Energy and Exergy Efficiencies in Urban Electric Transportation Systems

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Abstract: - This paper 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. The study case presented in the paper emphasized the operation of the static converters and the traction induction motors as an assembly, both in the traction regime and in the electric brake regime, for different urban underground metro trains produced by Craiova Electroputere Factory for Bucharest Underground Trasportation System. In this application, the exergy analysis can help improve and optimize the underground transportation system design and operation.

Key-Words: - Electric transportation, energy, environment, exergy, induction motor, static converters, underground train

1 Introduction

The vitality and perheps the future survival of the society is strongly depending on the management of physical, environmental and human resources [1]. The first human intelligence step against ignorance would be the understanding of concepts such sustainable development or energy and exergy efficiencies.

The *Sustainable Development* concept definition comes from the Brundtland Report [2], which states that "the Sustainable Development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The Sustainable Development does not focus only on the environmental issues. On a broader front, sustainable development policies encompass three general policy areas, concerning the economical development, the environmental issues and the social protection. 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 analyzation and the further alternatives knowledge. It is taken into account the Railway Transportation Systems, not simply in terms of technico-economical growth, but also as an achievement of the Sustainable Development. In the paper authors oppinion [3], [4], [5], 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 trasportation system.

Exergy is a well-established concept in engineering . The exergy of an energy or material quantity measures its usefulness or quality [6]. Although energy cannot be destroyed, exergy can [7]. Energy efficiencies do not always assess how nearly performance approaches ideality and do not properly describe factors that cause performance to deviate from ideality. Exergy analysis [8], [9], [10] 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.

2 Urban Vehicle Useful Movement

This study aims at examining energy and exergy efficiencies in an electric underground railway transportation vehicle viewed as a system. 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 [11], [12]. 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 [13]. At the running radius $r=D_r/2$, to motor torque M_R will correspond a motor force F_o[N] at wheels [11], [15]:

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

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.

The train useful movement is determined by the external forces action. According to Fig.1, these forces could be :

- traction active forces, with resultant $\overline{F_t}$ (of controllable magnitude, which are acting on useful moment sense and direction);

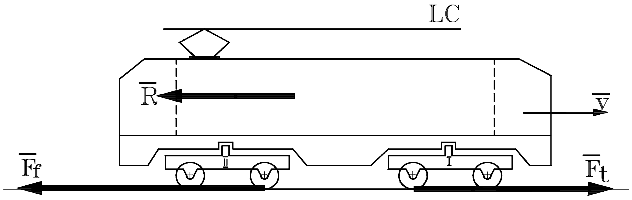

Fig.1 External forces on electric railway vehicle

- braking active forces, with resultant $\overline{F_f}$ (of controllable magnitude, which are acting on useful movement direction, but in opposite sense to speed vector $\overline{v}$);
- train running resistant forces, with resultant $\overline{R}$.

The traction $\overline{F_t}$ and braking $\overline{F_f}$ forces in whatever operation regime are not simultaneously acting , while the train running resistant force $\overline{R}$ it is acting all the time, even in the active forces absence (in the coasting regime without current).

3 Vehicle Mechanical Characteristic

Only the urban railway vehicles with electric motors at wheels are taken into account. The active force developed in traction or electric brake regime by each motor axle due to the traction motor torque it is tangentially transmitted towards the railway, on basis of adherence, through the contact surface points [11]. That force represents the active force (in traction or electric brake regime) at the rim F_0 and its magnitude is top limited by the maximum adherence force. The vehicle entire active force F is the result of a cumulative process, by summing the active forces (developed at rim) corresponding to the vehicle wheels and depending on electric traction motors number.

In traction or electric brake regime, the active mechanical power P_0 [W] developed at the vehicle motor wheels rims are depending both on useful movement speed v [m/s] and on active force F:

$$P_0\,[W] = F[N]\cdot v[m/s] \qquad (4)$$

Because in technical applications the active force F is usually given in [kN] and the speed v in km/h (meaning v [km/h] = 3,6 v [m/s]), the active power at rim P_0 in [kW] will be determined as:

$$P_0\,[kW] = \frac{F[kN] \cdot v[km/h]}{3,6} \qquad (5)$$

The graphical dependence between the total active force F and the vehicle running speed v represents the electrical vehicle mechanical characteristic. Depending on useful movement regime, the mechanical characteristic is named, respectively, traction characteristic (in case of electric traction regime) or electric brake characteristic (in case of electric brake regime).

The exergy issues [16], [17] require the vehicle electric motors are operating at designed rating power on a running speed interval as long as possible. Hence, the active power at rim P_0 will be constant and the active force F will depend on the speed according to the relation:

$$F[kN] = 3,6 \cdot \frac{P_0\,[kW]}{v[km/h]} \qquad (6)$$

On basis of relation (6) a hyperbole form of the active force F will result. Still, an exact representation of the ideal mechanical characteristic imposes the restrictions imposed by the adherence and the designed maximum speed had also taken into account.

