Input-output-based Life Cycle Energy Inventories and Modeling in Electric Trains with Traction Induction Motors Fed from DC Line

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***Abstract*—**In this paper life-cycle energy inventories and modeling of electric trains with traction induction motors fed from d.c. line on basis of input-output data study are presented. The data–Life Cycle Analysis (LCA) relationship is investigated, and the importance and role of data in LCA is reviewed. There are taken into account the electric trains with traction induction motors fed from d.c. line, not simply in terms of technico-economical growth, but also as achievements of the Sustainable Development. The paper presents data regarding the materials and energies in a lateral wall manufacturing process and assess an exergetic analysis on basis of mathematical models and structural diagrams of the traction induction motor, the voltage-source inverter and line-side converter used on the trains fed from d.c. line. The overall structural diagram construction for the principle schemes corresponding to modern electric trains fed from d.c. line is also presented. Through its rational and meaningful approach, the Life Cycle Energy Analysis, and particularly an Energy Inventory will help improve and optimize the design, manufacture, operation and final equipments deconstruction of a transportation system..

***Keywords*—**Electric transportation, Energy, Exergy, Induction motor, Life Cycle Analysis, Static converter.

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I. Introduction

For the moment, our correct activities must be referred into the frame of Sustainable Development. The concept definition 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" [1]. 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 emphasizes a number of sustainability-based concepts related as tools in order to analyse and optimize the operation of electric trains with traction induction motors fed from d.c. line.

Life Cycle Assessment or Life Cycle Analysis (LCA) is a tool to assess the potential environmental impacts of product systems or services at all stages in their life cycle – from extraction of resources, through the production and use of the product to reuse, recycling or final disposal. The immediate precursors of life cycle analysis and assessment (LCAs) were the global modelling studies and energy audits, which attempted to assess the resource cost and environmental implications of different patterns of human behaviour. LCA can be applied in e.g. strategic development, product development and marketing. The concept of conducting a detailed examination of the life cycle of a product or a process is a relatively recent one which emerged in response to increased environmental awareness on the part of the general public, industry and governments

Energy is a measure of the ability to do work and it is characterized by magnitude, form and quality. While the features of energy magnitude (e.g., calorie, joule, horsepower) and form (e.g., kinetic energy, potential energy, chemical energy, heat transfer) are well-established and widely known, few are familiar with the concept of energy quality, especially its quantification. Energy quality measures the capacity of energy, in its various forms, to do useful work [2]. Consequently, the concept of *exergy* has been described as a measure of energy quality. The exergy of a system is the maximum work possible during the processes of energy conversion. Exergy is then the energy available to be used. Energy is never destroyed during a process; it changes from one form to another, but the exergy can be destroyed. The ratio of exergy to energy in a substance can be considered a measure of energy quality [3]. Exergy is useful when measuring the efficiency of an energy conversion process. Making a comparison of energy and exergy change of a process, some aspects must be emphasized: while the energy is conserved by the first law of thermodynamics, the exergy is only conserved for reversible processes and destroyed by irreversible processes; the energy is different from zero and independent of environment parameters, while the exergy is equal to zero at equilibrium with the environment and dependent on environment parameters; energy is a measure of quantity only, but exergy is a measure of quantity and efficiency of utilization. Hence, due to its traits, the exergy is highly multidisciplinary. Exergy analysis 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 [4]. The exergy concept is mostly used within energy optimization studies, where different energy forms occur and even in engineering modelling. Exergy is the physical value of a resource that can be compared not only to the techico-economical value, but to the environmental value [5],[6],[7].

II. Locomotive Lateral Wall Manufacturing Process

Taking as an example the case of a manufactured product, an LCA involves making detailed measurements during the manufacture of the product, from the mining of the raw materials used in its production and distribution, through to its use, possible re-use or recycling, and its eventual disposal. LCAs enable a manufacturer to quantify how much energy and raw materials are used, and how much solid, liquid and gaseous waste is generated, at each stage of the product's life. Such a study would normally ignore second generation impacts, such as the energy required to fire the bricks used to build the kilns used to manufacture the raw material. In this study it is taken into account the manufacturing process of a lateral wall of a d.c. locomotive (Fig.1). Hence in Fig.2 there are presented the recyclable materials used in manufacturing process, while the process energies diagrams are represented in Fig.3.

