ANALYSIS OF THE PERMANENT SINUSOIDAL REGIME OF THE ASYNCHRONOUS MOTOR OF THE PRIMARY CIRCUIT PUMPS FROM A NUCLEAR POWER PLANT

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The Matlab program allows the analysis of the behavior of asynchronous motors in different operating modes. The development of the programs ACAP (Analogue Circuit Analysis Program) and SYSEG (SYmbolic State Equation Generator) together with the state equations adapted for the sinusoidal induction motor determines the predicted behavior of the motors according to several variable parameters. In this paper, there are presented a series of results obtained by simulating the operation of the motor in permanent sinusoidal mode when using the state equations, very important for the safety of electrical equipment used in the primary circuit of NPP (Nuclear Power Plant).

Keywords: asynchronous motor, sinusoidal regime, Matlab

1. Introduction

Modeling the behavior of asynchronous motors is one of the most important ways to develop motors, simulating the evolution of several physical parameters, identifying most of the problems that may occur and avoiding them. The best projects, the best materials and the best production methods are used in nuclear energy. An important element for nuclear safety is given by the behavioral simulations of the components of a power plant. Electrical systems play an important role, and the motors of the primary circuit pumps are considered a priority in ensuring the nuclear safety of the NPP, which can be the cause of a LOCA (Loss Of Coolant Agent) type accident [1].

The programs ACAP (Analogue Circuit Analysis Program) [2] and SYSEG (SYmbolic State Equation Generator) [3] are used for the analysis of asynchronous motors in permanent sinusoidal regime using state equations in the Matlab programming environment. By entering constant or variable parameters, results can be obtained on the actual behavior of the primary circuit pump motors. This paper presents the analyzes performed for asynchronous motors in permanent sinusoidal regime using the ACAP and SYSEG programs to determine the differences of the main parameters of the motor depending on the dependence on

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the pulsation of the rotor currents. The emphasis is on the behavior of the engine parameters when starting it and comparing the results obtained to improve the necessary knowledge in the nuclear field. The main advantages of the asynchronus motor comparing with the synchronus ones are: construction simplicity, low producing cost, high safety in operation, high technical performance, stability in operation and manipulation easy maintenance, direct coupling to triphasic power supply.

2. Permanent asynchronous motor simulation

Permanent asynchronous motor simulation can be performed using several methods. A first analysis can be performed by deriving in relation to time the equations of state that are thus canceled, minus the equation of motion. Integrate the equation of state corresponding to the equation of motion over a period of time (until the permanent mode is obtained). Another method uses the CSAP (Circuit Symbolic Analysis Program) program [4]. The equivalent circuit on a sinusoidal phase is analyzed completely symbolically. In this way the characteristic dimensions of the motor can be obtained (currents, voltages, electromagnetic torque, Joule losses, mechanical power, power factor, etc.) depending on all motor parameters R_s, L_s, R'_r, L'_r, L_m, $R_{Fe} = R_w$ and slipping s.

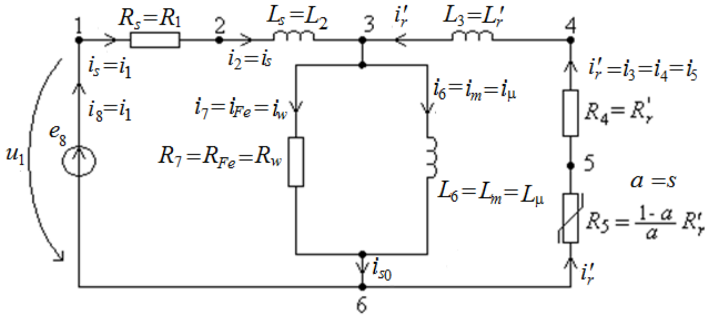


Fig.1. Induction motor equivalent scheme

In the above figure, the parameters are described as follows [5], [6]:

u_1 – power voltage;

$R_s=R_1$ – stator winding resistance;

$L_s=L_2$ – stator leakage reactance;

$i_1=i_s=i_8=i_2$ – statoric current;

i_{s0} – statoric current;

