Energy Saving in Electric Trains with Traction Induction Motors

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Abstract: The real world processes involving energy and matter need to be linked to the technical and environmental engineering education, design and operation. Energy systems involving coversion chain processes are highly irreversible and, consequently, they could have low exergy efficiencies. In electric railway transportation systems, achieved energy provides a basis for increasing exergy efficiency, reducing both energy losses and environmental damage. Further on, achieved energy modeling can help in optimizing designs and making operating decisions.

Key-Words: Electric Transportation, Energy, Environmental Engineering, Exergy, Induction Motor

1 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 [2]. The first human intelligence step against ignorance would be the understanding of concepts such achieved energy, exergy and embodied energy applied in technical achievements.

On a broader front, an utmost human world priority should 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 achieved energy and exergy [2]. This paper is related to our other studies [3],[4],[5] and aimes at establishing the minimum of energy consumption of an electric train on basis of operation analysis at variable frequency with controlled stator flux .

2 Transport System with Induction Motors Operating at Variable Frequency and Flux Control

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 Electric Transportation System, not simply in terms of technico-economical growth, but also as an achievement of the Sustainable Development. In this 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 the transportation systems operation regimes.

The electric 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 [6]. 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 traction regime and the electric braking regime of the electric vehicle.

The operation at variable frequency with controlled flux is proceeded to induction motors in drive systems with vectorial control [7]. The vectorial regulation and control method is based on space phasor theory, taking into consideration the control both of the flux and of the induction machine electromagnetic torque M [8]. As principle, the stator current space phasor is decomposed in two perpendicular components (a flux component and a torque component) which are separately controlled. In this paper will be analyzed the permanent harmonics regime of variable frequency operation with controlled stator flux. It must be noted that in the theoretical achievements it will be taken into account the induction machine with constant parameters, without iron losses or saturation.

The three-phase induction machine equations (with phase quantities) depending on stator flux ψ_s are specified by the system (1) and correspondingly to the operation with ψ_s = ct. and ω_s = var., the phase equivalent scheme of induction machine [9] is presented in Fig.1.

$$\begin{aligned} &\underline{U}_s = R_s \underline{I}_s + j\,\omega_s \underline{\Psi}_s \\ &0 = \frac{\omega_s}{\omega_r} R_{r'} \left(\frac{L_s}{L_u}\right)^2 \left(\frac{L_u}{L_s}\underline{I}_{r'}\right) + \\ &+ j\,\omega_s \frac{\sigma L_s}{1-\sigma}\left(\frac{L_u}{L_s}\underline{I}_{r'}\right) + \omega_s \underline{\Psi}_s \\ &\underline{\Psi}_s = L_s \underline{I}_{ms} \\ &\underline{I}_{ms} = \underline{I}_s + \frac{L_u}{L_s}\underline{I}_{r'} \end{aligned} \qquad (1)$$

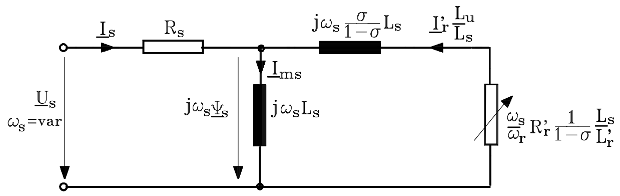

Fig.1 Equivalent scheme at ψ_s=ct. and ω_s=var.

Because of $\underline{\psi}_s = L_s \cdot \underline{I}_{ms}$ it means that the stator flux $\underline{\psi}_s$ control is reducing actually at the magnetizing current $\underline{I}_{ms}$ control. On the other hand, the equivalent scheme presented in Fig.1 allows the currents equation written as below:

$$\underline{I}_s = \underline{I}_{ms} + \left(-\underline{I}_{r'}\frac{L_u}{L_s}\right) \qquad (2)$$

where:

$$\underline{I}_{ms} = \frac{\underline{\psi}_s}{L_s}$$

$$-\underline{I}_{r'} \cdot \frac{L_u}{L_s} = \frac{\underline{\psi}_s}{\frac{\sigma}{1-\sigma}L_s} \cdot \frac{j}{\frac{R_{r'}}{\omega_r \sigma L_{r'}} + j} \qquad (3)$$

It means that within condition ψ_s = ct. the effective value $\underline{I}_s$ of stator current is not depending on the supply voltage (or current) frequency $f_s=\omega_s/(2\pi)$.