All products have some impact on the environment. Since some products use more resources, cause more pollution or generate more waste than others, the aim is to identify those which are most harmful. LCAs might be conducted by an industry sector to enable it to identify areas where improvements can be made, in environmental terms. LCA should help to identify those stages in production processes and in use which cause or have the potential to cause pollution, and those which have a heavy material or energy demand. Consequently, in this paper there are emphasized the important differencies which occur in two distinct situations, regarding the effects on environment and human beings: 1)

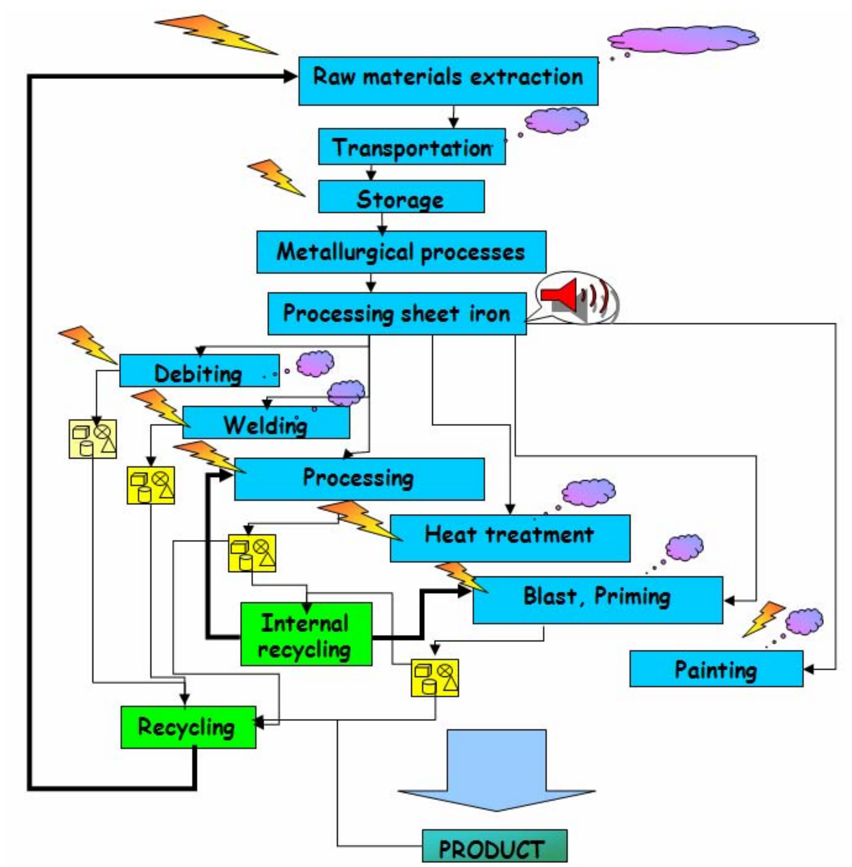

Fig.1.Manufacturing flux scheme for locomotive lateral wall

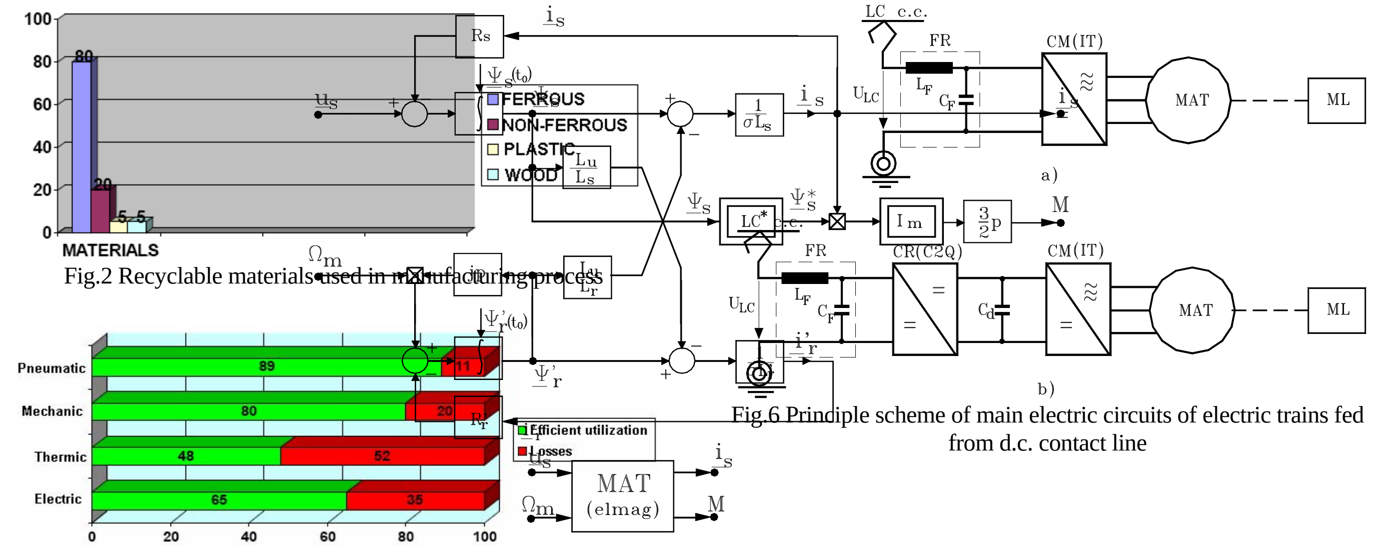

Fig.2 Recyclable materials used in manufacturing process

Fig.3. Diagrams of process energies

Fig.8 Structural diagram and mask block for electromagnetic part of induction motor