$R_7=R_{Fe}=R_w$ – magnetizing resistance;

$i'_r=i_3=i_4=i_5$ – rotoric current;

$L_3=L'_r$ - rotor leakage reactance;

$i_6=i_m=i_\mu$ – magnetization current;

$L_6=L_m=L_\mu$ – magnetizing reactance;

$R_4 = R'_r$ - rotor winding resistance;
R_5=load resistance (resistor)

The third method of simulation and transient analysis of the equivalent circuit corresponding to the induction motor using the equations of state or dynamically modified nodal equations (semi-state equations), in which the resistor *R'r/s* considers as a parametric circuit element (variable in time) until the permanent regime is obtained - the brute force method [2, 3, 4].

In all three procedures two cases can be considered:

1. Constant rotor parameters in relation to the frequency of rotor currents;
2. Variable rotor parameters with the frequency of rotor currents, due to the film effect.

The equations of state of the induction motor in sinusoidal regime are obtained from the equations of state in which the first order derivatives are canceled in relation to time, the mechanical pulsation ω at the rotor axis is kept as an independent variable and the equation of motion is considered identical to the equation (5). Therefore, the equations, in permanent sinusoidal regime become:

$$0 = -R_s\left(\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right) + \omega_s\phi_{sq} + \sqrt{2}U_1 \quad (1)$$

$$0 = -R_s\left(\frac{1}{\sigma L_s}\left(\phi_{sq} - \frac{L_m}{L'_r}\phi'_{rq}\right)\right) - \omega_s\phi_{sd} \quad (2)$$

$$0 = -R'_r\left(\frac{1}{\sigma L'_r}\left(\phi'_{rd} - \frac{L_m}{L_s}\phi_{sd}\right)\right) + (\omega_s - \omega)\phi'_{rq} \quad (3)$$

$$0 = -R'_r\left(\frac{1}{\sigma L'_r}\left(\phi'_{rq} - \frac{L_m}{L_s}\phi_{sq}\right)\right) - (\omega_s - \omega)\phi'_{ra} \quad (4)$$

$$\frac{d\omega}{dt} = \frac{3p^2}{2J}\left(\phi_{sd}\frac{1}{\sigma L_s}\left(\phi_{sq} - \frac{L_m}{L'_r}\phi'_{rq}\right) - \phi_{sq}\frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L'_r}\phi'_{rd}\right)\right) \quad (5)$$

$$\omega_2 = \omega_r = \omega_s - \omega \quad (6)$$

where,

R_s – stator winding resistance;

σ – material conductivity;

L_s – statoric reactance;

ϕ_{sd} – statoric nonlinear magnetization characteristic from *d* axis;

L_m – magnetizing reactance;

L'_r – rotor leakage reactance;

ϕ'_{rd} – rotoric nonlinear magnetization characteristic from *d* axis;

ω_s – stator mechanical pulsation;

Φ_{sq} – statoric nonlinear magnetization characteristic from q axis;
U_1 – power voltage;
R_r' – rotor winding resistance;
$\frac{d\omega}{dt}$ – frequency;

The electromagnetic torque can be calculated with one of the relations:

$$M = \frac{3p}{2}\left(\phi_{sd} i_{sq} - \phi_{sq} i_{sd}\right) = \frac{3p}{2}\left(\phi_{sd} \cdot \frac{1}{\sigma L_s}\left(\phi_{sq} - \frac{L_m}{L_r'}\phi_{rq}'\right) - \phi_{sq} \cdot \frac{1}{\sigma L_s}\left(\phi_{sd} - \frac{L_m}{L_r'}\phi_{rd}'\right)\right) \quad (7)$$

Or:

$$M = \frac{3p}{2}\left(\phi_{rd}' i_{rq}' - \phi_{rq}' i_{rd}'\right) = \frac{3p}{2}\left(\phi_{rd}' \frac{1}{\sigma L_r'}\left(\phi_{rq}' - \frac{L_m}{L_s}\phi_{sq}\right) - \phi_{rq}' \cdot \frac{1}{\sigma L_r'}\left(\phi_{rd}' - \frac{L_m}{L_s}\phi_{sd}\right)\right) \quad (8)$$

where,
M – electromagnetic torque;
p – number of electromagnetic poles.