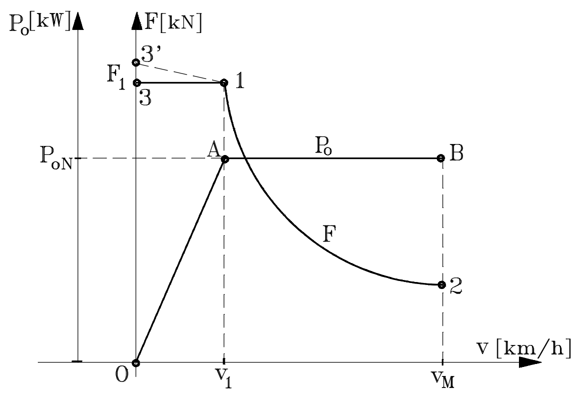

Fig.2 Ideal mechanical characteristic

Therefore, the ideal mechanical characteristic 3-1-2 is represented in Fig.2. On the characteristic there are emphasized two distinct domains: a) a constant force domain (i.e., zone 3-1) in range of speed between 0 and v_1 (i.e., rated speed); b) a constant power domain (i.e., zone 1-2), between rated speed v_1 (i.e., point 1) and maximum speed v_M (i.e., point 2).

The assessment of ideal mechanical characteristic of urban electric vehicle represents a step in this exergy study. Further on, the railway vehicle modelling as an assembly is required by the exergy efficiency analysis.

4 Electric Traction Motor Modelling

The exergy efficiency assessment [18],[19],[20] imposes an analysis of urban electric vehicle as a system. 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. As a complex electromechanical system [15], the induction motor could be conceptually decomposed into an electromagnetic part and a mechanical part (Fig.3).

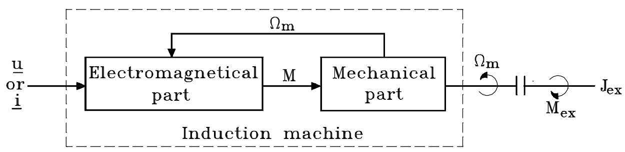

Fig.3 Functional parts of traction induction motor

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 [11]. 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 by the equations [21], [22], [23]:

$$\begin{gathered}
\frac{d\underline{\psi}_s}{dt} = \underline{u}_s - R_s \bullet \underline{i}_s \\
\frac{d\underline{\psi}_{r'}}{dt} = j \bullet p \bullet \Omega_m \bullet \underline{\psi}_{r'} - R_{r'} \bullet i_{r'} \\
\underline{i}_s = \frac{\underline{\psi}_s - \frac{L_u}{L_{r'}} \bullet \underline{\psi}_{r'}}{\sigma L_s}; \quad \underline{i}_{r'} = \frac{\underline{\psi}_{r'} - \frac{L_u}{L_s} \bullet \underline{\psi}_s}{\sigma L_{r'}} \\
M = \frac{3}{2} \bullet p \bullet Im\{\underline{i}_s \bullet \underline{\psi}_s^*\}
\end{gathered} \qquad (7)$$

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

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

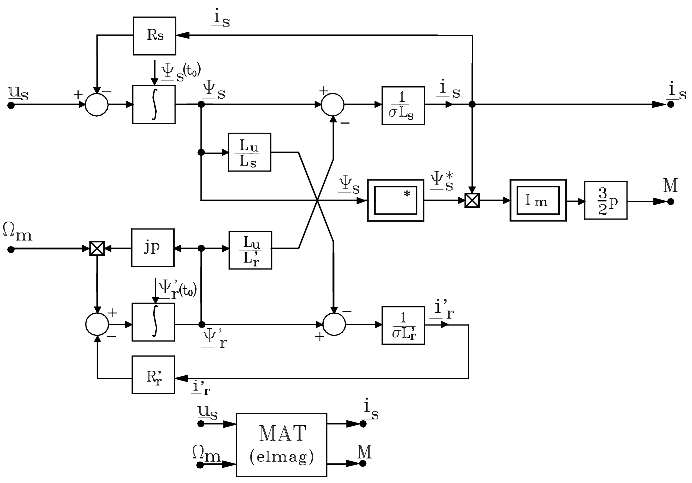

Fig.4 Structural diagram and mask block for electromagnetic part of induction motor

On basis of equations (7) the structural diagram and the mask block of the induction motor electromagnetic part are represented in Fig.4.

5. Useful Movement Modelling

The vehicle resistant forces R and the traction characteristics F=F(v) allow the study of the vehicle useful movement. In these conditions the useful movement equation is [11], [15],[24]:

$$m^* \cdot \frac{dv}{dt} = F - R; \quad m^* = m \cdot \xi \qquad (8)$$

where force F is either a traction regime force F_t or a braking regime force F_f, and ξ is a train mass increasing coefficient which take into account the presence and weight of the train structure turning parts (ξ=1.06…1.2).This way, through the mass increase coefficient agency it can make abstraction of the turning parts presence, replacing the train real mass "m" by a "fictitious mass" $m^*=m\cdot\xi$ in translation movement with the "v", the same of the considered vehicle. From the physical viewpoint, this is equivalently with fictitious replacement of the mechanical system of rigid solid parts through a material point with inertial mass $m^*=m\cdot\xi$.