Fig.6 Principle scheme of main electric circuits of electric trains fed from d.c. contact line

applying the method of manufacturing without filters and waste recycling (Fig.4), and 2) applying the method of manufacturing with filters and waste recycling (Fig.5).

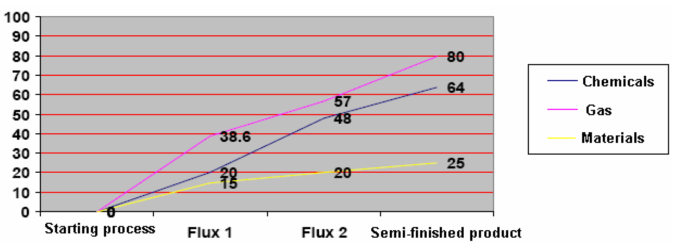

Fig.4. Effects diagram in case of manufacturing method without filters and waste recycling

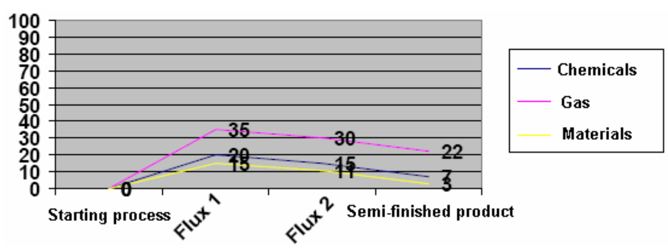

Fig.5.Effects diagram in case of manufacturing method with filters and waste recycling

III. Electric Train Exergetic Analysis

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 efficiency. Costs should reflect value and value is not associated with energy but with exergy and sustainability. In this paper 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 the electric train viewed as a system.Utilization in the electric traction of the induction motor with squirrel cage it is possibly only in this feeding conditions with a three-phase system by voltages of amplitudes and frequency controlled variable [8]. 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.6). Working mechanism (ML) stands for mechanical part of motor electric vehicle that it is composed between a movement transformer (reduction gear) and a movement converter (wheel + rail) which transforms the rotation movement into a translating movement.

A. Modelling of Induction Motor

In the power schemes of electric trains, the traction induction motor represents the final element in the conversion energy equipments chain [9]. After all, it achieves the electromechanical conversion of energy making thus possibly the movement. As a complex electromechanical system, the induction motor could be conceptually decomposed into an electromagnetic subsystem and a mechanical subsystem (Fig.7).

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 by the equations [11], [12]:

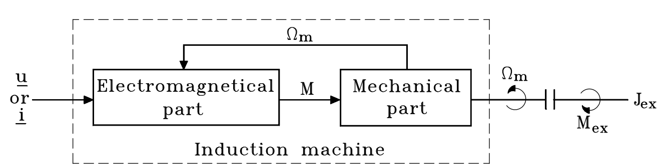

Fig.7 Functional parts of traction induction motor

$$\frac{d\underline{\psi}_s}{dt} = \underline{u}_s - R_s \cdot \underline{i}_s$$

$$\frac{d\underline{\psi}'_r}{dt} = j \cdot p \cdot \Omega_m \cdot \underline{\psi}'_r - R'_r \cdot i'_r \qquad (1)$$

$$\underline{i}_s = \frac{\underline{\psi}_s - \frac{L_u}{L'_r} \cdot \underline{\psi}'_r}{\sigma L_s}; \quad \underline{i}_{r'} = \frac{\underline{\psi}'_r - \frac{L_u}{L_s} \cdot \underline{\psi}_s}{\sigma L_{r'}}$$

$$M = \frac{3}{2} \cdot p \cdot \mathrm{Im}\{\underline{i}_s \cdot \underline{\psi}_s^*\}$$

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.8.

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.