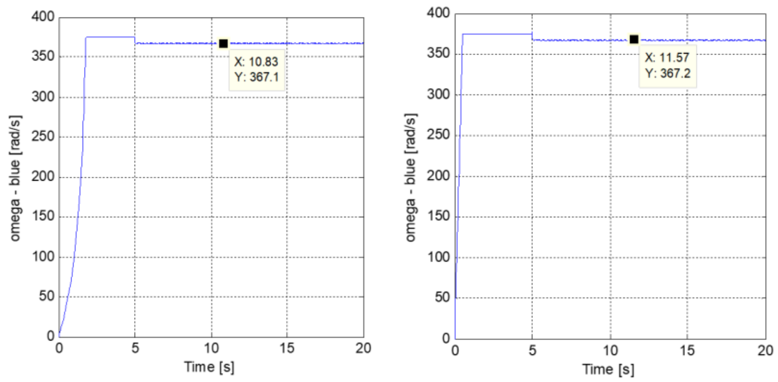
Currents through the three stator phases i_A, i_B, i_C and the currents of the three rotor phases i_a', i_b', i_c' can be expressed according to the stator and rotor currents in the axes d, q with the relations:

$$i_A(t) = i_{ds}(t) \cdot cos(\omega_1 t) - i_{qs}(t) \cdot sin(\omega_1 t) + i_{0s};$$
$$i_B(t) = i_{ds}(t) \cdot cos\left(\omega_1 t - \frac{2\pi}{3}\right) - i_{qs}(t) \cdot sin\left(\omega_1 t - \frac{2\pi}{3}\right) + i_{0s};$$
$$i_C(t) = i_{ds}(t) \cdot cos\left(\omega_1 t + \frac{2\pi}{3}\right) - i_{qs}(t) \cdot sin\left(\omega_1 t + \frac{2\pi}{3}\right) + i_{0s};$$
$$\text{as a rule } i_{0s} = 0,$$
$$i_a'(t) = i_{dr}'(t) \cdot cos((\omega_1 - \omega)t) - i_{qr}'(t) \cdot sin((\omega_1 - \omega)t) + i_{0r};$$
$$i_b'(t) = i_{dr}'(t) \cdot cos\left((\omega_1 - \omega)t - \frac{2\pi}{3}\right) - i_{qr}'(t) \cdot sin\left((\omega_1 - \omega)t - \frac{2\pi}{3}\right) + i_{0r};$$
$$i_a'(t) = i_{dr}'(t) \cdot cos\left((\omega_1 - \omega)t + \frac{2\pi}{3}\right) - i_{qr}'(t) \cdot sin\left((\omega_1 - \omega)t + \frac{2\pi}{3}\right) + i_{0r};$$
$$\text{as a rule } i_{0r} = 0. \quad (9)$$

where,
i_A, i_B, i_C – currents through stator's phase A, phase B and phase C;
i_a', i_b', i_c' – currents through rotor's phase A, phase B and phase C;

3. Results and discussions

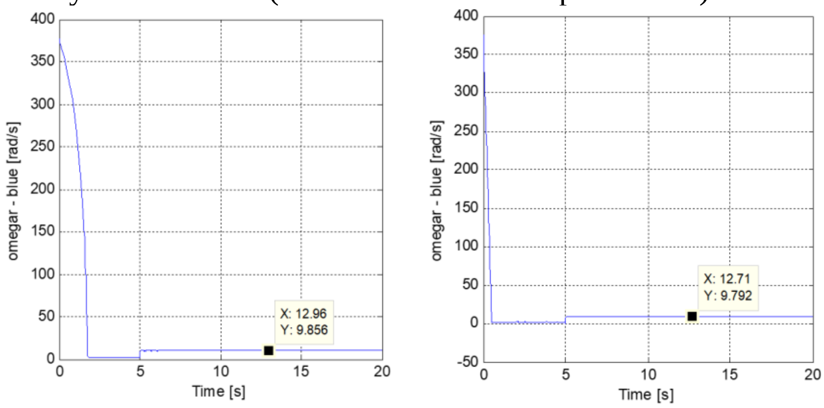
The simulations used the ACAP and SYSEG programs and state equations 1-9 run in the Matlab programming environment. Each parameter analyzed was simulated according to time or other parameters using two slightly different scenarios: for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r in variant A and the scenario in which L_r' şi R_r' are variable in relation to the angular frequency of rotor currents, ω_r, variant B. Fig. 1 shows the angular frequency dependencies ω depending on the time for constant or variable parameters L'_r şi R'_r in relation to the angular frequency of the rotor currents.