For an exercy dynamic approach of the useful movement [4], [15], [25], [26] a mathematical model is necessary. Hence, it is considered an electric vehicle of mass $m[t]$ and mass increasing coefficient ξ having the train resistant force r [daN/t]. On the useful movement duration, the speed v(t) and the distance x(t) are ruled at the equations

$$m \cdot \xi \cdot \frac{dv}{dt} = F - R \,; \quad \frac{dx}{dt} = v \qquad (9)$$

If the movement is obtained under the useful torques action M_2 developed by "z" traction motors on the electric vehicle, then in accordance with the relations (1) and (3):

$$\Omega_m = \frac{2 \cdot i}{D_r} \cdot v \,; \quad F = z \cdot \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \qquad (10)$$

Moreover, if the train mass m is expressed in [t], the total train resistant force R[N] is assessed by

$$R[\mathrm{N}] = r[\mathrm{daN/t}] \cdot m[\mathrm{t}] \cdot 10 \qquad (11)$$

The equations assembly (9), (10), (11) determines the mathematical model of the useful movement. Written together, in shape of

$$v = \frac{1}{m \cdot \xi} \int (F-R)dt \,; \quad \Omega_m = \frac{2 \cdot i}{D_r} \cdot v; \quad x = \int v \cdot dt \,;$$
$$F = z \cdot \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \,; \quad R = (r_{ps}(v) \pm i_{de}(x) + r_c(x)) \cdot m \cdot 10 \qquad (12)$$

allow a structural diagram construction of the useful movement , as it is shown in Fig.5.

In the mask block the torque M represents the input quantity, while the speed Ω_m is the output quantity during the useful movement.

Further on, by coupling this scheme (Fig.5) at the structural diagram of traction motor electromagnetic part (Fig.4) it had achieved the model presented in Fig. 6. This way, it can be simulated the useful movement of any electric vehicle in the aim to meet the optimum vehicle control modalities. Accordingly, the running diagrams v(t) and x(t) can be represented. The modification both on vehicle mass and on

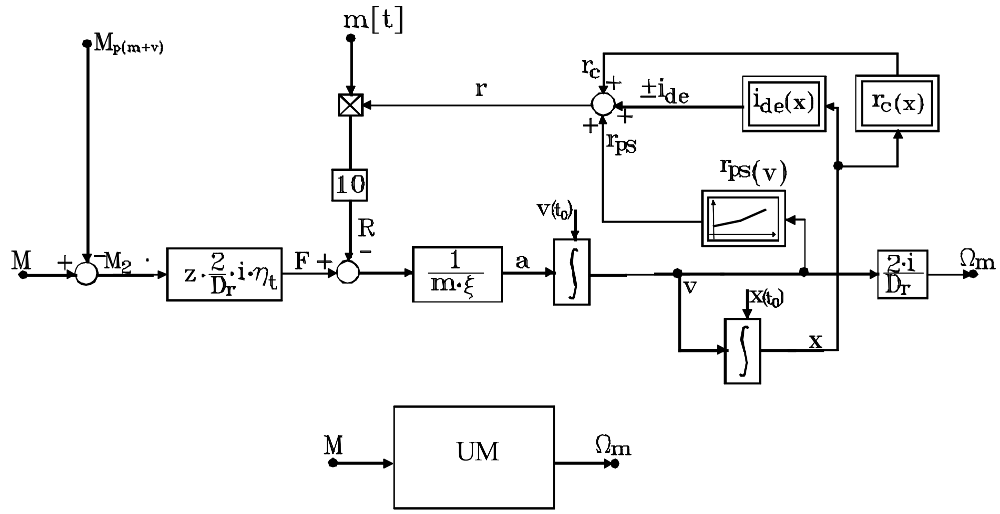

Fig.5 Structural diagram and mask block of useful movement

dependences i_{de}(x) or r_c(x), specific to certain vehicle or route, can be easily operated, obtaining an exact mathematical model, which respects all running conditions. Also, in case of motor wheels diameters inequalities , the scheme suffers a minor change, the total force F resulting as a sum of partial forces developed by each motor.

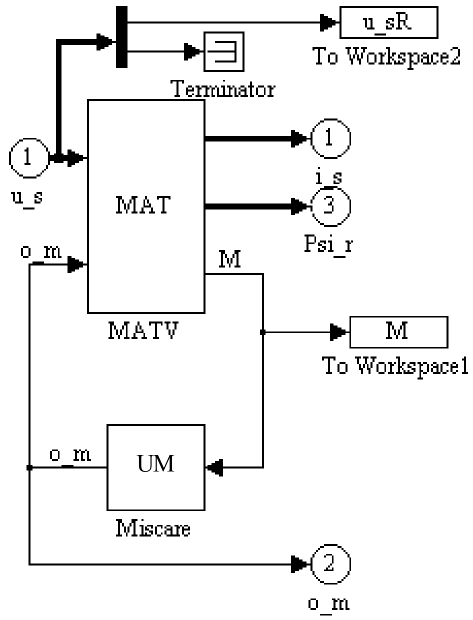

Fig.6 Traction induction motor model when train useful movement consideration

Further on, taking into account the achieved models, a railway transportation system exergy will be analyzed .

6 Exergy Case Study

The exergy of a system denotes equilibrium with the environment, but also exergy can interface broadly with economics [16], [18] [20]. In underground railway transportation systems, exergy provides a basis for increasing efficiency, reducing both energy losses and environmental damage. Further on, exergy more broadly can help in optimizing designs and making operating decisions.

In this paper, the exergy analysis presumes an understanding of electric transportation 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 [27]. An electric traction scheme with the power supply from the d.c. network must have the following elements [28] :

- an input circuit (known as a LC filter);
- a voltage and frequency converter;
- a braking chopper + a braking resistor + a shunt;
- a current connector to third rail + an axle contact;
- a loading contactor + a loading resistor;
- a rapid automatic circuit breaker;
- the wagons electric couplings;
- the electric traction motors.

In the paper a electric vehicle VM+VM it is taken into account (Fig.7), meaning two motor wagons which are elastic coupled. Variant V2 is defined by the coefficient K=2/2, meaning two static converters, each of them supplying two traction induction bi-motors installed on each unit [29], [30].