Analytically, in the complex frame (+1, +j), with the real axis along the phasor $\underline{\psi}_s$ (thus, with $\underline{\psi}_s=\psi_s+j0$), the stator current will be:

$$\underline{I}_s = \frac{\psi_s}{L_s} + \frac{\psi_s}{\frac{\sigma}{1-\sigma}L_s} \cdot \frac{j}{\frac{R_{r'}}{\omega_r \sigma L_{r'}} + j} = \qquad (4)$$
$$= I_{sx} + j \cdot I_{sy}$$

The stator current phasor diagram $\underline{I}_s$ is presented in Fig.2 [6].

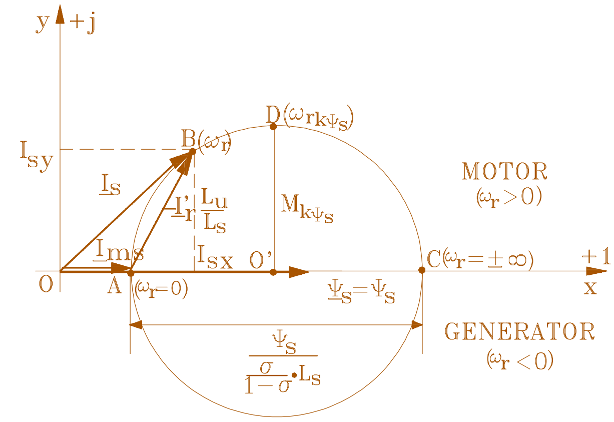

Fig.2 Stator current phasor $\underline{I}_s$ at ψ_s=ct. and ω_r=var.

It is obviously that when ψ_s = ct. and ω_r = var., the component $-\underline{I}'_r \cdot (L_u/L_s)$ of stator current $\underline{I}_s$ is variable in phase and magnitude, so that the point B will describe the circle ADC with diameter AC = $(1-\sigma)\psi_s/(\sigma L_s)$ = constant. Due to the constant value of the stator current component $\underline{I}_{ms}$, it means that the same circle will be describe by the phasor $\underline{I}_s$ when the flux ψ_s = ct. and the pulsation ω_r = var.

The mathematics calculus allows for the stator current components the relations as following:

$$\begin{aligned} I_{sx} &= \frac{\psi_s}{L_s} + \frac{1-\sigma}{\sigma L_s}\,\frac{\psi_s}{\frac{R_{r'}}{\omega_r \sigma L_{r'}} + \frac{\omega_r \sigma L_{r'}}{R_{r'}}}\,\frac{\omega_r \sigma L_{r'}}{R_{r'}} \\ I_{sy} &= \frac{1-\sigma}{\sigma L_s}\,\frac{\psi_s}{\frac{R_{r'}}{\omega_r \sigma L_{r'}} + \frac{\omega_r \sigma L_{r'}}{R_{r'}}} \end{aligned} \qquad (5)$$

The stator current absolute value can be determined by formula $I_s = (I_{sx}^2 + I_{sy}^2)^{1/2}$.

Electromagnetic torque M in complex coordinates axes system (oriented on $\underline{\psi}_s$) is:

$$\begin{aligned} M &= 3p \cdot Im\{\underline{I}_s \cdot \underline{\psi}_s^*\} = \\ &= 3p \cdot Im\{(I_{sx} + jI_{sy}) \cdot \psi_s\} = \\ &= 3p \cdot \psi_s \cdot I_{sy} \end{aligned} \qquad (6)$$

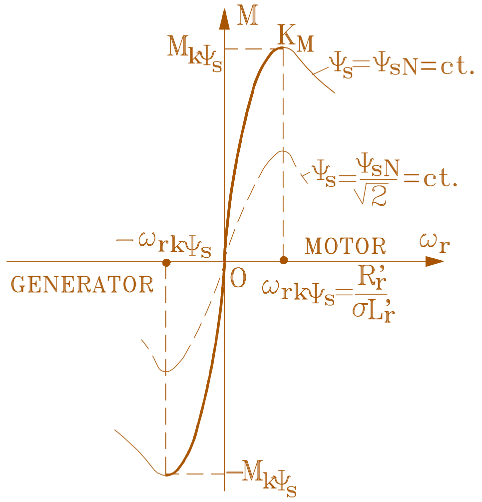

Fig.3 Torque characteristic $M=f(\omega_r)$ at controlled stator flux

Replacing I_{sy} from (5), the torque M relation becomes:

$$M = 3p \cdot \frac{1-\sigma}{\sigma L_s} \cdot \frac{\psi_s^2}{\frac{R_{r'}}{\omega_r \sigma L_{r'}} + \frac{\omega_r \sigma L_{r'}}{R_{r'}}} \qquad (7)$$

