Some synoptic aspects of electric technical applications as a confluence of industrial and natural ecosystems

Cornelia A. Bulucea, Doru A. Nicola, Nikos E. Mastorakis, Marc A. Rosen

Abstract Although science has not clarified the relations between and unified technical and ecological viewpoints, a set of conditions for the performance of sustainable electrical systems needs to be formulated. The work reported here aims to enhance the paradigm and thinking that human activities cannot be separated from the functioning of the entire system on Earth. Learning from nature means to accept that the technical systems and processes involving energy conversion and matter transformation need to be linked to environment engineering. This paper adopts a dualist view, incorporating technical and environmental dimensions, to describe the applicability of exergy to electrical ecosystems. Industrial ecology permits an alternate view of human applications, related both to technical and environmental reference systems.

Keywords: Electric System, Energy Conversion, Exergy, Industrial Ecology

I. Introduction

INDUSTRIAL ecology is an emerging framework within sustainable development [1,2]. The concepts, tools and goals of industrial ecology have to be addressed, along with the understanding that sustainable development is not about certificates or licenses, but needs to address the vitality of life on Earth. Future needs for sustainable development include a human moral change through education, and an industrial metabolism shift through responsible practical actions. Since nature generated life, industrial ecology seeks a new approach to industrial systems, viewed not in isolation from the natural surroundings systems, but in concert with them. The framework of industrial ecology, an approach for technical systems created by humans and ecological systems created by nature, treated as parts of the same system, the industrial ecosystem, could provide a holistic view of the interactions and symbiotic interrelationships among human activities, industrial practices and ecological processes [3,4,5].

A sustainable industrial metabolism, integrating technical and ecological aspects should be one of the greatest challenges of humanity within the present industrial world. Although science not clearly unified on technical and ecological viewpoints, a set of conditions for the performance of sustainable electrical systems needs to be formulated. Starting from the observation that nature generated ordered structures and human beings are only one component in the complex web of ecological interactions, and thus are a part of the huge evolutionary process in nature [6,7], the focus of this paper is to enhance the way of thinking that human activities cannot be separated from the functioning of the entire system.

Traditionally, the basic concepts of *energy*, *exergy* and *embodied energy* are founded in the fields of physics and engineering, having however environmental and economical significance as well. These concepts be explained, interpreted and applied in a more universal manner, due to their multidisciplinary traits [8,9]. Energy and/or matter flow through a system. The motive force of the flow of energy or matter through a system is the contrast, or the gradient, or the level of order. The quality of the energy or matter constantly deteriorates in the flow passing through the system [6,7]. The concept of entropy or rather negentropy, relating to exergy, is a measure of the level of order. So, exergy measures the physical concept of contrast or gradient, which quantifies its power of action. A system in complete equilibrium with itself and the environment does not have any exergy, meaning no power of action. In physics and engineering, work is a specific form of action, and exergy is defined based on work, i.e. ordered motion, or ability to perform work [6,7]. On the other hand, if there were always to be no exergy destruction, there would be no action, and everything would remain the same forever.

While energy is a measure of quantity only, exergy is a measure of quantity and quality or usefulness. Since energy is often thought of as motion and exergy as work [10], the electromagnetic torque developed by an electrical ecosystem can be interpreted, regardless of the reference frame considered, as the driving force of useful work, i.e. the ecosystem output exergy.

The objective of this article is to enhance thinking such that human activities are viewed in concert with the entire system

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on Earth, and to apply such ideas to industrial technologies: an electromagnet and an electric train.

II. Electromagnet Industrial Ecosystem

We highlighted [14] that industrial ecology permits an alternate view of human applications, related both to technical and environmental reference systems. In line with this idea, a convincing example of the usefulness of the *exergy* and *embodied energy* concepts for analyzing systems which convert energy is an electromagnet system.

A. Useful Mechanical Work of Armature in Motion

For any electromagnet with embedded energy in the ferromagnetic core [15], the electromagnetic forces draw the armature to the core and reduce the air gap as a result.

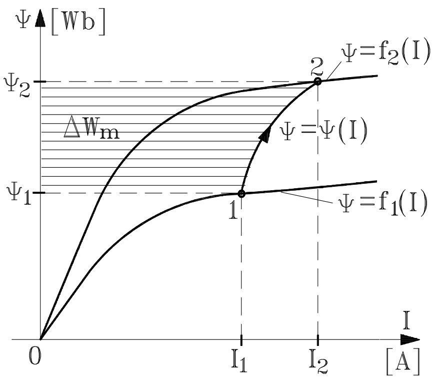

Fig. 1 Evolution curve $\psi = \psi(I)$ and the change in magnetic energy ΔW_m when the armature moves

In the evaluation of the mechanical work W_{12} caused by the magnetic field forces (when the armature is in movement), we have considered [15] an electromagnet characterized at the initial equilibrium point by the air gap magnitude δ_1 and the flux curve $\Psi = f_1(I)$ on which, in the first stable regime, the operation has been stabilized at point 1, with the coordinates I_1 and Ψ_1 (see Fig. 1). After the armature attraction, the final stable state is described by the air gap δ_2 (with $\delta_2 < \delta_1$) and by the flux characteristic $\Psi = f_2(I)$, on which is found the second equilibrium point (point 2), with coordinates I_2 and Ψ_2. In these conditions, during the armature movement (from δ_1 to δ_2), a dual energy change occurs between the source and the magnetic field. First, the source provides to the electromagnet the change in energy ΔW_m, proportional to the hatched surface corresponding to the flux variation from Ψ_1 to Ψ_2 on the evolution curve $\Psi(I)$ in Fig. 1:

$$\Delta W_m = \int_{\psi_1}^{\psi_2} i \cdot d\psi = surface(\psi_1 12 \psi_2) \qquad (1)$$

Second, the magnetic field forces perform mechanical work W_{12}, corresponding to the displacement $\Delta\delta$ of the electromagnet armature.