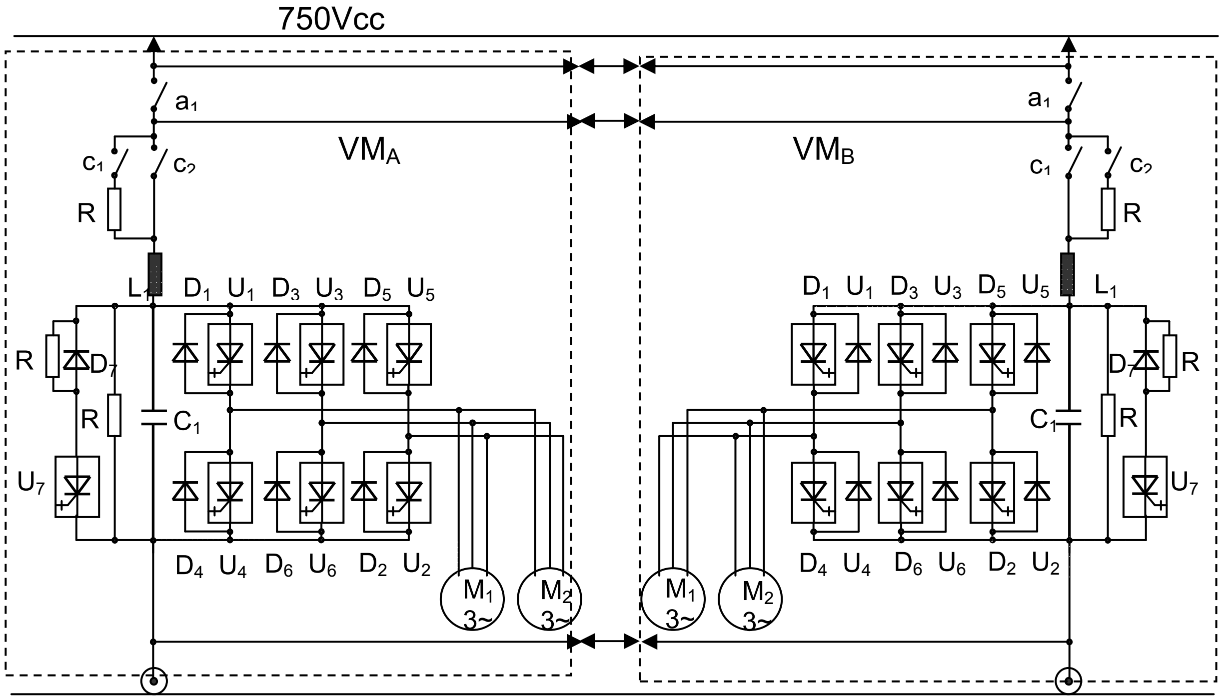

Fig. 7. Electric traction scheme variant K=2/2

The train operation can be followed on the scheme. After the connectors coupling and the circuit breakers and contactors switching, the control of the inverters on VM_A and VM_B , respectively, is made. Therefore, the traction induction bi-motors groups are supplied from the three-phase voltage inverters with variable voltage and frequency (with pulse-width modulation PWM). Consequently, the urban electric train is prepared to running. At the minimum adjusted frequency $f_{min} = s*f_n$. the traction motors M_1 and M_2 placed on VM_A (respectively M_1 şi M_2 placed on VM_B) are immobile. When the frequency exceeds that value, the motors get in motion, the operation having been on the frequency mechanical characteristic corresponding to the minimum supply frequency. The electric train is accelerating at constant traction torque, the operation having been on the mechanical characteristics at U_i/f_i, up to f_{sn} , when $U_1=U_{1n}$ and then, over f_{sn}, at constant power .

The three-phase traction induction motors are reversing the rotation sense by a simple supply commutation, by the stator phases succession switching. Moreover, the motors have identical characteristics for both rotation senses. Hence, the non-autonomous electric vehicles are with bi-direction and the mechanical characteristics for the two movement senses are symmetrically in the axes coordinates (speed v and force F), having been placed in the quadrants I or III of the frame VOF.

Since the electric driving systems with static converters and traction induction motors are used, by a appropriate control, with the same motors it can be realized the electric braking regime of the electric traction vehicles [4], [5].

For a certain running direction, the passing from the traction regime to the electric brake regime will correspond to the active force F sign change. In this conception, the mechanical characteristic F=f(v) will be placed in any of the four quadrants of the frame VOF, as it is shown in Table 1.

Table 1

No	Quadrant	v	F	Vehicle operation regime
1	I	+	+	traction, running "forward"
2	II	-	+	brake, going "back"
3	III	+	-	traction, running "forward" in opposite sense
4	IV	-	-	brake, going "back" in opposite sense

It is obviously that, in the traction regime v and F have the same sign, while in the braking regime v and F have opposite signs.

With a view to electric train braking, the traction induction motors are passing into the electric generator regime, by the decreasing control of the supply voltage frequency. The electric traction machines will operate in the generator regime on the mechanical characteristics in the quadrants II and IV, respectively. In that situation, which is complex from the view point of the powers circulation, the inverter provides the reactive energy for the traction machine in generator regime by the capacitors battery from the LC circuit and through the recovery diodes group (D_i, i=1...6) the electrical machine supplies as a induction generator into the voltage intermediary circuit. This recovered energy it is taken by other running underground trains or, if the intermediary circuit voltage exceeds $1{,}2U_d$ (meaning, over 1,2*750=900 V), it is automatically controlled the operation of the braking chopper U_7/VM_A and U_7/VM_B, which are realizing an electric rheostatic brake on the braking resistors R_2 and D_7/VM_A respectively R_2 and D_7/VM_B.