When stator flux is constant (ψ_s=ct.) then electromagnetic torque magnitude depends on rotor currents pulsation ω_r and doesn't depend on stator supply frequency f_s. The torque curve $M = f(\omega_r)$ at ψ_s = ct. will not linearly depend on ω_r, having two symmetrical extremes, as below:

$$\frac{\partial M}{\partial \omega_r} = 0\,; \quad \omega_{rk\psi_s} = \pm \frac{R_{r'}}{\sigma \cdot L_{r'}}\,;$$
$$M_{k\psi_s} = M(\omega_{rk\psi_s}) = \pm \frac{3p}{2} \cdot \frac{1-\sigma}{\sigma \cdot L_s} \cdot \psi_s^2 \qquad (8)$$

The graphical dependence $M = f(\omega_r)$ at ψ_s = ct. is represented in Fig.3.

In motor regime, taking into account the coordinates of maxima point K_M , the relation (7) can be achieved as "Kloss formula":

$$M = \frac{2M_{k\psi_s}}{\frac{\omega_r}{\omega_{rk\psi_s}} + \frac{\omega_{rk\psi_s}}{\omega_r}} \qquad (9)$$

In steady-state regime, a stable operation (with $\partial M/\partial\omega_r > 0$) is performed only on the ascendent zone of the characteristic $M = f(\omega_r)$ presented in Fig.3 and it is corresponding at small rotor pulsations, according the condition $|\omega_r| \leq \omega_{rk\psi s}$. Mechanical characteristics family $M = f(n)$ of induction motor operating at ψ_s=ct., for different constant values of stator frequency (f_s = ct.) are shown in Fig.4.

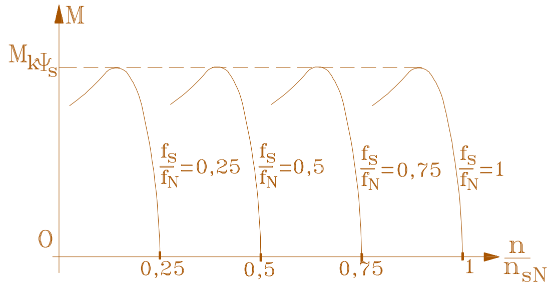

Fig.4 Mechanical characteristics M=f(n) at ψ_s=ct. for different frequency f_s values ($f_s \leq f_N$)

These characteristics had been drawn on basis of relation (9), taking into account that, to any value of frequency $f_s=\omega_s/(2\pi)$, it will result $\omega_r=\omega_s-\omega_m$ with $\omega_m=p\cdot\Omega_m=p\cdot2\pi n/60$.

The constant stator flux magnitude (ψ_s=ct.) to any stator frequency f_s value and to torque M (respectively, any rotor pulsation ω_r) impose an exact control either of the supply voltage U_s or of supply current I_s.

As magnitude, the stator voltage U_s effective value results from the electric equivalent presented in Fig.1. When ψ_s = ct. the voltage U_s will depend on both ω_s and $\omega_r = \omega_s - \omega_m$.

Absolutely similar, the stator current I_s at constant stator flux (ψ_s=ct.) can be expressed as depending on ω_r or on electromagnetic torque M. As dependence of electromagnetic torque M, with $\omega_r\cdot\sigma\cdot L'_r/R'_r$ from (6), as below:

$$\frac{\omega_r \sigma L_{r'}}{R_{r'}} = \frac{M_{k\psi_s}}{M} - \sqrt{\left(\frac{M_{k\psi_s}}{M}\right)^2 - 1} \qquad (10)$$

there will be obtained the two components I_{sx} and I_{sy} of stator current I_s:

$$I_{sx} = \frac{\psi_s}{L_s} + \frac{\psi_s}{L_s}\frac{1-\sigma}{2\sigma}\left[1 - \sqrt{1-\left(\frac{M}{M_{k\psi s}}\right)^2}\,\right]$$
$$I_{sy} = \frac{M}{3p\psi_s} = \frac{\psi_s}{L_s}\frac{1-\sigma}{2\sigma}\frac{M}{M_{k\psi s}} \qquad (11)$$