Consequently, in the absence of dissipative magnetic forces, the energy balance of the electromagnet in the technical reference frame, under the varying conditions of the state-quantities due to the armature movement, is described by the following equation:

$$W_{m1} + \Delta W_m = W_{m2} + W_{12} \qquad (2)$$

Within the reference frame of industrial ecology, it is helpful to write the exergy balance for the previous situation on the basis of input-output analysis:

$$X_{in} + \Delta X_{sys} - X_{out} - X_{des} = 0 \qquad (3)$$

where X_{in} is the input exergy, corresponding to the magnetic field embodied energy in the initial stable state; ΔX_{sys} is the change in exergy of the system during the transient process; X_{out} represents the output exergy (including both the magnetic field embodied energy in the final stable state and the net exergy transfer by useful mechanical work); and X_{des} is the exergy destruction by the dissipative magnetic forces of the system.

Neglecting the exergy destroyed by dissipative forces, the meanings of equations (2) and (3) are similar, but they are expressed in technical and ecological terms, respectively. The use of exergy, as noted earlier, provides insights into environmental and ecological impact.

With the general expression $W_m = \frac{1}{2} \cdot I \cdot \psi$ for the embedded magnetic energy, the mechanical work expressions $W_{12'}$ (performed for the armature in motion) can be written in a unitary mode with the following expressions:

$$W_{12'} = \Delta W_{m12}|_{I=ct.}$$
$$W_{12''} = -\Delta W_{m12}|_{\psi=ct.} \qquad (4)$$

B. Electromagnet Force and Torque

When the electromagnet armature undergoes a displacement $\Delta\delta$ (from steady-state position δ_1 to steady-state position $\delta_2 < \delta_1$), the attraction force determines the mechanical work L_{12}. The corresponding embedded magnetic energy variation is $\Delta W_{m12} = W_{m2} - W_{m1}$. The relations in (4) apply between the performed mechanical work L_{12} and the magnetic energy variation ΔW_{m12}.

Moreover, the elementary mechanical work dL for elementary displacements $d\delta$ or $d\alpha$ of the electromagnet armature over small distances is determined with the following formulas:

$$dL = F \cdot d\delta$$
$$dL = M \cdot d\alpha \qquad (5)$$

Here, $d\alpha$ denotes the armature rotation angle when the air-gap is modified linearly by $d\delta$ (determined by the action of the force F and the torque M, respectively).

Corresponding to the elementary displacements, the relations (4) can be rewritten as

$$dL = dW_m|_{I=ct.} \;; \quad dL = -dW_m|_{\psi=ct.} \qquad (6)$$

The following formulas result as a consequence of (5) and (6):

a) for the force:

$$F = \frac{dW_m}{d\delta}\Big|_{I=ct.} \quad \text{or} \quad F = -\frac{dW_m}{d\delta}\Big|_{\psi=ct.} \qquad (7)$$

b) for the torque:

$$M = \frac{dW_m}{d\alpha}\Big|_{I=ct.} \quad \text{or} \quad M = -\frac{dW_m}{d\alpha}\Big|_{\psi=ct.} \qquad (8)$$

These results are general and identical with those determined via electrotechnics with the method of "Generalized Forces in Magnetic Field". But these formulas should also be interpreted within the framework of industrial ecology. Energy is sometimes thought of as motion and exergy as work [7]. So, the magnetic force F or the torque M developed by the electromagnet can be interpreted, regardless of the reference frame considered (technical or ecological), as the driving force of the mechanical work, i.e. the electromagnet output exergy.

B1) Electromagnet Operation with Constant Current-turns

In the case of d.c. electromagnets, the absorbed current I does not vary with the armature displacement. Consequently, when $I = const.$ (and the current turns $\theta = w \cdot I = const.$) and taking into account that $\psi = L \cdot I$, the magnetic energy expression becomes $W_m = \frac{1}{2} \cdot L \cdot I^2$ (noting that here L denotes the static inductance L_s). The magnetic energy varies with the armature displacement. Thus, at $\theta = w \cdot I = const.$ (i.e., $I = const.$), the force F and the torque M can be written as follows:

$$F = \frac{dW_m}{d\delta}\Big|_{I=ct.} = \frac{1}{2} \cdot I^2 \cdot \frac{dL}{d\delta}$$

$$M = \frac{dW_m}{d\alpha}\Big|_{I=ct.} = \frac{1}{2} \cdot I^2 \cdot \frac{dL}{d\alpha} \qquad (9)$$