For the train disconnection from the supply network it must proceed into reverse sense given the starting situation.

The electric traction scheme V2, presented as before, meets the criteria both of the vehicle running behavior safety and of the traction scheme reliability.

The Bucharest Underground Rayway System (METROREX) is based on trains equipped with traction induction motors MAB T_1, MAB T_2 and MAB T_3 produced by Electroputere Factory in Craiova City [29],[30]. The following railway vehicles types (Table 2) are considered:
- urban electric train - heavy implementation REU-G, with the weight 36t / wagon;
- urban electric train - medium implementation REU-M, with the weight 25t / wagon;
- urban electric train - light implementation REU-U, with the weight de 15t / wagon.

Table 2

System input parameters	Electric train heavy execut. REU-G	Electric train medium execut. REU-M	Electric train light execut. REU-U
Urban electric train structure	VM + VM	VM + VM	VM + VM
Motor wagon axles formula	$B_o' + B_o'$	$B_o' + B_o'$	$B_o' + B_o'$
Traction motor	MAB T2 (Y)	MAB T1 (Y)	MAB T3 (Y)
Rated power P_n [kW]	100	70	50
Traction motors number (N_M)/ VM+VM	8	8	8
Wagon weight [t]	36	25	15
Electric train wagons number (n_{VM})	2	2	2
Operation maximum speed (v_M) [km/h]	80	80	85
Reducing gear efficiency (η_a)	0,95	0,95	0,95
Reducing gear transmission ratio (i_a)	1/5,375	1/5,375	1/5,375
Maximum acceleration (a_M) [m/s^2]	1,223	1,233	1,175
Weight factor (k)	0,9	0,9	0,9
Wheel diameter, medium used (D_{med}) [m]	0,87	0,87	0,87

The vehicles propulsion parameters are presented in Table 3.

Table 3

System propulsion parameters	Electric train heavy execut. REU-G	Electric train medium execut. REU-M	Electric train light execut. REU-U
Urban electric train structure	VM + VM	VM + VM	VM + VM
VM axles formula	$B_o' + B_o'$	$B_o' + B_o'$	$B_o' + B_o'$
Traction motor	MAB T2 (Y)	MAB T1 (Y)	MAB T3 (Y)
P_n [kW]	100	70	50
p	3	3	2
n_M [rot/min]	2623,4	2623,4	2623,4
n_{0M} [rot/min]	2700	2700	2700
f_M[Hz]	135	135	90
F_{oM} [kN]	79,27	55,48	31,77
F_{MMT} [kN]	10,43	7,3	4,18
M_{MMT} [Nm]	844	591	338
n_i [rot/min]	1131,5	1131,5	1414,5
v_i [km/h]	34,5	34,5	43,13
n_{0i} [rot/min]	1200	1200	1500
f_i [Hz]	60	60	50
M_{nM} [Nm]	364	254,8	182
F_{oVM} [kN]	34,18	23,93	17,09

The electric traction motors are properly designed, meeting the safety and efficiency criteria. For instance, the motor MAB T_2 has the parameters presented in Table 4

Table 4

No	Type	Symbol	MAB T_2 (Y)
1	Rated power [kW]	P_n	100
2	Rated voltage [V]	U_n	560
3	Rated current [A]	I_n	130
4	Starting current [A]	I_p	975
5	Rated frequency [Hz]	f_n	60
6	Variation range of supply voltage frequency [%]	D	200
7	Rated power factor	$\cos\varphi_n$	0,87
8	Poles pairs number	p	3
9	Rated speed [rot/min]	n_n	1168
10	Rated efficiency [%]	η_n	0,9
11	Motor weight [kg]	m	1250
12	Rated torque [Nm]	M_n	817,6
13	Starting torque [Nm]	M_p	899,4
14	Stator resistance [Ω]	R_1	0,0557

6.1 Experimental Traction Characteristics

The appropriate energy efficiencies of the conversion chain elements represent just a step in the exegy study. Further on, the experimental characteristics in vehicle traction regime will be presented. A comparison with the ideal mechanical characteristic it is compulsory in the exergy study.

In Fig. 8, Fig.9 and Fig.10, respectively, the experimental diagrams of traction force Fo, traction power Po and running resistant force Rp depending on vehicle speed v are represented for the train types taken into account: REU-G, REU-M and REU-U. According to these charactersitics, the magnitudes data are presented in Tab.5, Tab.6 and Tab.7, respectively

Table 5 {REU-G)

Rp [N]	Po [kW]	Fo [kN]	v [km/h]	No.
1419	0	79.27	0	1
1474	110	79.27	5	2
1539	220	79.27	10	3
1617	330	79.27	15	4
1709	440	79.27	20	5
1812	550	79.27	25	6
1926	661	79.27	30	7
2053	760	79.27	35	8
2194	760	68.37	40	9
2344	760	60.77	45	10
2508	760	54.70	50	11
2684	760	49.72	55	12
2872	760	45.60	60	13
3070	760	42.07	65	14
3281	760	39.07	70	15
3506	760	36.46	75	16
3743	760	34.18	80	17

