will depend on stator frequency f_s by a law $U_s=U_s(f_s)$ which will not respect a proportionality with f_s. In a particular case, the law of voltage variation with frequency $U_s=U_s(f_s)$ will be obtained if in motor regime a certain condition it is imposed, meaning the torque $M_k(f_s)$ must remain equal to the torque $M_{Km}(f_N)$. For $U_s=U_N$ and $f_s=f_N$ it will result:

$$M_{kM}(f_N) = \frac{1}{2}\frac{3p}{\omega_N}\frac{(1-\sigma)X_s U_N^2}{R_s(1-\sigma)X_s + \sqrt{[R_s^2 + X_s^2][R_s^2 + (\sigma X_s)^2]}} \qquad (7)$$

The condition $M_k(f_s)=M_{Km}(f_N)$ imposes the law $U_s=U_s(f_s)$ as the form:

$$U_s(f_s) = U_N\sqrt{\frac{\frac{f_s}{f_N}R_s(1-\sigma)X_s + \sqrt{\left[R_s^2 + \left(\frac{f_s}{f_N}X_s\right)^2\right]\left[R_s^2 + \left(\frac{f_s}{f_N}\sigma X_s\right)^2\right]}}{R_s(1-\sigma)X_s + \sqrt{[R_s^2 + X_s^2][R_s^2 + (\sigma X_s)^2]}}} \qquad (8)$$

In accordance, the mechanical characteristics are represented in Fig.2.

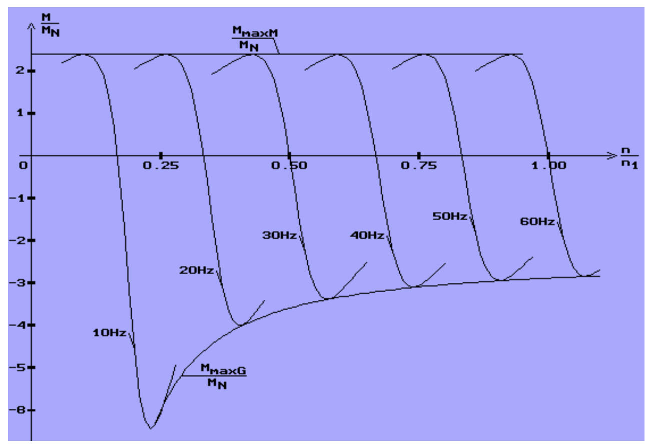

Fig.2 Mechanical characteristics of induction machine supplied with $U_s = U_s(f_s)$ in accordance with rel. (7)

Further on it will be analyzed the induction machine asymptotical behavior at low frequencies.

The torque curve shape is mainly determined by the extreme points coordinates values. Because both ω_{rk} and M_k are depending on f_s it will be expected a deformation of torque curve $M = f(n)$ when the supply frequency is modifying. For instance, for an induction machine with constant parameters and f_s=variable (with $f_s \ll f_N$) the critical rotor pulsation ω_{rk} will "collapse", which is directing towards a mechanical characteristics rigidity. Mathematically, at low frequencies $f_s \ll f_N$ [7] the expressions of electromagnetic torque M, critical rotor pulsation ω_{rk} and maximum torque M_k will be, respectively:

$$\lim_{f_s \to 0} M(f_s, \omega_r) = \frac{3p(1-\sigma)L_s I_s^2}{\frac{R_{r'}}{\omega_r L_{r'}} + \frac{\omega_r L_{r'}}{R_{r'}}} = M_{Is}(\omega_r) \qquad (9)$$

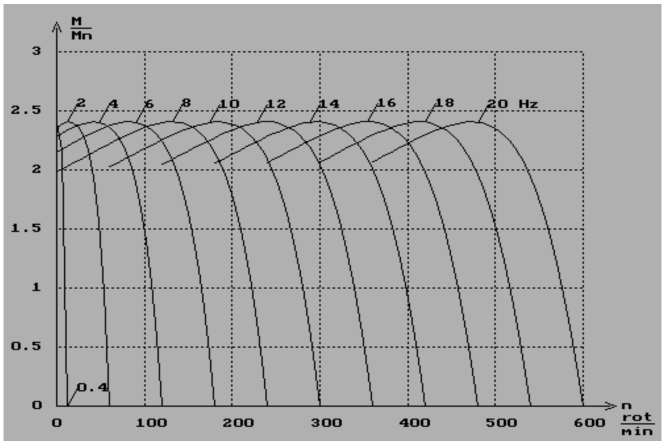

Fig.3 Mechanical characteristics (with M_k=ct. at $f_s \leq 20$ Hz) of induction machine