Since the inductance $L = w^2 / R_m$ depends on the total magnetic resistance (reluctance) R_m of the electromagnet magnetic circuit, it is useful to highlight the two components of R_m: R_{mFe} which denotes the reluctance associated with the iron part of the electromagnet and $R_{m\delta}$ which denotes the reluctance of the electromagnet air gaps. Since $R_{m\delta} \ll R_{mFe}$,

$$R_m = R_{mFe} + R_{m\delta} \approx R_{m\delta} \qquad (10)$$

and, as a result,

$$L = \frac{w^2}{R_m} \approx \frac{w^2}{R_{m\delta}} = w^2 \cdot \Lambda_\delta \qquad (11)$$

Consequently, the expressions (9) can be rewritten in the simplified forms:

$$F \approx \frac{1}{2} \cdot \theta^2 \cdot \frac{d\Lambda_\delta}{d\delta} \quad ; \quad M \approx \frac{1}{2} \cdot \theta^2 \cdot \frac{d\Lambda_\delta}{d\alpha} \qquad (12)$$

Here, $\Lambda_\delta = 1/R_{m\delta}$ denotes the permeance of the air gaps.

B2) Electromagnet Operation with Constant Magnetic Flux

To assess the case of electromagnet operation with a constant magnetic flux, we consider a.c. electromagnets. When a magnetizing winding having electric resistance R is supplied from a sinusoidal voltage source with a r.m.s. value $U = const.$ and frequency $f = const.$, in a steady-state sinusoidal regime between the r.m.s. voltage U and the r.m.s. current I, we can write:

$$U = \sqrt{(R \cdot I)^2 + \left(\omega \cdot \frac{\psi}{\sqrt{2}}\right)^2} \qquad (13)$$

Assuming the voltage drop on the resistance $R \cdot I$ can be neglected (at $U = const.$ and $\omega = 2\pi f = const.$, with $U \gg R \cdot I$), relation (13) expresses the condition of the electromagnet operation at constant flux:

$$U \approx \omega \cdot \frac{\psi}{\sqrt{2}} \;\Rightarrow\; \psi = \frac{\sqrt{2} \cdot U}{\omega} = const. \qquad (14)$$

When $\psi = const.$, $d\psi/d\delta = 0$ and the force F and the torque M can be determined as follows:

$$F = -\frac{dW_m}{d\delta}\Big|_{\psi=ct.} = -\frac{1}{2} \cdot \psi \cdot \frac{dI}{d\delta}$$

$$M = -\frac{dW_m}{d\alpha}\Big|_{\psi=ct.} = -\frac{1}{2} \cdot \psi \cdot \frac{dI}{d\alpha} \qquad (15)$$

Since $I = \frac{\psi}{L}$, the current derivative at $\psi = const.$ is

$$\frac{dI}{d\delta} = -\frac{\psi}{L^2} \cdot \frac{dL}{d\delta} \quad ; \quad \frac{dI}{d\alpha} = -\frac{\psi}{L^2} \cdot \frac{dL}{d\alpha} \qquad (16)$$

Substitution of the formulas (16) into the relations (15) leads to the expressions in (9).

B3) Discussion of Forces

The total force developed by an electromagnet can be determined as the sum of the attraction forces $F_{\delta i}$ corresponding to all electromagnet active air gaps:

$$F = \sum_{i=1}^{k} F_{\delta i} \qquad (17)$$

The attraction force in an air gap $F_{\delta i}$ can be determined applying the formula for Maxwell tensions in uniform magnetic field:

$$F_{\delta i} = T_{ni} \cdot S_{\delta i} = w_{mi} \cdot S_{\delta i} = \frac{B_{\delta i}^2}{2\mu_0} \cdot S_{\delta i} = \frac{1}{2\mu_0} \cdot \frac{\phi_i^2}{S_{\delta i}} \qquad (18)$$

Here, $T_{ni} = \frac{B_{\delta i} \cdot H_{\delta i}}{2} = \frac{B_{\delta i}^2}{2\mu_0} = w_{mi}$ is the Maxwell tensor in the air-gap i; w_{mi} represents the magnetic energy density in the considered air gap; $B_{\delta i}$ represents the magnetic field in the air gap; $S_{\delta i}$ is the equivalent cross section of the air gap; $\mu_0 = 4 \cdot \pi \cdot 10^{-7}\ [H/m]$ is the permeability of free space; and $\phi_i = B_{\delta i} \cdot S_{\delta i}$ is the magnetic flux through the air gap considered.

This result can be applied in the case of air gaps with a magnetic field that is uniformly distributed at all points of the cross-section ($B_\delta = const.$). If the magnetic field in the air gap is not constant, then the cross-section area S_δ is divided into elementary parts $\Delta S_{\delta k}$, where the magnetic field B_δ can be considered constant, i.e., $B_{\delta k} = const.$ Consequently, for each air gap, the attraction force is determined as the sum of the elementary forces $\Delta F_{\delta k} = B_{\delta k}^2 \cdot \Delta S_{\delta k} /(2 \cdot \mu_0)$ corresponding to the individual attractions of each elementary section.

III. Electric Train Industrial Ecosystem

The study of electric trains is based on the concept that the negative effects on efficiency of large exergy destructions and the corresponding long-term environmental degradation can be understood and improved only by viewing the electric train as an industrial ecosystem. This research extends earlier work by the authors [16,17,18,19,20].