Consequently, at constant stator flux (Ψ_s = ct.), the effective value of stator current $I_s = (I_{sx}^2 + I_{sy}^2)^{1/2}$ will depend on electromagnetic torque M according to relation:

$$I_s = \frac{\psi_s}{L_s}\sqrt{\left[\frac{1\sigma}{2\sigma} - \frac{1-\sigma}{2\sigma}\sqrt{1-\left(\frac{M}{M_{k\psi_s}}\right)^2}\,\right]^2 + \left[\frac{1-\sigma}{2\sigma}\frac{M}{M_{k\psi_s}}\right]^2} \qquad (12)$$

3 Variation Range of Stator Frequency

When the supply voltages (or currents) are with variable frequency, it is important to establish the limit values, meaning the minimum frequency f_{smin} and the maximum frequency f_{smax} of the stable operation range of the induction machine.

3.1 Minimum Frequency at Constant Stator Flux Operation

In steady-state regime, to any stator frequency value f_s, among the pulsation ω_r, $\omega_s=2\pi\cdot f_s$ and $\omega_m=p\cdot\Omega_m=p\cdot 2\pi\cdot n/60$, according to *Frequencies Theorem* it is true the relation as below:

$$\omega_s = \omega_m + \omega_r \quad (13)$$

Consequently, for any given value of stator frequency f_s and rotor pulsation ω_r, respectively, it will be possible to establish the steady-state rotor speed n:

$$2\pi f_s = p\frac{2\pi n}{60} + \omega_r$$
$$\Rightarrow n = \frac{60}{p}\left(f_s - \frac{1}{2\pi}\omega_r\right) \quad (14)$$

If the normal operation at the frequency f_s is proceeding with constant stator flux $\Psi_s=\Psi_{sN}$=ct., then the speed n_k corresponding to the maximum electromagnetic torque M (see the point K_M in Fig.5)) will be calculated as following:

$$n_k = \frac{60}{p}\left(f_s - \frac{1}{2\pi}\omega_{rk\psi_s}\right)$$
$$n_k \geq 0 \quad (15)$$

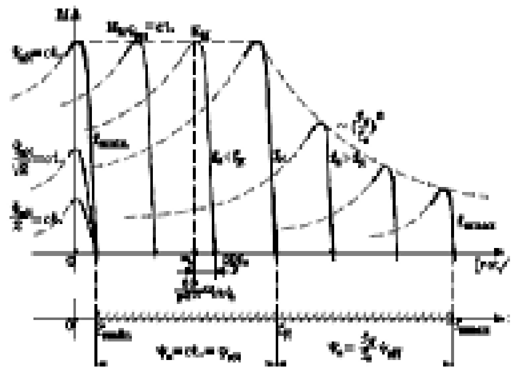

Fig.5 Stator frequency f_s extreme values

Hence, the minimum stator frequency f_{smin} which makes possible the operation conditions as before will correspond to the limit case when n_k = 0, resulting f_{smin}:

$$f_{smin} = \frac{1}{2\pi}\omega_{rk\psi_s} = \frac{1}{2\pi}\frac{R_{r'}}{\sigma L_{r'}} \quad (16)$$

This is the minimum frequency value which must be provided by the supply source. It is depending on induction machine parameters R'_r, L'_r and σ.

Also, in Fig.5 it is emphasized the slide starting method, by a progressive increase of stator flux Ψ_s from 0 to Ψ_{sN} (at the minimum value f_{smin} = ct. of supply stator frequency).

3.2 Maximum Frequency at Operation with Weaken Stator Flux

In the over-rated frequency range $f_s > f_N$, because of the stator voltage limitation at $U_s = U_N$, the induction machine will operate in weaken stator flux conditions. Normally, the stator flux Ψ_s decrease is proceeding by the law "$1/\omega_s$" written as below:

$$\psi_s = \psi_{sN}\frac{\omega_N}{\omega_s} = \frac{U_N}{\omega_s} \quad (17)$$

As result, the decrease of flux Ψ_s will determine a loss in capability of maximum torque $M_{k\psi_s}$ which at $f_s>f_N$ becomes:

$$M_{k\psi_s} = \frac{3p}{2}\frac{1-\sigma}{\sigma L_s}\left[\psi_{sN}\frac{\omega_N}{\omega_s}\right]^2 =$$
$$= M_{k\psi_{sN}}\left(\frac{\omega_N}{\omega_s}\right)^2 \quad (18)$$

Consequently, the electromagnetic torque M determined at ω_r=ct. and $f_s>f_N$ will decrease in the same ratio. Graphically, in the right side of Fig.6 there are represented three mechanical characteristics M=f(n) at decreased flux according to the law $\Psi_s=\Psi_{sN}\cdot\omega_N/\omega_s$ and f_s = ct. (with $f_s>f_N$).