$$\lim_{f_s \to 0} \omega_{rk}(f_s) = \pm \frac{R_{r'}}{L_{r'}} = \omega_{rkIs} \quad (10)$$

$$\lim_{f_s \to 0} M_k(f_s) = \pm \frac{3p}{2}(1-\sigma) L_s I_s^2 = M_{kIs} \quad (11)$$

Accordingly in Fig.3 for stator frequency values under 20 Hz the mechanical characteristics M=f(n) in motor regime are represented.

It needs to be also notified that when frequency $f_s \to 0$ the operation becomes possible only on unstable part of mechanical characteristic with all well-established disadvantageous consequences.

B. Operation at high frequency

In case of induction machine supplied from a variable frequency voltage source when rated speed is reached (induction motor supplied at U_N and f_N) the further speed increasing will be possible only by stator frequency magnitude increasing over rated frequency $f_s > f_N$. It must be emphasized that because of both converters voltage restriction and induction machine windings insulation considerations, the

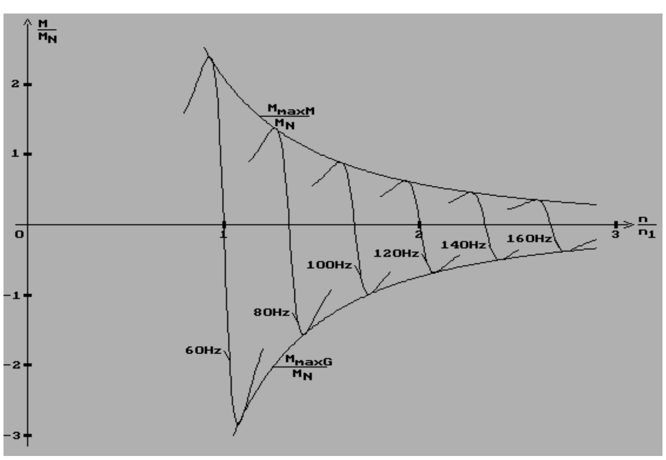

Fig.4 Mechanical characteristics at $U_s = U_N$=ct. and $f_s > f_N$

stator voltage will be limited and maintained at constant magnitude $U_s = U_N$ on all high frequency domain. Consequently, when $f_s > f_N$ and $U_s = U_N = |R_s \cdot \underline{I}_s + j \cdot \omega_s \cdot \underline{\psi}_s|$, the induction machine will operate in weaker flux conditions. From exergical viewpoint it must be notified that because flux and stator pulsation are into a inverse proportionality relation $\Psi_s = U_N / \omega_s$ the torque capability will be strongly affected. The sudden decreasing of induction machine torque is illustrated in Fig.4 by the mechanical characteristics corresponding to $U_s = U_N$=ct. and $f_s > f_N$.

The assessment of induction machine operation at variable frequency represents just a step in the vehicle exergetical study. Further on, the analysis of railway vehicle as an assembly in the goal of achieved energy establishment is required .

IV. Achieved Energy in Vehicle Operation

In underground railway transportation systems, achieved energy provides a basis for increasing exergy efficiency, reducing both energy losses and environmental damage. Further on, exergy more broadly can help in optimizing designs and making operating decisions.

The exergy efficiency assessment [9] imposes an analysis of urban electric vehicle as a system. The electric urban underground trains supplied from a d.c. contact line are equipped with three-phase induction motors (having squirrel cage rotors) and variable voltage and frequency inverters. In the power electrical chain there are many types of energy conversion. For instance, the induction motors produce the final electromechanical conversion, making thus possible the vehicle movement.The exergy issues require the vehicle electric motors are operating at designed rating power on a running speed interval as long as possible. As a complex electromechanical system [7], the induction motor could be conceptually decomposed into an electromagnetic part and a mechanical part .