Electric railway trains supplied by a d.c. contact line are equipped with three-phase induction motors and variable voltage and frequency inverters [21]. Since electric drive systems are used with static converters and traction induction motors, with appropriate controls these machines can realize both traction and electric braking regimes of electric traction vehicles. Utilization in electric traction of an induction motor with a rotor squirrel cage is possible only in the conditions of a three-phase supply system with controlled variable frequency and r.m.s. voltages [21,23].

A. Induction Machine Operation at Variable Frequency

An industrial ecosystem does not have a single equilibrium point [3]. Rather, the system moves among multiple stable states [4,5]. The dynamic regimes in electric train operation, e.g. starting or braking processes, can be viewed as representing the industrial ecosystem movement among points of equilibrium.

We follow a dualist view [16], in which the transportation system is taken to be surrounded by two environments: technical and ecological. Within the technical surroundings, the electric transportation system is closed, whereas it is seen as open within the ecological environment.

Vehicle regulation speed is determined examining the static converter and electric machine as an assembly [21]. The traction motor speed regulation is based on stator voltage and frequency variation, so that to achieve high exergy efficiency, the first requirement of the train control system concerns passing of the motor operation equilibrium point from one mechanical characteristic to another.

In the range of frequencies lower than the rated frequency, $f_s < f_N$, in order to ensure a constant level of inductor machine stator flux $\Psi_s = \Psi_{sN}$, we have to simultaneously modify the frequency f_s and the supply voltage magnitude U_s so the supply r.m.s. voltage U_s varies with the frequency f_s according to $U_s(f_s)=\left| R_s\underline{I}_s+j2\pi f_s\underline{\Psi}_{Sn} \right|$, where R_s is the stator resistance and Ψ_s the stator flux. In any steady-state regime for any constant stator frequency f_s=const., with $f_s \le f_N$, the induction machine operation at U_s/f_s=const.=U_N/f_N can be followed taking into account the electromagnetic torque expression:

$$M = \frac{\frac{3p}{\omega_N}(1-\sigma)X_s(\frac{f_s}{f_N}U_N)^2}{\frac{\omega_N R_{r'}}{\omega_r X_{r'}}[R_s^2+(\frac{f_s}{f_N}X_s)^2]+2\frac{f_s}{f_N}R_s(1-\sigma)X_s+\frac{\omega_r X_{r'}}{\omega_N R_{r'}}[R_s^2+(\frac{f_s}{f_N}\sigma X_s)^2]} \quad (19)$$

If we substitute $\omega_r=\omega_s-\omega_m$, where the mechanical pulsation ω_m depends on rotor speed n according to $\omega_m=2\pi pn/60$, then for any constant frequency $f_s<f_N$ the mechanical characteristics M=f(n) of the induction machine supplied with a variable voltage $U_s=U_N f_s/f_N$ corresponding to various stable states of low frequencies motor operation can be obtained.

Energy is often thought of as motion and exergy as work [7]. So the electromagnetic torque M developed by the electrical motor can be interpreted, regardless of the reference frame considered, as the driving force of useful work, i.e. the motor output exergy. From an exergetic viewpoint we emphasize an important drawback of operation at U_s/f_s=const., concerning a sudden decrease of maximum torque M_k in the motor regime when the stator frequency f_s is reduced to under 20 Hz (generally under f_N/3 Hz). The physical explanation for this decrease in maximum torque M_k is based on the motor flux decrease at low frequencies, when the stator voltage $U_s=U_N f_s/f_N$ is already reduced while the voltage drop on the stator resistance R_sI_s remains almost invariable in magnitude at all low frequencies $f_s \le f_N$. As a consequence, in the operation regime with U_s/f_s=const., at low frequencies the induction motor performance is strongly affected, because of the severe flux decrease which produces a significant loss of induction motor torque capability, representing an important exergy destruction.

This situation can be avoided only by the forced increasing of the terminal voltage U_s. Consequently, this voltage depends on the stator frequency f_s by function $U_s=U_s(f_s)$ which is not proportional to f_s. In a particular case, the law of voltage variation with frequency $U_s=U_s(f_s)$ is obtained if in motor regime a certain condition is imposed, implying the torque $M_k(f_s)$ must remain equal to the torque $M_{Km}(f_N)$.

In the case considered subsequently of an induction machine supplied by a variable frequency voltage source, when the rated speed is reached (i.e. the induction motor is supplied at U_N and f_N) a further increase in speed is possible only by increasing the stator frequency magnitude over the rated frequency $f_s>f_N$. Note that because of the voltage restriction on both converters and induction machine winding insulation considerations, the stator voltage is limited and maintained at a constant magnitude $U_s=U_N$ for the entire high frequency domain, and the induction machine operates in weakened flux conditions [21]. From an exergetic viewpoint it is noted that, because the stator flux and pulsation exhibit an inverse proportionality relation $\Psi_s=U_N/\omega_s$, the machine torque capability is strongly affected, and the exergy destruction can not be avoided. This is the reason for the limited increase of stator frequency.

We conclude that the induction machine supplied from a variable frequency and voltage source operates with full field $\psi_s=\psi_{Sn}$=const. in the low frequency range $f_s \leq f_N$ and with a weakened field ($\psi_s<\psi_{Sn}$) in the increased frequency domain $f_s>f_N$ (when the supply r.m.s. voltage remains constant $U_s=U_N$=const.).

