

Assessment of Three-phase Induction Motor Dynamic Regimes Following Ecosystem Patterns

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Abstract: Within the present industrial society the humans further challenges are doubtless related to a sustainable industrial metabolism, integrating industrial activity into ecological systems. An approach of technical systems and ecological systems as parts of the same system, the industrial ecosystem, could provide a holistic view of the interactions and symbiosis interrelationships among human activities, technical systems operation and ecological processes. In this study are pointed the ecosystem key-features suitable for the electrically driven transportation systems analysis. By modeling the electrical traction machines dynamic regimes according to an industrial ecosystem pattern, one could attempt to minimize the environmental impacts and optimize the efficiency of energy use within the transportation systems operation.

Key-Words: Dynamic Regimes, Induction Machine, Industrial Ecosystem, Transportation System

1 Introduction

Industrial Ecology as a science is defined within the framework of Sustainable Development [1], and considers the technical systems created by humans and the ecological systems of Nature as parts of the same system, the *industrial ecosystem*, that can exist on a multitude of temporal and spatial scales. Within the framework of sustainability, Industrial Ecology implies a new picture of energy and matter conversion systems, and aims in designing the technical systems more like ecosystems [2]. It means that the laws of the Universe should be used in assessing the viability of the human technical applications according to the ecosystems models.

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 impacts limitation and exergy efficiency increase.

This study aims to find the analogies between the ecosystems and electrical transportation systems regarding the key features of structure and function.

We are taking into consideration the electric trains supplied from a d.c. contact line equipped with three-phase induction motors (having squirrel cage rotors) and variable voltage and frequency inverters [3].

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 traction vehicles [4].

One could start from the key-feature setting that *an industrial ecosystem does not have single equilibrium point, but the system move among multiple stable states* [5], [6]. It means that every steady-state operation regime of the transportation system can be seen as a stable state of an analogue ecosystem. In the power electrical chain there are many types of energy conversion, and the induction motors produce the final electromechanical conversion, making thus possible the vehicle movement. Hence, an analysis of the electric machine behavior at variable frequency operation is one of the compulsory steps in the achievement of an optimum control of the electric train [7].

2 Induction Machine Operation at Variable Frequency with Controlled Flux

The vehicle regulation speed is performed looking at the static converter and electric machine as an assembly. The traction motors speed regulation is based on stator voltage and frequency variation, so

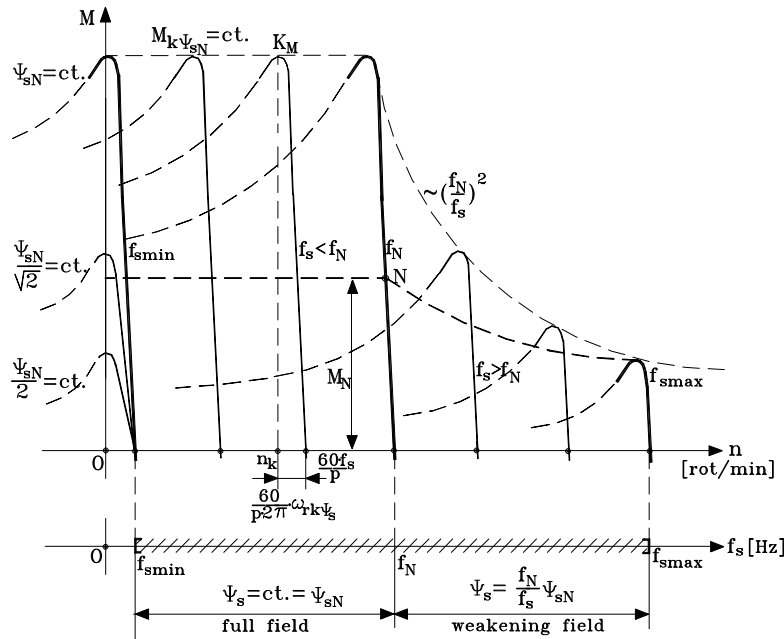


Fig.1 Mechanical characteristics $M=f(n)$ for different stator frequency f_s values

that, in the aim of a *high exergy efficiency*, an utmost requirement of the train control system is concerning the passing of operation equilibrium point from one mechanical characteristic to another. Step by step, one could present a new point of view regarding the analysis of transportation system behavior in dynamic regimes.

In the range of the frequencies lower than rated frequency $f_s < f_N$, in order to ensure a constant level of inductor machine stator flux $\Psi_s = \Psi_{sN}$, at the same time have to be modified the frequency f_s and the supply r.m.s. voltage U_s .

In case of induction machine supplied from a variable frequency voltage source when rated speed is reached (induction motor supplied at U_N and f_N) the further speed increase will be possible only by increasing the stator frequency magnitude over the rated frequency $f_s > f_N$. It must be emphasized that because of both converters voltage restriction and induction machine windings insulation considerations, the stator voltage will be limited and maintained at constant magnitude $U_s = U_N$ on all high frequency domain, and the induction machine will operate in weakened flux conditions [7]. From exergetic viewpoint it must be notified that, because the stator flux and pulsation are into a inverse proportionality relation $\Psi_s = U_N / \omega_s$, the machine torque capability will be strongly affected.