In that framework, the stator frequency maximum value f_{smax} will be established from the invariant electromagnetic power condition $P_M=M\cdot\Omega_s=M\cdot\omega_s/p$ for different stator frequency values f_s. Hence, in the aim to ensure P_M = ct. in the range of limit frequencies f_N and f_{smax} it is compulsory that:

$$M_N\frac{\omega_N}{p} = M_{f_{smax}}\frac{\omega_{smax}}{p} \quad (19)$$

If at the maximum stator frequency f_{smax} it is imposed the condition $M_{f_{smax}} = M_{k\psi_s}$, where $M_{k\psi_s}$ is determined by (18), then we will obtain:

$$M_N\cdot\frac{\omega_N}{p} = M_{k\psi_{sN}}\cdot\left(\frac{\omega_N}{\omega_{smax}}\right)^2\cdot\frac{\omega_{smax}}{p}$$
$$\Rightarrow \omega_{smax} = \frac{M_{k\psi_{sN}}}{M_N}\cdot\omega_N \quad (20)$$

or:

$$\lambda_M = \frac{M_{k\psi_{sN}}}{M_N}$$
$$\Rightarrow f_{smax} = \lambda_M\cdot f_N \quad (21)$$

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Hence, the increase of frequency f_{smax} could be obtained only by designing an induction machine with an increased overload torque capability λ_M. It is compulsory to be noticed that for the normal induction machines $\lambda_M = 2{,}2 \ldots 2{,}5$.

Consequently, when we are taken into account the induction machine operation with variable stator frequency, there must be emphasized that the supply voltage (or current) frequency minimum f_{smin} and maximum f_{smax} values are depending only on that induction machine parameters.

4 Energy Saving in Train Operation

In the power schemes of electric trains, the traction induction motor represents the final element in the conversion energy equipments chain [3]. After all, it achieves the electromechanical conversion of energy making thus possibly the movement. For an achieved energy dynamic approach both of the traction motor and of the useful movement mathematical models are neccessary. Further on, there will achieved the structural diagrams [4], so that, by an appropriate train control, the minimum of energy consumption will be obtained.

As a complex electromechanical system, the induction motor could be conceptually decomposed into an electromagnetic subsystem and a mechanical subsystem. Between these two functional parts, both the electromagnetic torque M and the rotor mechanical speed Ω_m are interacting as internal variables.The induction motor electromagnetic part will be described by the equations [5]:

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

$$\frac{d\underline{\psi}'_r}{dt} = j \cdot p \cdot \Omega_m \cdot \underline{\psi}'_r - R'_r \cdot i'_r \qquad (22)$$

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

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

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 (22) the structural diagram and the mask block of the induction motor electromagnetic part are represented in Fig.6, a. 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. In Fig.7 the structural diagram of useful moment is presented.

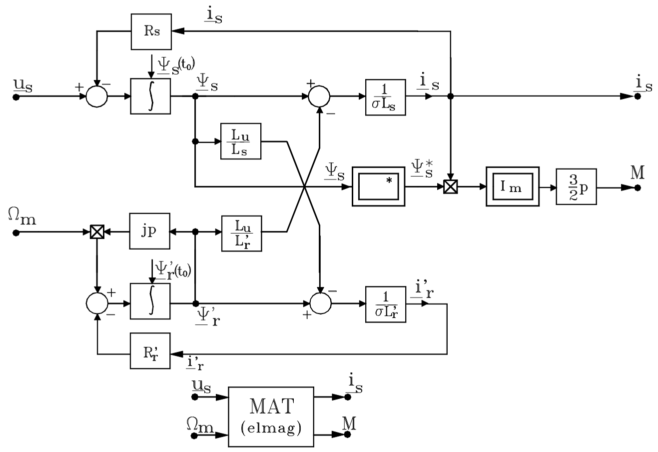

Fig.6 Structural diagram and mask block for electromagnetic part of induction motor