B. Transport System with Induction Motors Operating at Variable Frequency and Controlled Flux

The operation at variable frequency with controlled flux is preceded for induction motors in drive systems with vectorial control [21]. The vectorial regulation and control method is based on space phasor theory, taking into consideration the control of both the flux and the induction machine electromagnetic torque M. In principle, the stator current space phasor is decomposed into two perpendicular components (a flux component and a torque component) which are separately controlled. One could analyze the permanent harmonics regime of variable frequency operation with controlled stator flux, controlled useful flux or controlled rotor flux. As an example, we present the operation with controlled stator flux.

The following relations can be derived for the stator current components [23]:

$$I_{sx}=\frac{\psi_s}{L_s}+\frac{1-\sigma}{\sigma L_s}\frac{\psi_s}{\dfrac{R_{r'}}{\omega_r\sigma L_{r'}}+\dfrac{\omega_r\sigma L_{r'}}{R_{r'}}}\frac{\omega_r\sigma L_{r'}}{R_{r'}}$$
$$I_{sy}=\frac{1-\sigma}{\sigma L_s}\frac{\psi_s}{\dfrac{R_{r'}}{\omega_r\sigma L_{r'}}+\dfrac{\omega_r\sigma L_{r'}}{R_{r'}}} \qquad (20)$$

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

Within the ecological framework, the electromagnetic torque M is again related to the system output exergy. We can express M in complex coordinates axes system (oriented on $\underline{\psi}_s$) as

$$\begin{aligned}M&=3p\cdot Im\{\underline{I}_s\cdot\underline{\psi}_s^*\}=\\&=3p\cdot Im\{(I_{sx}+jI_{sy})\cdot\psi_s\}=\\&=3p\cdot\psi_s\cdot I_{sy}\end{aligned} \qquad (21)$$

Substituting I_{sy} from (20), the torque relation becomes

$$M=3p\cdot\frac{1-\sigma}{\sigma L_s}\cdot\frac{\psi_s^2}{\dfrac{R_{r'}}{\omega_r\sigma L_{r'}}+\dfrac{\omega_r\sigma L_{r'}}{R_{r'}}} \qquad (22)$$

If the stator flux ψ_s is constant, the electromagnetic torque magnitude depends on the rotor current pulsation ω_r but not the stator supply frequency f_s. The torque curve $M=f(\omega_r)$ at ψ_s=const. is not linearly dependent on ω_r, having two symmetrical extremes:

$$\frac{\partial M}{\partial\omega_r}=0\,;\ \omega_{rk\psi_s}=\pm\frac{R_{r'}}{\sigma\cdot L_{r'}}\,;$$
$$M_{k\psi_s}=M(\omega_{rk\psi_s})=\pm\frac{3p}{2}\cdot\frac{1-\sigma}{\sigma\cdot L_s}\cdot\psi_s^2 \qquad (23)$$

The dependence of $M=f(\omega_r)$ at ψ_s=const. is shown in Fig. 2. In a steady-state regime, a system stable operation (with $\partial M/\partial\omega_r>0$) is performed only on the ascendant zone of the characteristic $M=f(\omega_r)$ in Fig. 2 and corresponds at small rotor pulsations to the condition $|\omega_r|\leq\omega_{rk\psi s}$. The mechanical characteristics family M=f(n) of the induction motor operating at ψ_s=const., for different stator frequencies f_s are shown in Fig. 3.

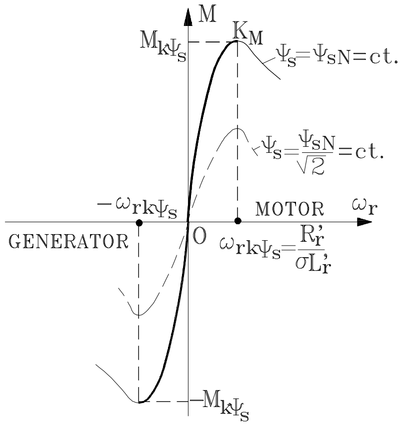

Fig. 2 Torque characteristic $M=f(\omega_r)$ at controlled flux

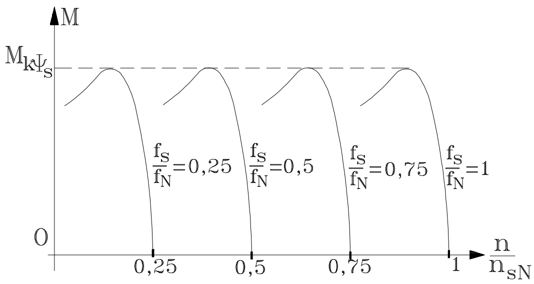

Fig. 3 Mechanical characteristics M=f(n) at ψ_s=const. for different frequency f_s values ($f_s\leq f_N$)

The constant stator flux magnitude ψ_s for any stator frequency f_s and torque M (respectively, any rotor pulsation ω_r) imposes an exact control of either the supply voltage U_s or the supply current I_s. We see again an analogy between this electrical system and an ecosystem. An appropriate technical system control must be achieved for reducing exergy destruction when the equilibrium point passes from one stable state (represented by the operation point on a certain mechanical characteristic) to another stable state (on another mechanical characteristic). This observation implies the system control needs to be assessed next.