Between these two functional parts, both the electromagnetic torque M and the rotor mechanical speed Ω_m are interacting as internal variables. In the motor vehicle case, the mechanical part of traction induction motor is coupled (through the transmission medium) with the motive axle and can be modelled in the shape of the useful movement or/and the elastic mechanical transmissions [10]. In the goal to be connected, the models must be achieved in accordance with same principles, indifferently of described phenomenon nature, i.e., an electromagnetic phenomenon or a mechanical one. A fixed reference system, related at stator it is taken into account. Hence, the induction motor electromagnetic part will be described [10] by the following equations :

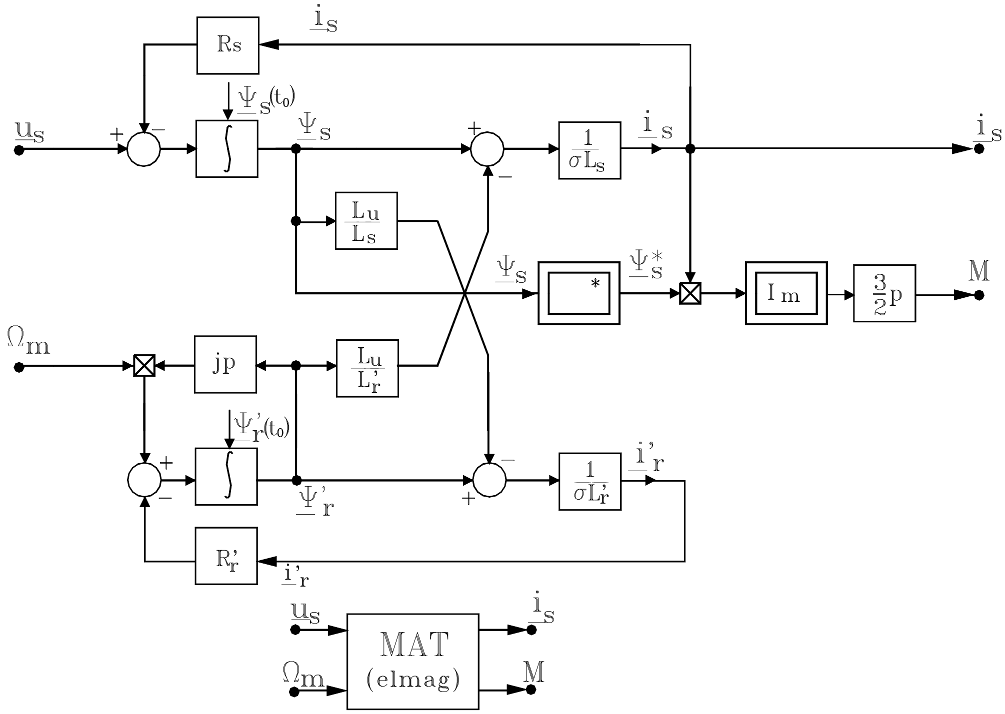

Fig.5 Structural diagram and mask block for induction motor electromagnetic subsystem

$$\frac{d\underline{\psi}_s}{dt} = \underline{u}_s - R_s \cdot \underline{i}_s$$
$$\frac{d\underline{\psi}_{r'}}{dt} = j \cdot p \cdot \Omega_m \cdot \underline{\psi}_{r'} - R_{r'} \cdot \underline{i}_{r'} \qquad (12)$$
$$\underline{i}_s = \frac{\underline{\psi}_s - \frac{L_u}{L_{r'}} \cdot \underline{\psi}_{r'}}{\sigma L_s}; \quad \underline{i}_{r'} = \frac{\underline{\psi}_{r'} - \frac{L_u}{L_s} \cdot \underline{\psi}_s}{\sigma L_{r'}}$$
$$M = \frac{3}{2} \cdot p \cdot Im\{\underline{i}_s \cdot \underline{\psi}_s^*\}$$

where :$\underline{u}_s$ is stator voltage vector, $\underline{i}_s$ is stator current vector, $\underline{i}_r$' is rotor current vector, $\underline{\Psi}_s$ is stator flux vector, $\underline{\Psi}_r$' is rotor flux vector, L_u is magnetizing inductance, L_s is stator inductance, L_r' is rotor inductance, *p* is pole pairs number, R_s is stator resistance, R_r' is rotor resistance and $\sigma = 1 - \frac{L_u^2}{L_S \cdot L_{r'}}$ is motor leakage coefficient.

On basis of equations (12) the structural diagram and the mask block of the induction motor electromagnetic part are represented in Fig.5.