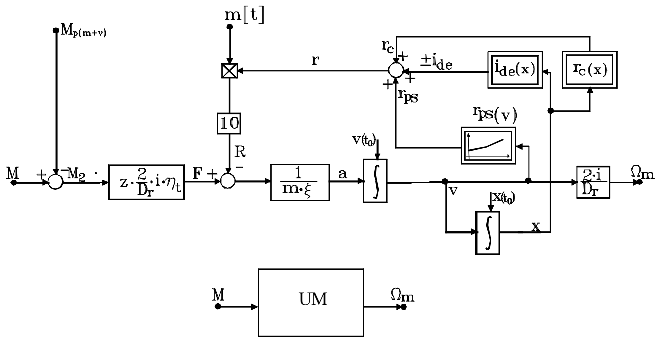

Fig.7 Structural diagram and mask block of useful movement

The next step of train operation achieved energy analysis encompass the numerical simulations of different train operation regimes. Hence, the validity and trustfulness of the achieved mathematical models and structural diagrams had been verified by simulations of traction induction motor regimes.

In Fig.8 the SIMULINK – SimPowerSystems Model [10] for traction motors (MABT1, MABT2 and MABT3) transient starting regime simulation is presented, and on this basis, in Fig.9 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). Further on, the simulation and test results (Fig.10) were compared in order to establish the match.

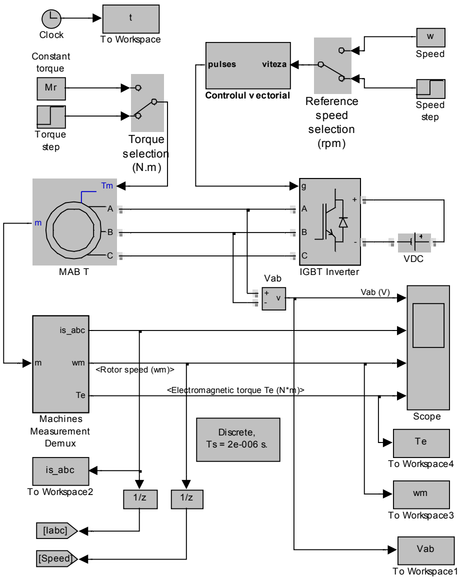

Fig.8 SIMULINK – SimPowerSystems Model for study of traction induction motors supplied at variable voltage and frequency source

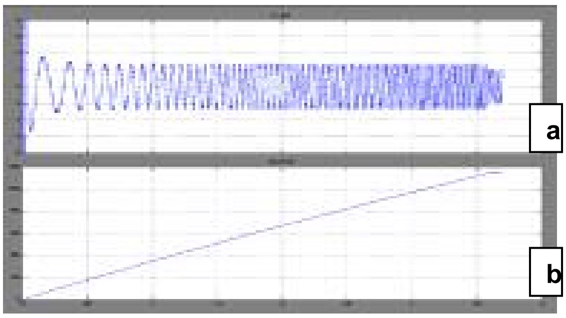

Fig.9 Transient starting regime simulation of traction induction motor supplied at variable voltage and frequency source $n^*=1135$ rot/min ($\omega^*=118{,}9$rad/s)
a) Phase current; b) Speed

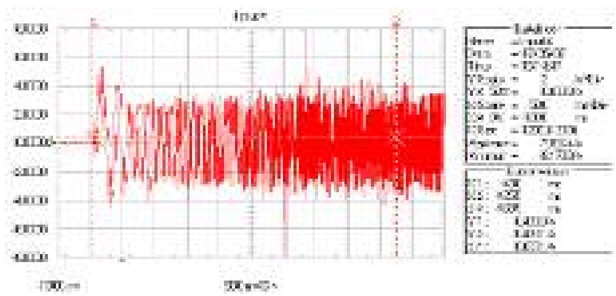

Fig.10 Transient starting regime test of traction induction motor supplied at variable voltage and frequency source $n^*=1135$ rot/min ($\omega^*=118{,}9$rad/s)

5 Conclusions

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 observation also implies that there is great potential for improving the performance of such systems. This paper emphasizes the achieved energy analysis, related as tool in order to describe, analyse and optimize energy conversion in electric railway transportation systems. This way, it could be obtained a high exergy efficiency, due to the matching of simulation and experimental data. In traction regime, the electric trains accomplishes remarkable results. Using the structural diagrams and high techniques converters, an appropiate vehicle control can be achieved. The power converters and the efficient anti-skidding systems have ensured the optimum traction characteristics and a minimum of energy consumption.

In a longterm, the important application of this research is to address sustainability issues in a qualitative and quantitative fashion through a complete analysis of the electric railway transportation systems.

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