A **B**

Fig. 2. Time pulse dependence for $L_r^{'}$ şi $R_r^{'}$ constants in relation to the angular frequency of the rotor currents ω_r **A and variables, B**

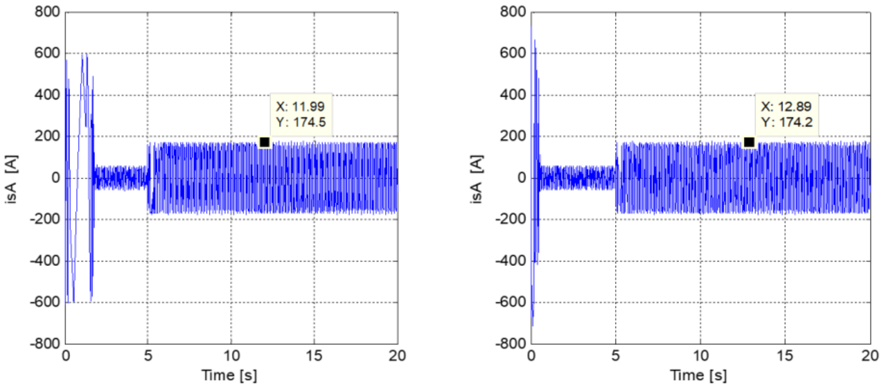
Matlab simulation shows faster increase in angular velocity over time ω for variable parameters, as well as a stabilization at a slightly higher value (y = 367.2 variable parameters versus y = 367.1 for constant parameters). The explanation for the slower increase in angular velocity is given by the fact that in the first moments after starting the engine, the electromagnetic torque is small. The simulation of the dependence of the angular speed of time is presented in Fig. 3 for both analyzed situations (constant and variable parameters).



A **B**

Fig. 3. variation ω_r in relation to the time for L'_r şi R'_r constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B**

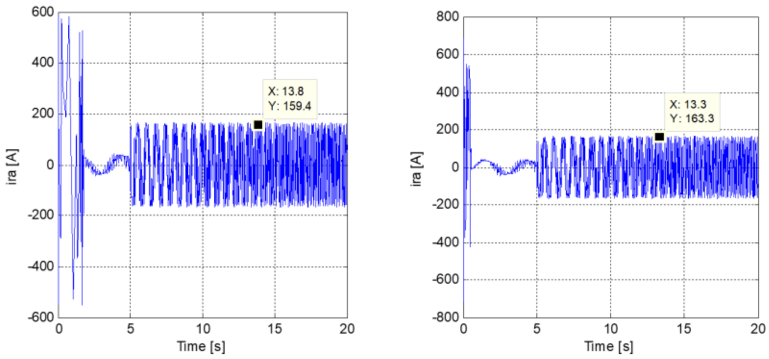
For variable rotor parameters, the increase in angular velocity is rapid (Fig. 3B) because the electromagnetic torque at start-up is high and remains high throughout the start-up process. When the torque jump occurs, the angular velocity becomes practically the same in both simulated situations. Fig. 4 shows the variations of stator currents i_{sA}.