The mathematical model of induction motor mechamnical transmission is based on the relation between motor torque, resistant torque and mass inertia equivalent moment:

$$M - \frac{1}{i} M_r = J_{ec} \frac{d\Omega_m}{dt} \qquad (13)$$

$$\Omega_{rt} = \frac{1}{i} \Omega_m \qquad (14)$$

On basis of equations as before in Fig. 6 the structural diagram and the mask block for the induction motor mechanical transmission are represented.

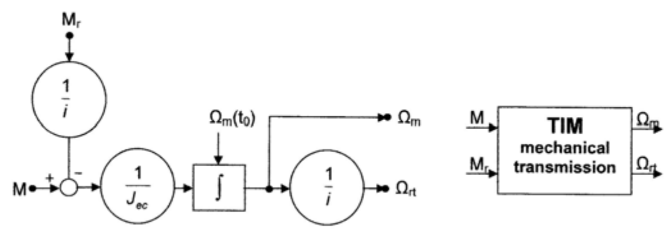

Fig 6 Structural diagram and mask block for induction motor mechanical transmission

The high exergy in vehicle operation impose also the assessment of the inverter mathematical model [11]. On basis of principle electronic scheme in Fig.7 the structural diagram and mask block of the three-phase voltage inverter with λ levels commutation are presented.

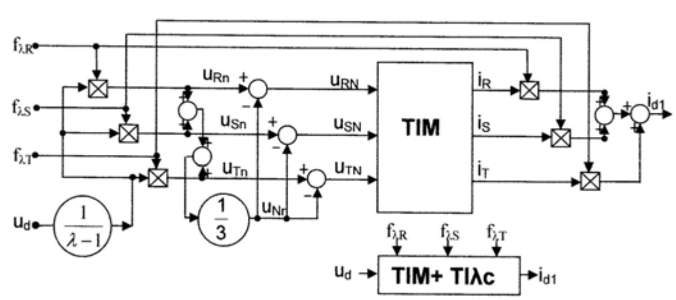

Fig.7 Structural diagram and mask block for three-phase voltage invertor with λ levels commutation

Further on, the achievement of vehicle drive system structural diagram becomes possible.

In the paper it is taken into account a urban electric train MW + MW [6], meaning two motor wagons which are elastic coupled. The vehicle electric scheme is in variant V2, which is defined by the coefficient K=2/2, meaning two static converters, each of them supplying two traction bi-motors. Viewed as a system, on basis of the previous structural diagrams, the urban electric vehicle structural diagram it is assessed in Fig.8.

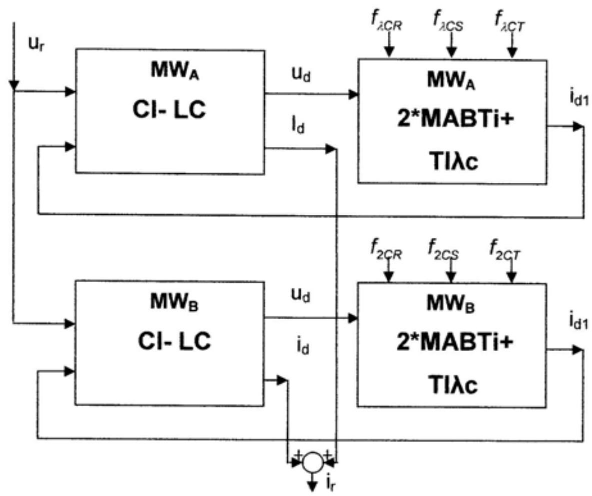

Fig 8 Structural diagram of urban electric vehicle MW + MW, K=2/2

Consequently, in normal operation of vehicle the exergetical issues can be accomplished by an appropriate control of the urban electric train [10], on basis of the structural diagram of useful moment presented in Fig.9.

Further on, taking into account the assessed models, the achieved energy of an urban railway transportation system will be analyzed .

V. CASE STUDY

The exergy of a system denotes equilibrium with the environment, but also exergy can interface broadly with economics [3],[4],[5]. In underground railway transportation systems, the achieved energy provides a basis for exergy efficiency increasing, reducing both energy losses and environmental damage. Further on, achieved energy and exergy more broadly can help in optimizing designs and making operating decisions.

The achieved energy analysis presumes an understanding of electric transportation system operating in certain conditions.The electric traction scheme presented as before, meets the criteria both of the vehicle running behavior safety and of the traction scheme reliability.