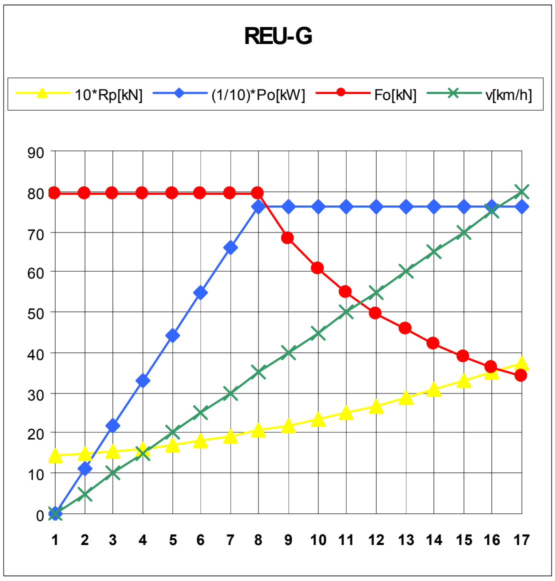

Fig.8 Diagrams Rp, Po, Fo and v for REU-G

Table 6 {REU-M)

Rp [N]	Po [kW]	Fo [kN]	v [km/h]	No.
1278	0	55.48	0	1
1319	77	55.48	5	2
1369	154	55.48	10	3
1433	231	55.48	15	4
1509	308	55.48	20	5
1598	385	55.48	25	6
1697	462	55.48	30	7
1810	532	55.48	35	8
1935	532	47.85	40	9
2071	532	42.53	45	10
2220	532	38.28	50	11
2382	532	34.80	55	12
2554	532	31.90	60	13
2738	532	29.45	65	14
2934	532	27.34	70	15
3145	532	25.52	75	16
3366	532	23.93	80	17

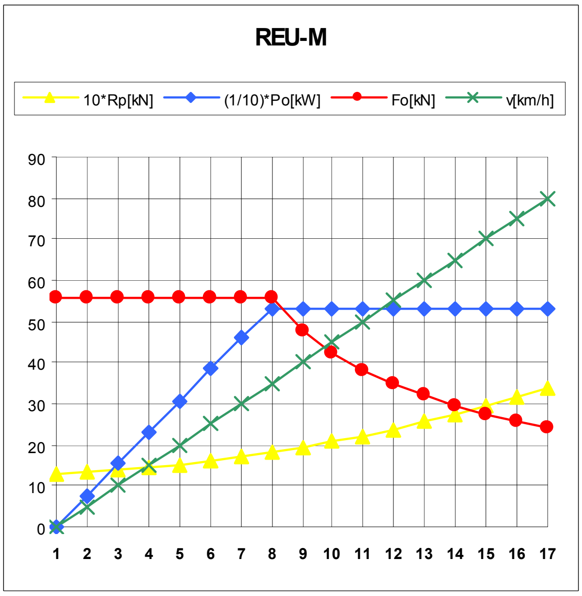

Fig.9 Diagrams Rp, Po, Fo and v for REU-M

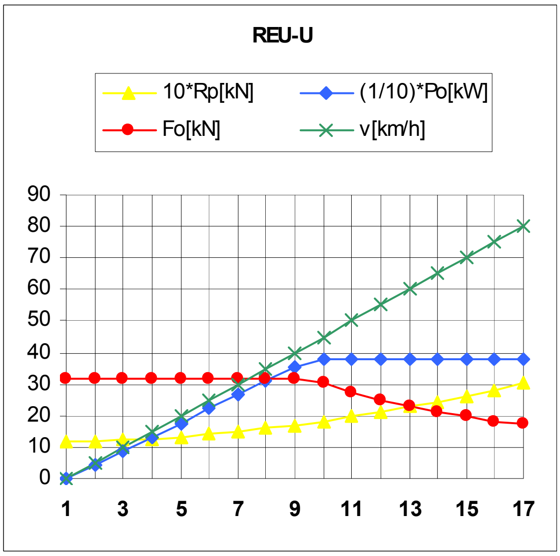

Fig.10 Diagrams Rp, Po, Fo and v for REU-U

Table 7 (REU-U)

Rp [N]	Po [kW]	Fo [kN]	v [km/h]	No.
1151	0	31.77	0.00	1
1178	440	31.77	5.00	2
1215	880	31.77	10.00	3
1265	1320	31.77	15.00	4
1328	1760	31.77	20.00	5
1403	2210	31.77	25.00	6
1489	2650	31.77	30.00	7
1588	3090	31.77	35.00	8
1700	3530	31.77	40.00	9
1823	3810	30.45	45.00	10

1959	3810	27.41	50.00	11
2107	3810	24.91	55.00	12
2266	3810	22.84	60.00	13
2436	3810	21.08	65.00	14
2619	3810	19.57	70.00	15
2816	3810	18.27	75.00	16
3024	3810	17.13	80.00	17

Reffering to REU-G vehicle, for instance, the data in Tabel.6 and the corresponding diagram in Fig.8 are emphasizing that:

- up to speed 34,5km/h, the electric vehicle REU-G it is developing a maximum constant traction force $F_{oM} = 79{,}27$kN;
- in speed interval (34,5 – 80) km/h it is proceed a speed control at maximum constant power P_{oM} =760kW.

The experimental charactersitics in traction regime have the shape imposed by the ideal mechanical charactersitic. It can be said that both the energy and exergy efficiencies are achieved.