As conclusion at this point, one could highlight that the induction machine supplied from a variable frequency and voltage source will operate with full field $\Psi_s = \Psi_{sN} = ct.$ in the low frequencies range $f_s \leq f_N$ and with weaken field ($\Psi_s < \Psi_{sN}$) in the increased frequencies domain $f_s > f_N$ (when the supply r.m.s. voltage remains constant $U_s = U_N = ct.$).

When and how the movement of machine operation point from a mechanical characteristic to another is performed means, in fact, to know how the control of the electrically driven system must be proceeded.

The operation at variable frequency with controlled flux is performed to induction motors in electrically driven systems with vectorial control [8]. The vectorial regulation and control method is based on space phasor theory, taking into account the control of (both) the induction machine flux and electromagnetic torque M . 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 it is considered 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 exergy losses or saturation.

3 Modeling of Three-phase Induction Machine in Dynamic Regimes

Basically, by the *induction machines modeling* one could understand the use of *conventional representations* (geometric constructions, electrical circuits, structural diagrams etc.) to describe the behavior (or for the simulation) of various operation states or regimes [9]. The classic models, meaning the equivalent electric schemes and the phasor diagrams of the induction motors, could be considered only in the permanent regimes operation, when all the state-quantities have a sinusoidal variation in time. In dynamic regimes, they lose their validity and other models should be developed [10].

Physically, dynamic regimes of induction motors are characterized by the variation in time of both "electromagnetic status" (the currents and fluxes) and "mechanical status" (movement) of the rotors. Qualitatively, the dynamic phenomena of electromagnetic nature in the induction machines are fast and are developing with small time-constant (usually, between 1 and 100 ms). In contrast, the dynamic phenomena of mechanical nature match the acceleration and / or deceleration of rotating mass and held relatively the large time-constant (usually, between 100 ms and 0.5 s).

Mathematically, the processes dynamics (both electromagnetic and mechanical) of induction motors are described by differential equations which, in most cases, are nonlinear. Based on the *mathematical model equations*, in this paper will be presented the *structural diagrams method*, as a *modeling method of induction motors in dynamic regimes*. Among others, the benefit derived from the easily conversion of structural diagrams in Matlab-Simulink implementations.

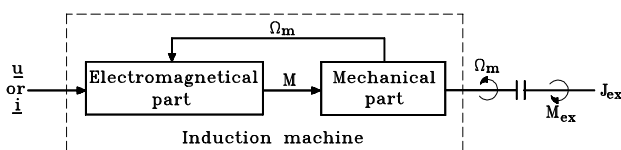


Fig.2 Three-phase induction motor modeling
($\omega_m = p \cdot \Omega_m$; p = poles pairs number)

Regardless of the application, induction motors are complex systems, which perform an electromechanical conversion of energy. Concretely, they receive "at the terminals" the electric energy $W_{1(el)}$ and after covering the "losses" (in fact, energy flows, about 8-20% of the energy received) they provide "at the axle" the useful mechanical energy

$W_{2(mec)}$. Therefore, for modeling, it is necessary an overview of the electric motor system from terminals towards axle and a formal split into an "electromagnetic part and a" mechanical part", the two subsystems having been interconnected, exactly as it is shown in Fig.2.

The idea of imaginary decomposing of induction motor in the two parts makes possible the picture of integrating it within the two systems that need to be controlled. Thus, the *electromagnetic part model* coupled with the *power supply side model* ("in current" or "in voltage") represents the *system controlled by electrical methods*. Absolutely similar, the *mechanical part model* coupled with the *mechanical transmission model* will form the *mechanically controlled system* (by mechanical methods).

Physically, *the mechanical part* of the induction motor will contain only the inertia of the rotating masses, and it is governed by the laws of classical mechanics.

In the diagram of the induction motor electromagnetic part modeling, *the input quantity* is either the space phasor \underline{u} , (supplying "in voltage") or the space phasor \underline{i} (supplying "in current"). As *output quantity* is resulting the electromagnetic torque M . Both magnetic fluxes, and rotor and stator currents are internal quantities, and do not appear explicitly in the modeling diagram of Fig.2.

In the diagram of the induction motor mechanical part modeling, *the input quantity* is the electromagnetic torque M . As *output quantities* are resulting the rotor mechanical angular speed Ω_m and the useful torque M_2 transmitted to the axle.

On the other hand, both the electromagnetic torque M , and the mechanical pulsation ω_m (or the rotor angular speed Ω_m , with $\omega_m = p \cdot \Omega_m$) are *direct and inverse interaction quantities* between the two fundamental parts of the induction motor. Based on this idea, further on, one could construct the *structural diagrams* of the induction motor electromagnetic part.

3.1 Modeling of Electromagnetic Subsystem of Three-phase Induction Motors Supplied by Voltage Sources

One could consider the three-phase induction motors with the stator supplied by a phase voltages system as the form u_{sa}, u_{sb}, u_{sc} either from the electric network (with constant frequency $f_s = 50$ Hz) or from a three-phase voltage static convert with variable frequency f_s . Whatever is the three-phase voltages supply source, for describing the dynamic electromagnetic phenomena the *space phasors method* will be applied.