From viewpoint of exergy efficiency and environment issues, a special aspect, in case of the non-autonomous vehicles with electric traction it is represented by an abnormal but frequent situation of train operation, concerning the unequal charge of the traction induction motors [7].The vehicle motor wheels could be considered as mechanical coupled through the same railway mechanical contact. Because the brake blocks are submitted for different intervals time to different braking forces during this regime it will appear the wheels rollers wear. The unequal brake blocks wears will determine the motor wheels diameter difference and, further on, it means that the electric motors rotors will operate at different speed of each other. Consequently, the traction induction motors will be unequally charged, meaning a motor will be overcharged and another motor will be undercharged. From the viewpoint of the achieved energy, this is one of the most unfavorable vehicle operation regime.That's why in this paper there are presented numerical simulations and experimental data related to unequally charged motors regime.

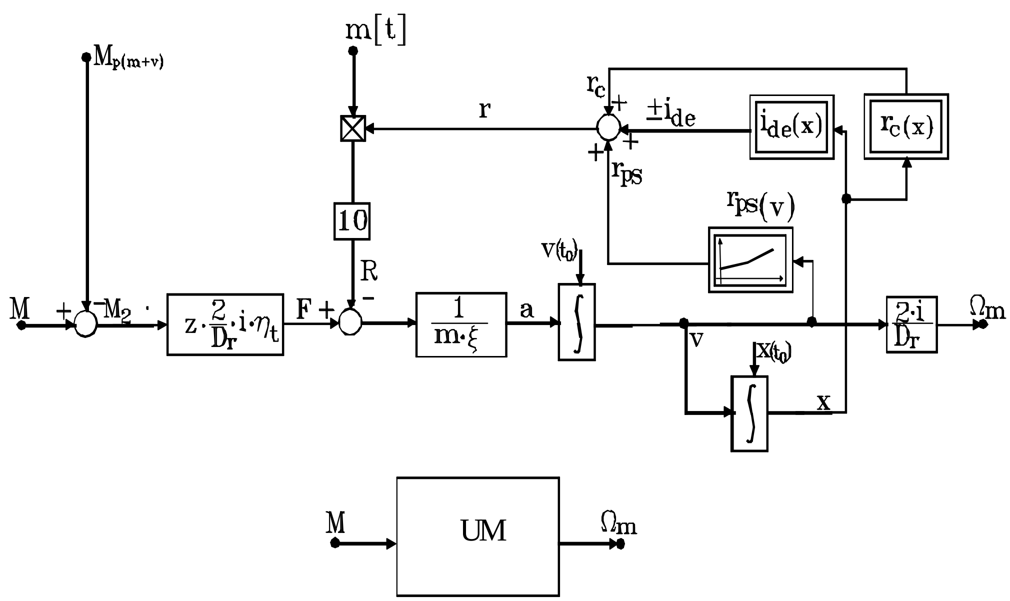

Fig.9 Structural diagram and mask block of useful movement

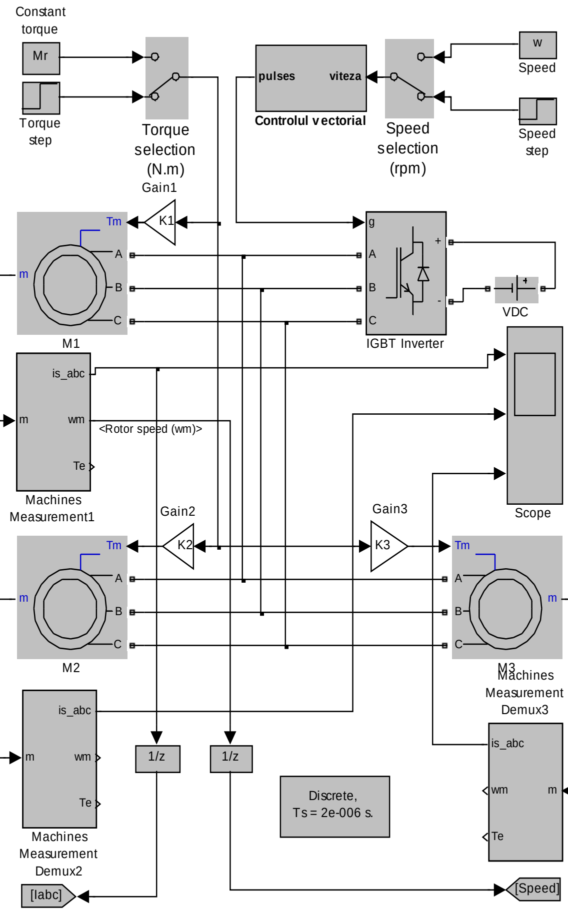

Fig 10 SIMULINK – SimPowerSystems Model for unequally charged induction motors

For an urban electric train equipped with three-phase induction motors and variable voltage and frequency inverters [11] the SIMULINK – SimPowerSystems Model for unequally charged traction motors regime was achieved and presented in Fig.10. For the traction motors MABT2 [12] the simulations of currents waves in unequally charged motors regime are presented in Fig.11, for frequency fs=50 Hz , and in Fig.12, for the frequency fs=40 Hz .

In accordance with Fig.11, in an unequally charged motors regime defined by the motor wheel wear deviation u, at the inverter output voltage frequency f=50 Hz, the following data have resulted [12]:

- when comparing the motors M_1 and M_2 with u=4,5% it results $\Delta I_1 = 11{,}5/\sqrt{2} = 8{,}156\ Arms$;
- when comparing the motors M_1 and M_2 with u=9% it results $\Delta I_1 = 22{,}5/\sqrt{2} = 15{,}957\ Arms$

In accordance with Fig.12, in an unequally charged motors regime defined by the motor wheel wear deviation u, at the inverter output voltage frequency f=40 Hz, the following data have resulted:

- when comparing the motors M_1 and M_2 with u=4,5% it results $\Delta I_1 = 12{,}9/\sqrt{2} = 9{,}149\ Arms$;
- when comparing the motors M_1 and M_2 with u=9% it results $\Delta I_1 = 24{,}5/\sqrt{2} = 17{,}447\ Arms$.

Numerical simulations achieved with SIMULINK-SimPowerSystems Model had been validated by experimental tests accomplished on the Electrical Traction Experimental Lab Stand (Fig.13) of the Faculty of Engineerings in Electromechanics and Environment Craiova. Among the electric traction specific phenomena which had been studied

Fig.13 Electrical Traction Experimental Lab Stand

in this lab framework the unequally charged motors regime takes its place. To this purpose, on the static voltage converter terminals had been parallel connected two traction motors with unequal motor wheels diameters. The traction motors are rigid coupled through the railway-wheel contact and mechanical transmission. The tests have been realized for unequally charged motors regime at different frequencies (f=50 Hz, f=40 Hz, f=30 Hz) and defined by the motor wheel wear deviation u corresponding to simulation conditions:

- when comparing the motor M_1 new wheel with diameter D_1 = 910 mm with the motor M_2 medium weared wheel with diameter D_1=870mm the deviation u=4,5% had resulted;

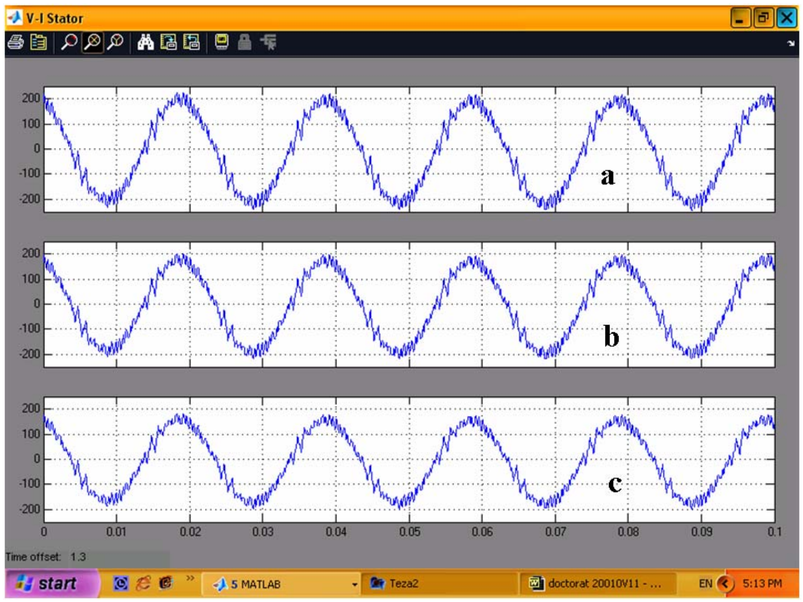

Fig.11 Unequally charged motors regime simulation , fs=50Hz:
a) Phase current M_1 – new wheel driving u=0%;
b) Phase current M_2 – medium weared wheel driving u=4,5%;
c) Phase current M_3 – weared wheel driving u=9%