For an exergetic dynamic approach of the useful movement [9] a mathematical model is neccessary. 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 had been made under the action of useful torques M_2 (identical), developed by "z" traction motors of motor electric vehicle, then the mathematical model of useful movement will be described by the following equations:

$$v[\mathrm{m/s}] = \frac{1}{m(1+\gamma)}\int (F - R)dt + v_0; \quad \Omega_m[\mathrm{rad/s}] = \frac{2 \cdot i}{D_r} \cdot v[\mathrm{m/s}]$$

$$S = \int v \cdot dt + S_0; \quad S_1[\mathrm{km}] = \frac{1}{1000} \cdot S[\mathrm{m}] \qquad (2)$$

$$F[\mathrm{N}] = z \cdot \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2[\mathrm{N \cdot m}]; \quad R[\mathrm{N}] = (r_p \pm i + r_c) \cdot G[\mathrm{kN}]$$

$$V[\mathrm{km/h}] = 3{,}6 \cdot v[\mathrm{m/s}]; \quad r_p = f(V)$$

which allow the structural diagram construction of useful movement (Fig.9). For the mask block there 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.

Further on, by coupling this scheme (Fig.9) at the structural diagram of traction motor electromagnetic part (Fig.8) it 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 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.

B. *Modelling of Machine-side Converter*

For the modelling of the machine-side converter, usually a voltage-source inverter, there are used the commutation functions in two levels or in three levels, respectively [13], [14]. 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 functions there have been considered that the used semiconductor devices they are ideally, there are neglected both the commutations times and the voltage drop at conduction in forward direction. A such

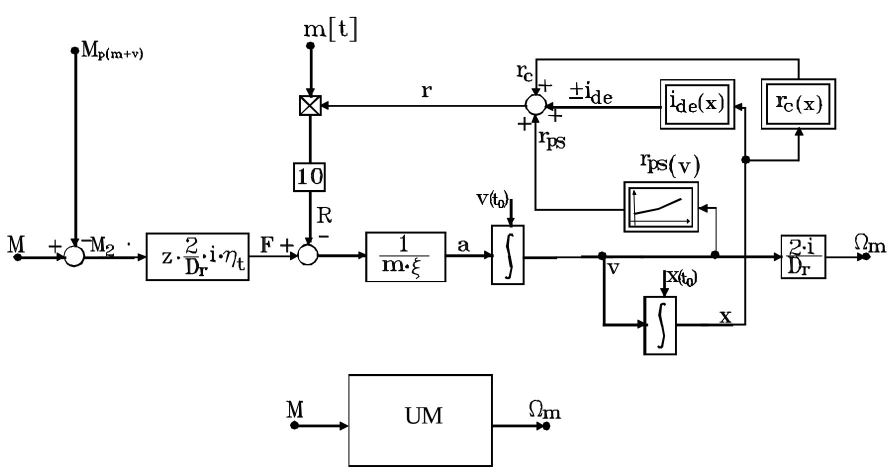

Fig.9 Structural diagram and mask block of useful movement

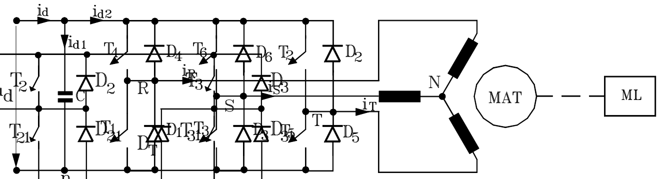

Fig.10 Three-phase voltage-source inverter with two levels

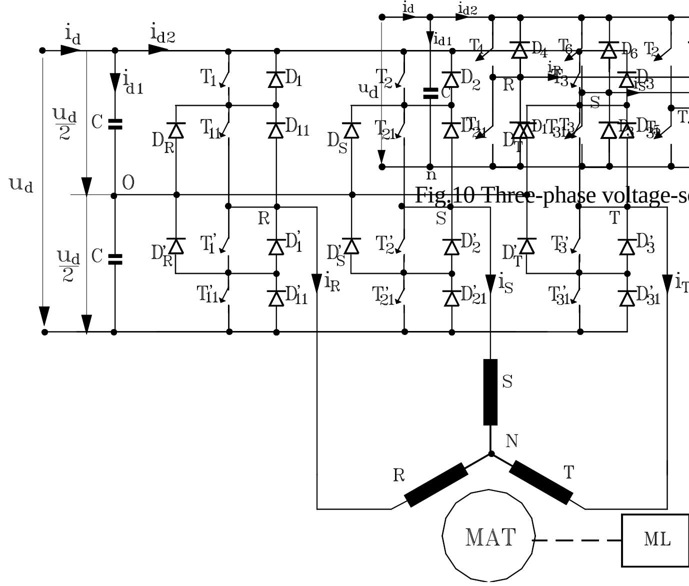

Fig.12 Three-phase voltage-source inverter with three levels

converter is ideal and it is considered without losses.