A **B**

Fig. 4. The variation of the current through the stator in relation to the time for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B**

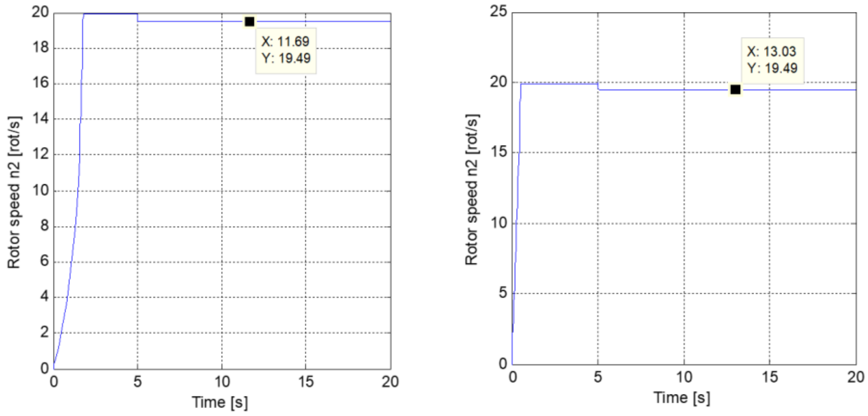
Fig. 4 shows that the transient current regime i_{sA} at start-up, for constant rotor parameters, it has a longer duration due to the low electromagnetic torque in the first moments of the start-up process. Fig. 5 shows the variations of the currents through the rotor for L_r' şi R_r' constants in relation to the pulsation of the rotor currents ω_r A and variables, B. The explanation is similar to that for stator currents.



A **B**

Fig. 5. The variation of the current through the rotor in relation to the time for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B**

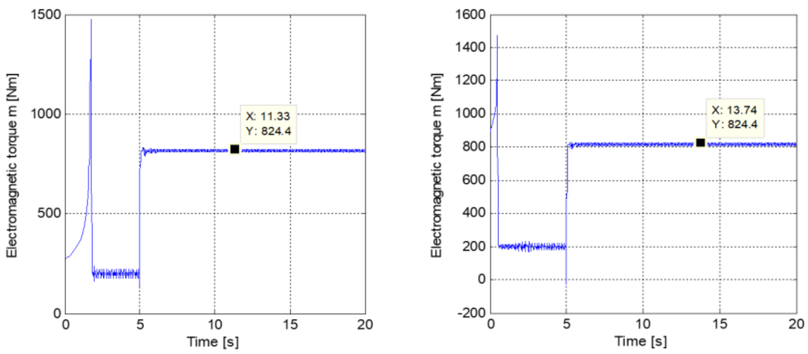
Fig. 6 shows the simulated asynchronous motor speeds for constant and variable parameters.



A **B**

Fig. 6. Engine speed dependence on time for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B**

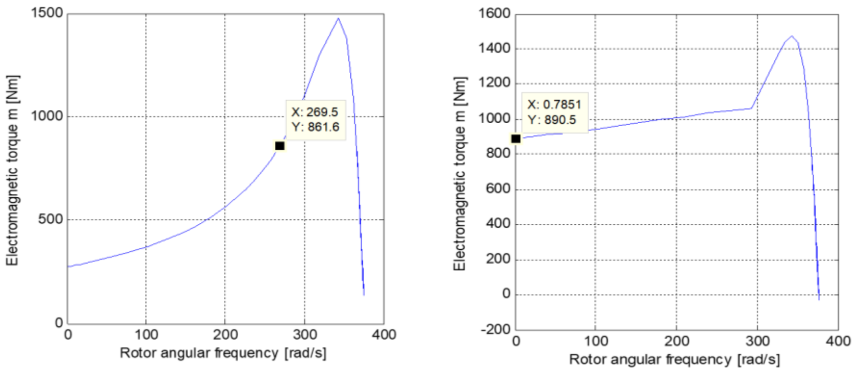
The faster increase in speed found in Fig. 6B is explained by the higher starting torque and which remains high during the transition process. The dependence of the time torque is shown in Fig. 7.