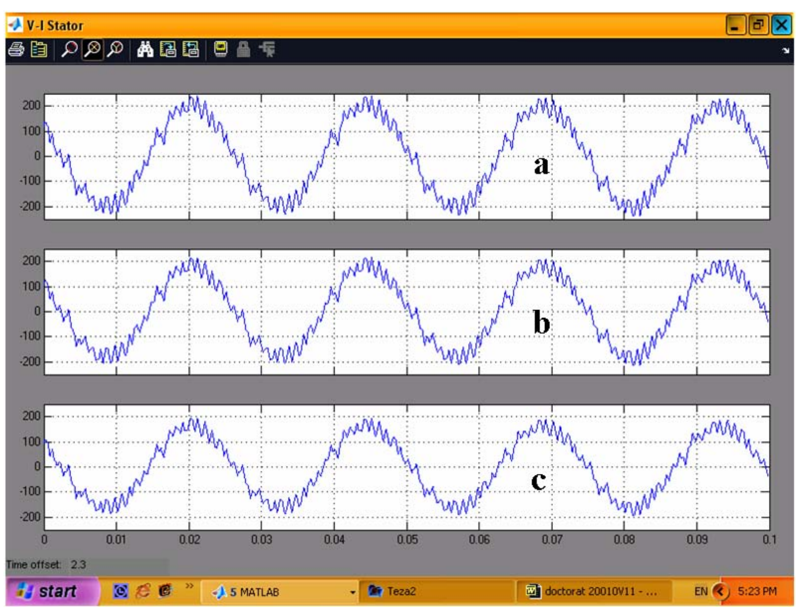

Fig.12 Unequally charged motors regime simulation , fs=40Hz:
a) Phase current M_1 – new wheel driving u=0%;
b) Phase current M_2 – medium weared wheel driving u=4,5%;
c) Phase current M_3 – weared wheel driving u=9%