Analysing the topology of three-phase voltage-source inverter with two levels (Fig.10) and using the commutation function"f_{2w}" (in two levels):

$$f_{2w} = \begin{cases} +1 \\ 0 \end{cases}, \quad \text{for each arm of converter,}$$

there are written the equations of inverter (without losses) model:

$$\begin{gathered} u_{Rn} = u_d \cdot f_{2wR};\ u_{Sn} = u_d \cdot f_{2wS};\ u_{Tn} = u_d \cdot f_{2wT}; \\ i_{d2} = i_R \cdot f_{2wR} + i_S \cdot f_{2wS} + i_T \cdot f_{2wT}; \\ u_{RN} = u_{Rn} - u_{Nn};\ u_{SN} = u_{Sn} - u_{Nn};\ u_{TN} = u_{Tn} - u_{Nn}; \\ u_{Nn} = \frac{u_{Rn} + u_{Sn} + u_{Tn}}{3}; \end{gathered} \qquad (3)$$

Based on the above equations system, the structural diagram and mask block of the three-phase voltage-source inverter with two levels are obtained in Fig.11. For modelling of three-phase voltage-source inverter with three levels (Fig.12) it is considered the ideal case, with two identical capacitors dividing in equal mode the voltage u_d. For modelling there are used the commutation function with three levels "f_{3w}":

$$f_{3w\,R,S,T} = \begin{cases} +1, & T_i, T_{i1}\,(I) \\ 0, & T_{i1}, T_i'\,(I),\ i=1, 2, 3 \\ -1, & T_i', T_{i1}'\,(I) \end{cases} \qquad (4)$$

Analysing the topology of three-phase voltage-source inverter with three levels (Fig.12) there can be written the equations:

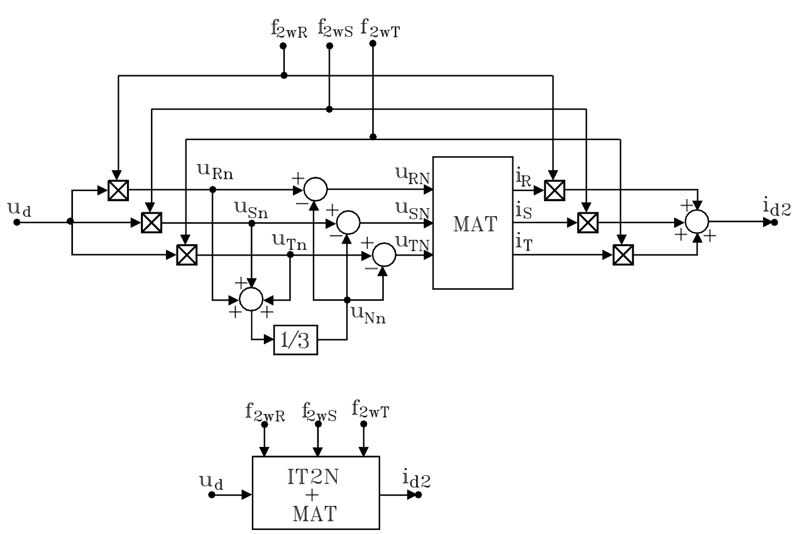

Fig.11 Structural diagram and mask block for three-phase voltage source inverter with two levels

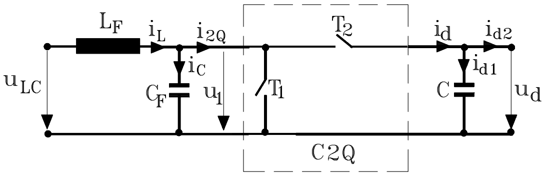

Fig.15 Equivalent structure of the two-quadrant line-side converter

$$
\begin{aligned}
&u_{RO} = \frac{u_d}{2} \cdot f_{3wR}; \quad u_{SO} = \frac{u_d}{2} \cdot f_{3wS}; \quad u_{TO} = \frac{u_d}{2} \cdot f_{3wT};\\
&i_{d2} = i_R \cdot f_{3wR} + i_S \cdot f_{3wS} + i_T \cdot f_{3wT};\\
&u_{RN} = u_{RO} - u_{NO};\, u_{SN} = u_{SO} - u_{NO};\, u_{TN} = u_{TO} - u_{NO};\\
&u_{NO} = \frac{u_{RO} + u_{SO} + u_{TO}}{3};
\end{aligned} \tag{5}
$$

On these equations basis, it is obtained the structural diagram of three-phase voltage-source inverter with three levels (Fig.13).

Those two models have comprised in their structure the MAT traction induction motor model (both the electromagnetic part and mechanic part), the link with this making through the voltage ($\underline{u}_s$) and respectively by the stator current ($\underline{i}_s$) space vectors.

C. Modelling of C2Q Line-side Converter

In order to obtain the mathematical model of the two-quadrant (C2Q) line-side converter, it must start from its structure shown in Fig.14.