C. Discussion of Operation at Constant Fluxes

One could notice in the permanent harmonic regime among the fluxes $\underline{\Psi}_s$, $\underline{\Psi}_u$, $\underline{\Psi}'_r$ and the currents $\underline{I}_s$, $\underline{I}'_r$ of any unsaturated induction machine, with electric and magnetic symmetry. Hence the following operating relations occur:

$$\begin{aligned} \underline{\psi}_s &= L_{s\sigma}\cdot \underline{I}_s + \underline{\psi}_u \\ \underline{\psi}_s &= \sigma\cdot L_s\cdot \underline{I}_s + \frac{L_u}{L_{r'}}\cdot \underline{\psi}'_r \\ \underline{\psi}'_r &= \underline{\psi}_u + L'_{r\sigma}\cdot \underline{I}'_r \\ 0 &= R'_r + j\,\omega_r\cdot \underline{\psi}'_r \end{aligned} \qquad (24)$$

Accordingly, shown in Fig. 4 are the fluxes and currents phasor diagram of induction machine operating in motor regime. In the complex reference system, with real axis (+1) along the direction of phasor $\underline{\Psi}'_r$ (with $\underline{\Psi}'_r=\Psi'_r+j\cdot 0$; $\underline{I}_s=I_{sx}+j\cdot I_{sy}$ and $\underline{I}'_r=0-j\cdot I'_r$), from the geometry of the rectangular triangles OAA' and OBB' (see Fig. 3) one could write:

$$\begin{aligned} \psi_s^2 &= [\frac{L_u}{L_{r'}}\cdot\psi'_r + \sigma\cdot L_s\cdot I_{sx}]^2 + (\sigma\cdot L_s\cdot I_{sy})^2 \\ \psi_u^2 &= \psi'^{\,2}_r + (L'_{r\sigma}\cdot I'_r)^2 \end{aligned} \qquad (25)$$

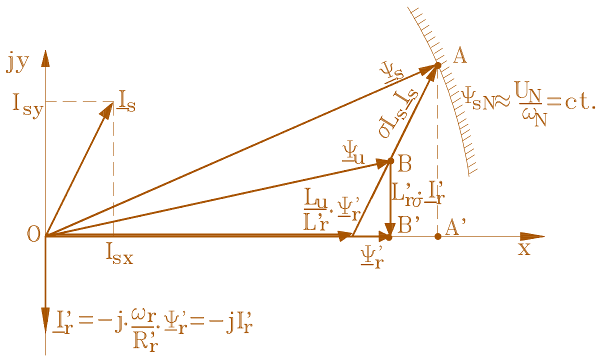

Fig. 4 Phasor representation of induction motor fluxes and currents at $\omega_r>0$

Furthermore, taking into consideration the components I_{sx} and I_{sy} , as well as the rotor current I'_r in accordance with the following relations:

$$I_{sx}=\frac{\psi'_r}{L_u};\ I_{sy}=\frac{\psi'_r}{L_u}\cdot\frac{L'_r}{R'_r}\cdot\omega_r;\ I'_r=\frac{\omega_r}{R'_r}\cdot\psi'_r \qquad (26)$$

and after mathematical calculation, the expressions of fluxes Ψ_u and Ψ'_r will be determined:

$$\begin{aligned} \psi_u(\omega_r) &= \psi_s\cdot\frac{L_u}{L_s}\cdot\sqrt{\frac{1+(\frac{L'_{r\sigma}}{R'_r}\cdot\omega_r)^2}{1+(\frac{\sigma\cdot L'_r}{R'_r}\cdot\omega_r)^2}} \\ \psi'_r(\omega_r) &= \psi_s\cdot\frac{L_u}{L_s}\cdot\frac{1}{\sqrt{1+(\frac{\sigma\cdot L'_r}{R'_r}\cdot\omega_r)^2}} \end{aligned} \qquad (27)$$

Consequently, one could highlight that the fluxes Ψ_u and Ψ'_r depend on Ψ_s, as well on machine parameters and on ω_r. But any induction machine designed to be supplied with phase voltage U_N at stator frequency f_N ($\omega_N = 2\pi\cdot f_N$) will have the stator flux Ψ_s approximately constant, with the magnitude Ψ_{sN}, where:

$$\psi_{sN}\approx\frac{U_N}{\omega_N}=ct. \qquad (28)$$

Hence, at the operation with constant stator flux ($\Psi_s = \Psi_{sN}$ = ct.), the reference levels of the fluxes Ψ_u=ct. and Ψ'_r = ct., respectively should established to such values so that, on the entire variation range of rotor pulsation ω_r, the stator flux Ψ_s will not exceed the established limit value. Therefore, in Fig. 5 there are represented the dependence $\Psi_s=\Psi_{sN}$=ct. in accordance with (28), $\Psi_u = f_1(\omega_r)$ and $\Psi'_r = f_2(\omega_r)$ according to (27) for the maximum variation range of ω_r ($|\omega_r|\le R'_r/L'_{r\sigma}$ when induction machine has stable operation at Ψ_u=ct.).