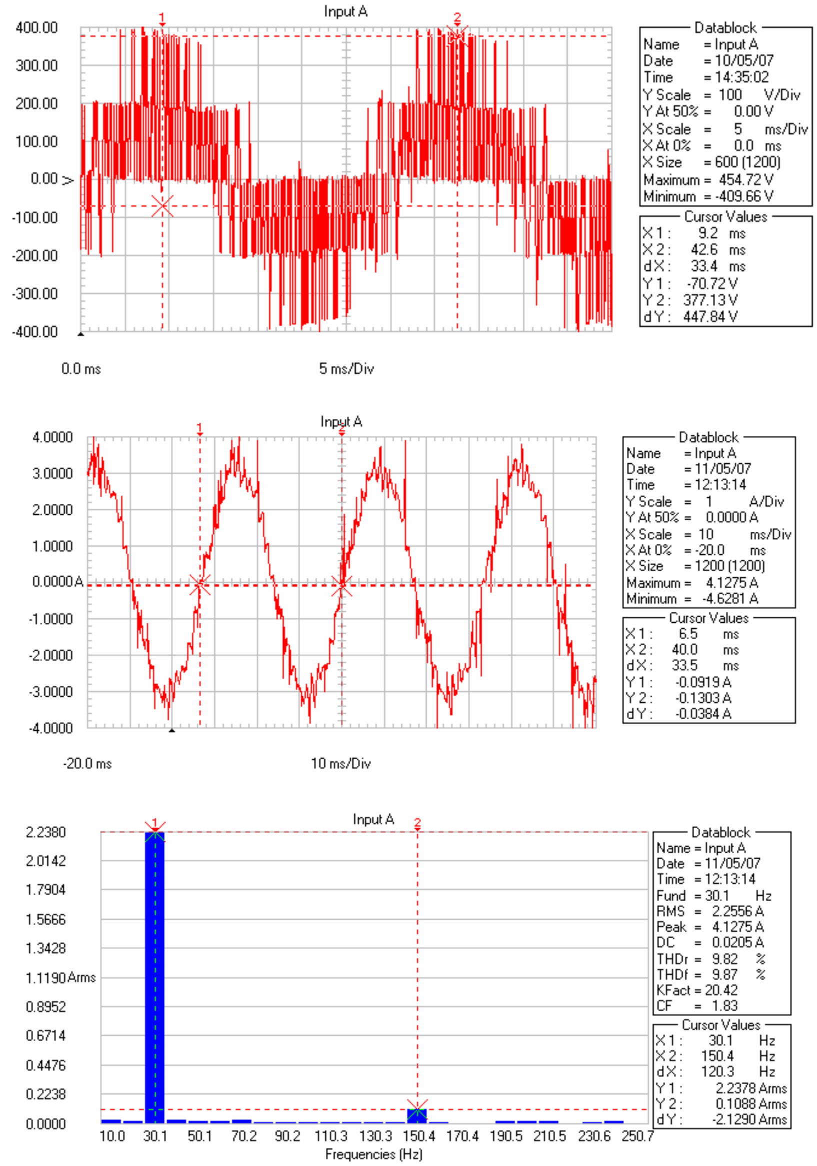

Fig.14 Experimental tests of assembly three-phase induction motor + 2 levels voltage inverter at fs=30Hz: a) Phase voltage; b) Phase current; c) Current harmonics hystogram.

- when comparing the motor M_1 new wheel with diameter D_1 =910 mm with the motor M_2 weared wheel with diameter D_1=830 mm the deviation u=9% had resulted.

In the studied case, because of the motors wheels diameters inequality, it had appeared an unbalanced regime with the motors operating at different speed, into an inverse relation with the wheels diameters. Consequently, as example, in Fig.14 there are presented [12] the experimental tests of assembly three-phase induction motor + 2 levels voltage inverter at fs=30Hz, concerning the phase voltage, the phase current and the current harmonics hystogram. The errors of expeimental data compared to simulation data are in the range of 6% in case of wear u=4,5% and in the range of 20% in case of wear u=9% (because of different railway-motor wheels adherence coefficients).

VI. Conclusions

The real world processes involving energy and matter need to be linked to the environmental engineering education, design and operation. This paper emphasizes a number of sustainability-based concepts, such achieved energy, exergy and embodied energy, related as tools in order to describe, analyse and optimize energy conversion in underground transportation systems. Energy systems involving coversion chain processes are highly irreversible and, consequently, they could have low exergy efficiencies. This observation also implies that there is great potential for improving the performance of such systems. These tools are useful in order to describe, analyse and optimize energy conversion in underground transportation systems. The living Nature and the human engineering actions can not anymore be separated and most important roles belong both to engineering processes and to environmental education

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 effienciency. Costs should reflect value and value is not associated with achieved energy but with exergy and sustainability. This paper aimed at examining an underground railway train 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.

In traction regime, the train case study accomplishes remarkable results. Using the structural diagrams and high techniques converters, an appropiate vehicle control can be achieved. This way, the train experimental dynamic characteristics respect the theoretical mechanical characteristic and the energy efficiency is equal to the exergy efficiency. The power converters and the efficient anti-skidding systems have ensured the optimum traction characteristics and a minimum energy consumption.The actual techniques allow to implement the driving systems on the basis of the variable voltage and frequency static converters and induction motors, which are leading to an improved electric braking regime, even with the energy recovery. In that operating regime, the vehicle provides energy in the d.c. network through the inverter.The recovered energy it is taken by other running underground trains. It means that the exergy efficiency is a great one.

But, at low speed the mechanical brake can't be avoid. Among the environment issues, from viewpoint of exergy efficiency, a special aspect, in case of the non-autonomous vehicles with electric traction it is represented by an abnormal but frequent situation of train operation, concerning the unequal charge of the traction induction motors. Because the brake blocks are submitted for different intervals time to different braking forces during this regime it will appear the wheels rollers wear. The unequal brake blocks wears determine the motor wheels diameter difference and, further on, it means that the electric motors rotors will operate at different speed on each other. Consequently, the traction induction motors will be unequally charged, meaning a motor will be overcharged and another motor will be undercharged. From the viewpoint of the achieved energy, this is one of the most unfavorable vehicle operation regime.

In a longterm, the important application of this research is to address sustainability issues in a qualitative and quantitative fashion through an underground transportation system analysis.

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