6.2 Experimental Electric Brake Characteristics

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 the braking regime, particularly electric brake [4], [5].

At very low speeds, the vehicle braking regime it is realized only by a mechanical way, on basis of the mechanical contact between the brake block and the motor wheel rim [11]. In this case, the environmental impact is important and it must be taken into account [3],[30], because the underground metro it is operating into a closed (underground) space and the material amount developed into the mechanical braking process (particularly, the brake shoe wear) it is considerable, depending on the unrecovered energy which it is resulting in the mechanical braking regime.

The environment impacts from the electric braking regime [5], particularly with a recovered energy, by passing the traction machines in electric generator regime, are considerably reduced. In that operating regime, the vehicle provides energy in the 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.

Table 8

REU-U F_F[kN]	REU-M F_F[kN]	REU-G F_F[kN]	v [km/h]	No.
0.00	0.00	0.00	0	1
18.78	33.56	46.36	5	2
36.36	66.24	92.71	10	3
24.24	44.16	58.32	15	4
18.18	33.12	43.74	20	5
14.55	26.50	34.99	25	6
12.12	22.08	29.16	30	7
10.39	18.93	24.99	35	8
9.09	16.56	21.87	40	9
8.08	14.72	19.44	45	10
7.27	13.25	17.49	50	11
6.61	12.04	15.90	55	12
6.06	11.04	14.58	60	13
5.59	10.19	13.46	65	14
5.19	9.46	12.50	70	15
4.85	8.83	11.66	75	16
4.55	8.28	10.93	80	17

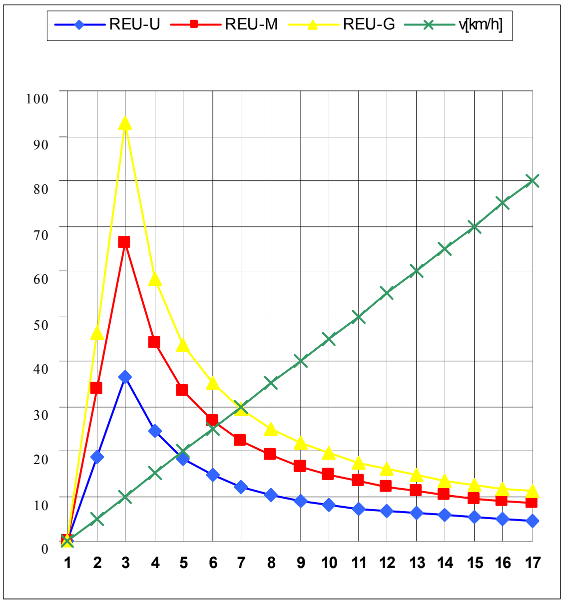

Fig.11. Diagrams F_F and v in braking regime for vehicles REU-U, REU-M, REU-G

The network capacity to receive this energy is continuous controlled by the vehicle control system. If the input circuit voltage exceeds $1{,}2U_d$ (meaning, over 1,2*750=900 V), it is automatically controlled the operation of the braking choppers, which are realizing an electric rheostatic brake regime. The braking resistances R_F allow the losses disipation (by Joule effect) of the uncirculated energy. In that case, a good energy efficiency it is obtained, but the exergy efficiency is drastically decrased.

The series data and diagrams from Tab.8 and Fig.11 are eloquently for the electrodynamic brake regime in case of urban electric trains, by types REU-G, REU-M and REU-U [5], [29].

7 Conclusions

The Universe Powers let us discover a part of its laws. We can not change the Nature laws but we must know and respect them. Most people, scientists and public authorities around the world are realizing that our 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 reffered into the frame of Sustainable Development. An utmost priority is 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. 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.

Concerning the train electric brake regime, the conclusions require further direction dicussions about the transportation system internal exergy consumptions..

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.

Another conclusion related to exergy efficiency improvement could seem paradoxically and it is reffering to the railway transportation system traffic intensity. At present, the energy recovered in electric brake regime can be provided only to the transporation system running trains. As the system running train number is increased as the recovered electric energy is properly used and the exergy efficiency is a great one. Contrary to that situation, in a traffic with few running trains, if the third rail voltage exceeds 900 V, the rheostatic brake regime it is authomatically controlled and, consequently, the electric recovered energy is transformed by Joule Effect in heating energy. That is an unfavorable situation, with an adequate energy efficiency, but a low exergy effiecncy.

In the long run, the electric braking regime with energy recovery should be compulsory in electric transportation systems and, moreover, a great elasticity of the reversible traction sub-stations equipments should be taken into account. Through its rational and meaningful approach, exergy analysis can help improve and optimize designs.

References:

[1] Goran W., *Exergy, Ecology and Democracy – Concepts of a Vital Society or A proposal for An Exergy Tax*, the 2nd European Congress on Economics and Management of Energy in Industry, Estoril, Portugal, April 5-9, 1994.

[2] Brundtland (1989), *Our Common Future, World Commission on Environment and Development*, Oxford University Press.

[3] Bulucea C.A. , Brandusa C.., *Experimental Characterization o f Environmental Impacts from Underground Electric Metro in Braking Regime*, 7th WSEAS/IASME International Conference on ELECTRIC POWER SYSTEMS, HIGH VOLTAGES, ELECTRIC MACHINES (POWER'07), Venice, Italy, Nov.21-23, 2007, 254-258.