The two-quadrant (C2Q) line-side converter consists of two choppers: a step-up chopper (T_1, D_1) for the traction regime, and a step-down chopper (T_2, D_2), for the braking regime. In the traction regime, T_1 and D_1 can be considered as being two ideal switches, working in a complementary way; in the braking regime, T_2 and D_2 can be, as well, considered as being two ideal switches, working in a complementary way [15]. But T_1 and D_2, as well as T_2 and D_1, are mounted in parallel, and, since the traction and braking regimes are complementary, the principle scheme of the two-quadrant line-side converter of Fig.14 can be simplified to the structure of Fig.15, in which the following switching function is used:

$$
f_{2w} = \begin{cases} 1, & T_1 \text{ deschis, } T_2 \text{ inchis} \\ 0, & T_1 \text{ inchis, } T_2 \text{ deschis} \end{cases} \tag{6}
$$

Equation (6) leads to equivalent relations:

$$
f_{2w} = 0 \Rightarrow \begin{cases} u_1 = 0 \\ i_d = 0 \end{cases}; \qquad f_{2w} = 1 \Rightarrow \begin{cases} u_1 = u_d \\ i_d = i_{2Q} \end{cases} \tag{7}
$$

$$
\text{and therefore:} \qquad \begin{cases} u_1 = u_d \cdot f_{2w} \\ i_d = i_{2Q} \cdot f_{2w} \end{cases} \tag{8}
$$

With reference to the equivalent electric circuit of Fig.15, the following equations can be added:

$$
\begin{aligned}
&u_{LC} = L_F \cdot \frac{di_L}{dt} + u_1\\
&i_L = i_C + i_{2Q}; \quad i_d = i_{d1} + i_{d2}\\
&u_d = \frac{1}{C} \cdot \int i_{d1} dt; \quad i_C = C_F \cdot \frac{du_1}{dt}
\end{aligned} \tag{9}
$$

Based on (8) and (9), the structural diagram of the two-quadrant line-side converter is built, which includes the L_F-C_F line filter and the C capacitor from the DC-link circuit (see Fig.16).

The structural diagram of Fig.16 has the contact line voltage u_{LC} as input variable, while the i_{d2} current and the u_d

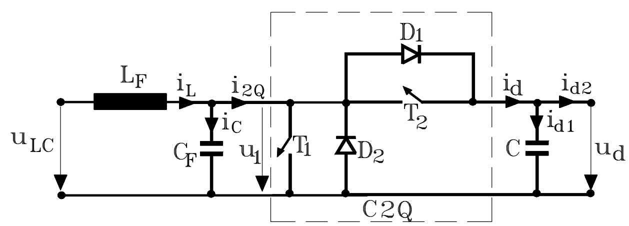

Fig.14 Structure of the two-quadrant line-side converter

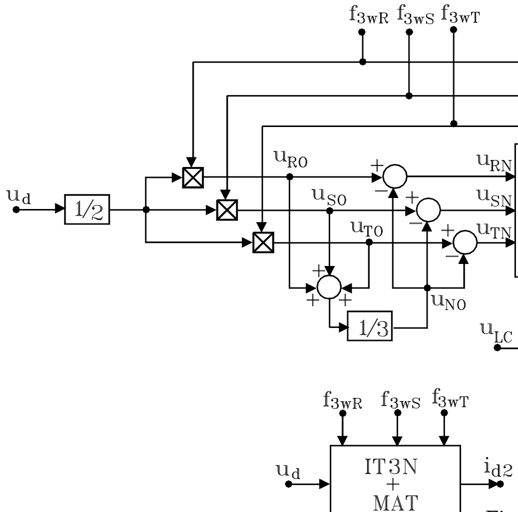

Fig.13 Structural diagram and mask block for three-phase voltage-source inverter with three levels

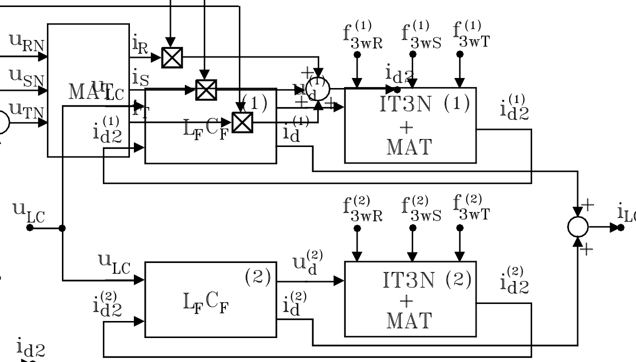

Fig.18 Structural diagram of main circuits corresponding to italian high-speed train locomotive ETR500