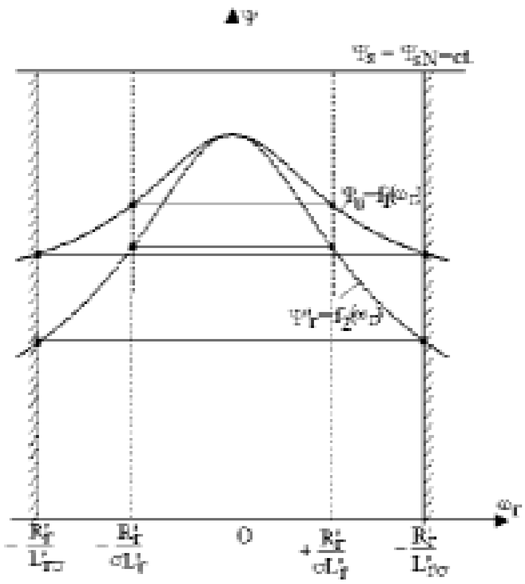

Fig. 5 Dependence of induction machine fluxes Ψ_s, Ψ_u and Ψ'_r on ω_r

Based on the curves of Fig. 5 and the mentioned relations the constant flux levels are determined:

$$\psi_s = \psi_{sN} = ct. \qquad (29)$$

$$\psi_u = f_1(\pm \frac{R'_r}{L'_{r\sigma}}) = \psi_s \cdot \frac{L_u}{L_s} \cdot \frac{\sqrt{2}}{\sqrt{1+(\frac{\sigma L'_r}{L'_{r\sigma}})^2}} = ct.$$

$$\psi'_r = f_2(\pm \frac{R'_r}{L'_{r\sigma}}) = \psi_s \cdot \frac{L_u}{L_s} \cdot \frac{1}{\sqrt{1+(\frac{\sigma L'_r}{L'_{r\sigma}})^2}} = ct. \;\; (\psi'_r = \frac{\psi_u}{\sqrt{2}})$$

For these constant values of fluxes Ψ_s, Ψ_u and Ψ'_r , an exergetic analysis imposes the electromagnetic torque characteristics $M = f(\omega_r)$ and stator current characteristics $I_s = f(\omega_r)$ will be compared on the stable operation intervals.

C1) Electromagnetic Torques Comparison at Ψ_s = ct., Ψ_u=ct. and Ψ'_r = ct.

For the three subsequent cases, the electromagnetic torque M will have the following expressions:

a) When stator flux is constant Ψ_s = ct.:

$$M = \frac{2 \cdot M_{k\psi_s}}{\frac{\sigma \cdot L'_r \cdot \omega_r}{R_{r'}} + \frac{R_{r'}}{\sigma \cdot L'_r \cdot \omega_r}} \qquad (30)$$

$$M_{k\psi_s} = \frac{3p}{2} \cdot \frac{1-\sigma}{\sigma \cdot L_s} \cdot \psi_s^2$$

b) When useful flux is constant Ψ_u = ct.:

$$M = \frac{2 \cdot M_{k\psi_u}}{\frac{L'_{r\sigma} \cdot \omega_r}{R'_r} + \frac{R'_r}{L'_{r\sigma} \cdot \omega_r}} \qquad (31)$$

$$M_{k\psi_u} = \frac{3p}{2} \cdot \frac{1}{L'_{r\sigma}} \cdot \psi_u^2$$

c) When rotor flux is constant Ψ'_r = ct.:

$$M = 3p \cdot \frac{\omega_r}{R'_r} \cdot \psi'^{\,2}_r \qquad (32)$$

Moreover, according to the constant flux levels (29), between the maximum torques $M_{k\Psi s}$ and $M_{k\Psi u}$ the following recurrence relationship can be demonstrated:

$$\frac{M_{k\psi_s}}{M_{k\psi_u}} = \frac{1}{2} \cdot (\frac{\sigma \cdot L'_r}{L'_{r\sigma}} + \frac{L'_{r\sigma}}{\sigma \cdot L'_r}) \qquad (33)$$

Also, since the electromagnetic torque is interpreted as output exergy, based on the observation $\Psi'_r = \Psi_u/\sqrt{2}$ = ct., at Ψ'_r = ct. a relationship for the electromagnetic torque M could be useful within the exergetic analysis:

$$M = M_{k\psi_u} \cdot \frac{L'_{r\sigma}}{R'_r} \cdot \omega_r \qquad (34)$$

Graphically, curves of the induction machine electromagnetic torque $M/M_{k\Psi s} = f(\omega_r)$ at Ψ_s = ct., Ψ_u = ct., and Ψ'_r = ct., respectively, are presented in Fig. 6.

C2) Stator Currents Comparison at Ψ_s = ct., Ψ_u = ct. and Ψ'_r = ct.