[4] Bulucea C.A., Brandusa C., Cismaru D., Nicola D.A., *Experimental Characterization of Environmental Impacts from Underground Electric Metro in Braking Regime*, WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT, Issue 8, Volume 3, August 2007, 139-149, ISSN 1790-5079.

[5] Bulucea C.A., Nicola D.A., Brandusa A., Brandusa C.., *Drive Systems in Underground Metro Saving Energy*, 3rd IASME/WSEAS Int. Conference on ENERGY & ENVIRONMENT, University of Cambridge, UK, February 23-25, 2008, 433-439.

[6] Szarkut J., *Exergy Method: Technical and Ecological Applications*, UK: WIT Press, 2005.

[7] Dincer I. and Rosen M.A., *Exergy: Energy, Environment and Sustainable Development*, Oxford, UK: Elsevier, 2007.

[8] Wall G., *Exegy tools*, Proc.Inst.Mechanical Engineers, Part A: J. Power and Energy, 217, 2003, 125-136.

[9] Yantovskii E.I., *Energy and Exergy Currents: An Introduction to Exergonomics*, New York: Nova Science Publishers, 1994

[10] Valero A., *Exergy Accounting: Capabilities and drawbacks*, Energy, 31, 2006, 164-180.

[11] Nicola D.A. Cismaru D.C., *Tractiune Electrica: Fenomene, Modele, Solutii*, Ed. SITECH Craiova, Romania, 2006.

[12] Perticaroli F., *Sistemi elettrici per i transporti. Trazione elettrica*. Ed. Masson, Milano-Parigi-Barcellona, 1994.

[13] Kaller R. Allenbach J.M., *Traction Electrique,* Vol.1, 2, PPUR, Lausanne, 1995.

[14] D.C. Cismaru, D.A.Nicola, Gh. Manolea, M.A. Drighiciu, *Modelling and Simulation of Locomotives with Traction Induction Motors and Three Levels Converters*, WSEAS ISTASC'07 Vouliagmeni, Athens, Greece, August 24-26, 2007

[15] Cismaru D.C., Nicola D.A., Manolea G., Drighiciu A., Bulucea C.A.., *Mathematical Models of High-Speed Trains Movement*, WSEAS TRANSACTIONS on CIRCUITS and SYSTEMS, Issue 2, Volume 7, February 2008, 379-388, ISSN 1109-2734.

[16] Hua B., Yin Q., Wu G., *Energy optimization through exergy-economic evaluation*, ASME J. Energy Resources Technology, 111, 1989, 148-153.

[17] Sciubba E.,*Cost analysis of energy conversion systems via a novel resource-based quantifier*, Energy, 28, 2003, 457-477.

[18] Rosen M.A., *A Concise Review of Energy-Based Economic Methods*, 3rd IASME/WSEAS Int. Conference on ENERGY & ENVIRONMENT, University of Cambridge, UK, February 23-25, 2008, 136-142.

[19] Edgerton R.H., *Available Energy and Environmental Economics*, Toronto: D.C. Heath, 1982.

[20] Honkasalo A., *Entropy, exergy and steady-state economy*, Sustainable development, 6, 1998, 130-142.

[21] L. KePing, G. ZiYou, , *An improved equation model for the train movement*, Simulation Modelling Practice and Theory Volume 15, Issue 9, October 2007, Pages 1156-1162.

[22] Klima J., *An Analytical Model and Investigation of Induction Motor Drive Fed from Three-Level Space-Vector Modulated VSI*, Proceedings of 6th WSEAS/IASME International Conference on ELECTRIC POWER SYSTEMS, HIGH VOLTAGES, ELECTRIC MACHINES (POWER'05), Tenerife, Spain, December, 2006.

[23] Jamoussi K., Ouali M., Charradi H., *A Sliding Mode Speed Control of an Induction Motor*, WSEAS TRANSACTIONS on SYSTEMS and CONTROL, Issue 7, Volume 2, July 2007, 379-388, ISSN 1991-8763.

[24] Botan C., Ostafi F., *Energetic Aspects Referring to Electrical Drive Systems*, Proceedings of 5th WSEAS/IASME International Conference on ELECTRIC POWER SYSTEMS, HIGH VOLTAGES, ELECTRIC MACHINES (POWER'05), Tenerife, Spain, December, 2005.

[25] Botan C.., Ostafi F., Onea A., *Free and FixedEnd-Point Optimal Control Problems for Linear Systems*, WSEAS TRANSACTIONS on SYSTEMS , Issue 3, Volume 3, May 2004, 1109-1113.

[26] Zimmermann A., Hommel G., *A train control system case study in model-based real time system design*, Parallel and Distributed Processing Symposium, 2003.

[27] Buhler H., *Reglage de Systemes d'Electronique de Puissance*, Vol.I, PPUR, Lausanne, 1997.

[28] Rahn T.Hochbruck H. Moller F.W., *ICE High--tech on Rails*, Hestra Verlag, Darmstadt, 1991.

[29] Brandusa C., *Driving Systems with Static Converters and Induction Motors in Electric Urban Traction*, Ph.D. Thesis, 2007.

[30] Juncu M., Brînduşa,C., Georgescu D., *Sisteme electrice de transport neconvenționale (A23); Rama de metrou acționată cu motoare asincrone; Execuție şi experimentare modele (Faza 23.1),* Contract cercetare 606C- Anexa A, Institutul Național de Cercetare şi Proiectare pentru maşini electrice, echipament electric şi tracțiune, Craiova, 1992.