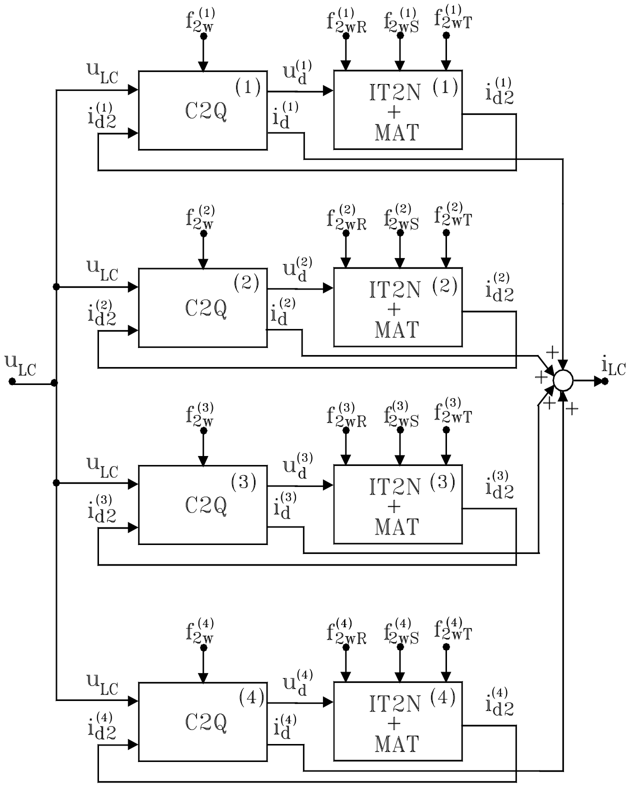

Fig.19 Structural diagram of main circuits corresponding to a locomotive with traction induction motors fed from d.c. contact line

voltage link the voltage-source inverter model in the main circuit of the DC-fed locomotive.

The two-quadrant line-side converter control is achieved by the f_{2w} switching function.

D. *Electric Train Structural Diagrams*

The presented mask blocks allow the structural diagrams achievement associated to the main electric circuits of electric trains with traction induction motors.

For case of electric trains fed from d.c. contact line, there have been created (Fig.17) the structural diagrams corresponding to the principle scheme from Fig.6, as well as the main electric circuits of italian high-speed train ETR500 (Fig.18). The previously defined mask blocks have been used, but with the observation that each from the "IT3N+MAT" blocks (Fig.17) includes the scheme fed in parallel by two traction induction motors from a voltage source inverter with three levels [16]. As input and output variables, which interact with the contact line, i.e. the u_{LC} voltage and the i_{LC} current absorbed by the train, have been considered.

Similarly, a structural diagram, corresponding to the main circuits of a locomotive fed from a DC contact line, has been built (Fig.19) by using four rows of two-quadrant line-side converters, voltage-source inverters and induction motors.

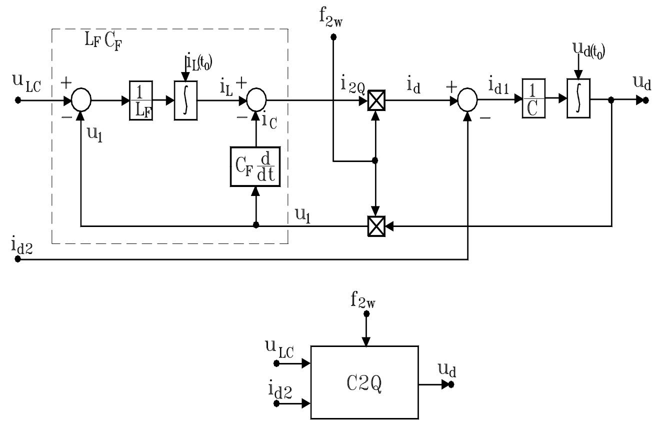

Fig.16 Structural diagram and mask block

IV. CASE STUDY SIMULATIONS

The exergy of a system denotes equilibrium with the environment, but also exergy can interface broadly with economics [17], [18]. In 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 purpose, taking into account the achieved models, simulations of induction traction

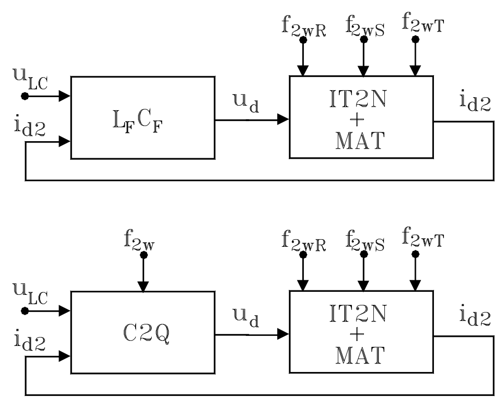

Fig.17 Structural diagrams of main electric circuits of Fig.6

motors will be presented.