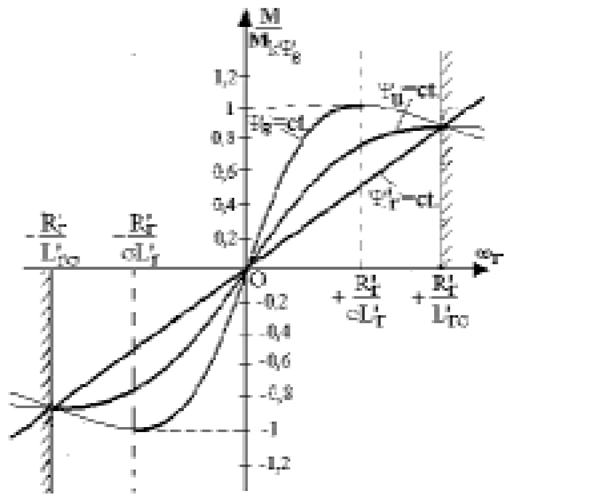

Fig.6 Curves of $M/M_{k\Psi s}=f(\omega_r)$ at constant flux

According to relationship (29) for the constant flux levels, the stator current I_s expressions become:

a) When stator flux is constant Ψ_s = ct.:

$$I_s = \frac{\psi_s}{L_s} \cdot \sqrt{\frac{1+(\frac{L'_r}{R'_r} \cdot \omega_r)^2}{1+(\frac{\sigma \cdot L'_r}{R'_r} \cdot \omega_r)^2}} \qquad (35)$$

b) When useful flux is constant Ψ_u = ct.:

$$I_s = \frac{\psi_s}{L_s} \cdot \frac{\sqrt{2}}{\sqrt{1+(\frac{\sigma \cdot L'_r}{L'_{r\sigma}})^2}} \cdot \sqrt{\frac{1+(\frac{L'_r}{R'_r} \cdot \omega_r)^2}{1+(\frac{L'_{r\sigma}}{R'_r} \cdot \omega_r)^2}} \qquad (36)$$

c) When rotor flux is constant Ψ'_r = ct.:

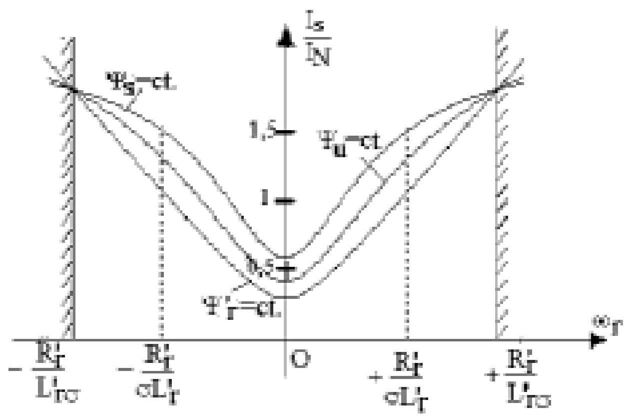

Fig. 7 Characteristics of $I_s/I_N=f(\omega_r)$ at constant flux

$$I_s = \frac{\psi_s}{L_s} \cdot \frac{1}{\sqrt{1+(\frac{\sigma \cdot L'_r}{L'_{r\sigma}})^2}} \cdot \sqrt{1+(\frac{L'_r}{R'_r} \cdot \omega_r)^2} \quad (37)$$

Graphically, in Fig. 7 had been represented the characteristics of stator current I_s at Ψ_s = ct., Ψ_u = ct., and Ψ'_r = ct., respectively.

C3) Discussion of Torques

The greatest magnitudes of electromagnetic torque are obtained in operating at Ψ_s=ct. Moreover, with the usual approximations $\sigma \cdot L'_r = L_{s\sigma} + L'_{r\sigma}$ and $L'_{r\sigma}$_$L_{s\sigma}$, the maximum torque relationship is obtained in the form:

$$M_{k\psi_u} \approx \frac{4}{5} \cdot M_{k\psi_s} \quad (38)$$

This emphasizes that the maximum electromagnetic torque in operating at Ψ_u = ct. is approximately with 20% smaller than the maximum torque in operating at Ψ_s = ct. The ratio of the critical rotor pulsations $\omega_{rk\Psi s}$ and $\omega_{rk\Psi u}$ is:

$$\frac{\omega_{rk\psi_s}}{\omega_{rk\psi_u}} = \frac{L'_{r\sigma}}{\sigma \cdot L'_r} \approx \frac{1}{2} \quad (39)$$

This means that an "inferior" maximum torque $M_{k\Psi u}$ is developed at the rotor pulsation with a double value that of the rotor pulsation corresponding to $M_{k\Psi s}$ ($\omega_{rk\Psi u} = 2 \cdot \omega_{rk\Psi s}$).

Moreover, at the imposed electromagnetic torque, the smallest value of rotor pulsation is obtained in operation with Ψ_s = ct.

From Fig. 7 similar conclusions are emphasized with regard to the stator currents. Actually, the smallest values of stator currents I_s are obtained in operation with Ψ'_r = ct.

The analysis of induction machine operation with constant flux highlights that only at Ψ'_r = ct. do the induction machine mechanical characteristics not have extremum points; they are straight lines. These linear characteristics are preferable for the applications which demand high dynamics in induction machine operation.

IV. Conclusions

The benefits of using sustainability concepts to understand the efficiencies of systems and devices which use and convert electrical energy and to guide improvement efforts have been demonstrated. The laws of nature should be used in assessing technical applications by considering the model of an ecosystem. It is concluded that the concepts encompassing exergy and embodied energy have a significant role to play in evaluating and increasing the efficiencies of such devices. Exergy should prove useful in such activities to engineers and scientists, as well as decision and policy makers. The results suggest that exergy analysis and its application to many other devices that convert and use electrical energy or are driven by electricity merit further investigation, within the framework of industrial ecology. Another step might be to view the magnetic induction (magnetic flux density) *B* and the electric current intensity *I* as environmental parameters.

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