The study case takes into account the Bucharest Underground Railway System (METROREX), that is based on electric trains equipped with traction induction motors MAB T_1, MAB T_2 and MAB T_3 produced by Electroputere Factory in Craiova City.

The following railway vehicles types (Table 1) are considered [19]:

- 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 1

System input parameters	Electric train heavy	Electric train	Electric train light

	execut. REU-G	medium execut. REU-M	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	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

Table 2

System propulsion parameters	Electric train heavy execut. REU-G	Electric train medium execut. REU-M	Electric train light execut. REU-U
Electric train structure	VM + VM	VM + VM	VM + VM
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 traction motor MAB T_2 has the parameters presented in Table3.

Table 3

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

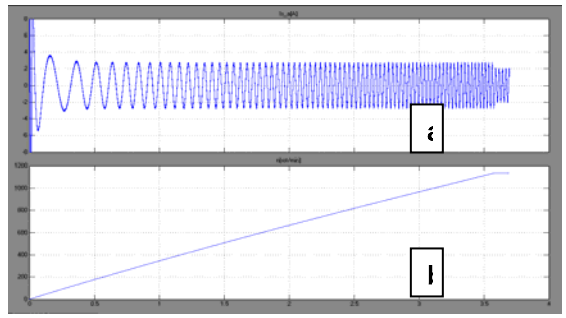

Fig.20 Transient starting regime simulation of traction induction motor supplied at variable voltage and frequency source n^*=1135 rot/min (ω^* =118,9rad/s)
a) Phase current; b) Speed

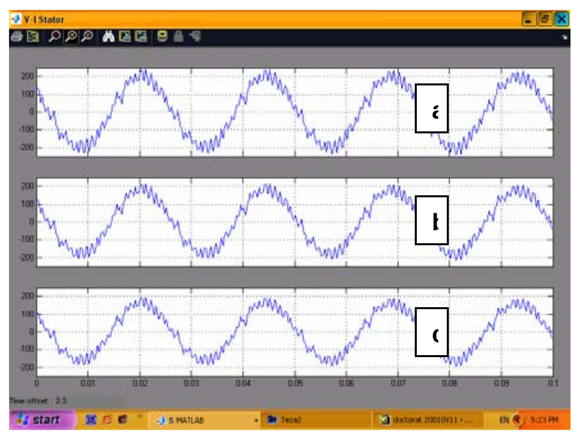

Fig.21 Unequally charged motors regime simulation , fs=40Hz: a) Phase current M_1 – new wheel driving u=0%; b) Phase current M_2 – medium weared wheel driving u=4,5%; c) Phase current M_3 – weared wheel driving u=9%

The validity and trustfulness of the achieved mathematical models and structural diagrams had been verified by simulations of traction induction motor regimes. Hence, in Fig.20 there are presented the simulations of phase current and speed in the transient starting regime of traction induction motor supplied at variable voltage and frequency source n^*=1135 rot/min (ω^* =118,9rad/s).

From viewpoint of exergy efficiency and environment issues, a special aspect, in case of the underground 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 underground train 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 exergetic viewpoint, this is one of the most unfavorable vehicle operation regime. In Fig.21 there are presented numerical simulations of the 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.

V. Conclusion and Further Direction

The exegy studies provide us with knowleadge of how effective and balanced a society is regarding the technical applications. If we are serious in our efforts to work towards a sustainable world, then information should be used to identify areas where technical and environmental improvements could be undertaken, and indicate the engineering world priorities.

The case study had emphasized that in traction regime, the train case study accomplishes remarkable results. The simulations had shown that using the structural diagrams and high techniques converters, an appropiate exergy efficiency can be achieved. This way, the electric motors dynamic characteristics respect the theoretical characteristics and the energy efficiency is equal to the exergy efficiency. The power converters and the efficient anti-skidding systems have ensured the electric trains optimum traction characteristics and a minimum energy consumption.

Further on, it must be said that around the world it is observed an exclusive utilization of the traction induction motors fed from the voltage-source inverter with two or three levels. The imposed specific features of the utilization in traction of these equipments can be studies 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 electric trains with traction induction motors fed from d.c. line contact.

It is remarkable the facile achievement of the structural diagram corresponding to a complex circuit on four levels, which is useful in a simulation environment. By integration of this diagram into more complex ones, it is possible to analyze, for example, the interaction between d.c. traction substations and contact line-fed vehicles.

Another conclusion related to exergy efficiency improvement could seem paradoxically and it is referring 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 an increased 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 automatically 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 efficiency.

In the long term, 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.

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