A **B**

Fig. 7. Electromagnetic torque as a function of time for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B**

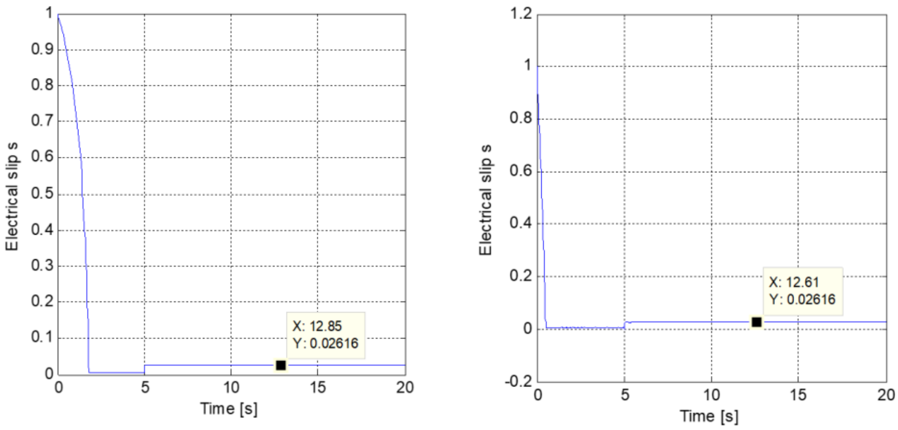
For constant rotor parameters (Fig. 7A), the starting torque is small and therefore the rotor accelerates more slowly. For variable rotor parameters (Fig. 7B), the starting torque is high and therefore the rotor accelerates much faster. Fig. 8 shows the electromagnetic torques as a function of the angular frequency of the rotor for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B.** It can be seen that the maximum torque value is approximately the same in both cases, because the motor parameters have the same values in the range [0; ω_{rx}] but the starting torque differs substantially in the two cases as it results from the relations analyzed previously. From the point of view of using the asynchronous motor for the primary circuit pumps in a nuclear power plant, this torque difference is essential, being preferable the situation in which, at start-up, the motor provides a higher torque, even if it decreases and stabilizes when it reaches the permanent sinusoidal regime.



A **B**

Fig. 8. Dependence of the electromagnetic torque on the angular frequency of the rotor for L_r' şi R_r' constants in relation to the pulsation of the rotor currents ω_r **A** and variables, **B**

Fig. 9 shows the electric slips as a function of time.



A **B**

Fig. 9. Electric slip as a function of time for L_r' şi R_r' constants in relation to the angular frequency of the rotor currents ω_r **A** and variables, **B**

The studied asynchronous motor works on the characteristic electromagnetic torque - sliding corresponding to the case when it is considered that the electrical parameters of the rotor vary with the rotor frequency, from the start (s = 1, f_r = 0 Hz) until slipping s_1 = 0.215 ($\omega_r = \omega_{rx}$ = 81.0 rad/s, fr = 12.9 Hz), then switch to the electromagnetic torque - slip characteristic when the electrical parameters of the rotor are constant [7], [8].

4. Conclusions

The results obtained by simulating the asynchronous motor in permanent regime, using the equations of state, lead to some conclusions as it follows. The purpose of simulating the asynchronous motor in dynamic mode is to obtain, after a sufficiently long integration time, the permanent mode (sinusoidal) - brute force method. For constant rotor parameters, the increase of the mechanical angular speed (at the shaft) is slower (Fig. 2A) because the electromagnetic torque at start-up is small and still remains small in the first moments of the start-up process. When the torque jump occurs, the angular velocity decreases rapidly because the moment of inertia is small and the dynamic regime is short-lived. For variable rotor parameters, the increase in angular velocity is rapid (Fig. 3B) because the electromagnetic torque at start-up is high and remains high throughout the start-up process. When the torque jump occurs, the angular velocity changes as in the previous case. From the figures showing the variation of the stator current i_{sA} it is found that the transient regime of the current i_{sA} at start-up, for constant rotor parameters, it has a longer duration due to the low electromagnetic torque in the first moments of the start-up process. At the torque jump, the current acquires a new higher value without a significant dynamic regime. In the case of variable rotor parameters the situation is similar only that the duration of the transient process at start-up is shorter because the rotor acceleration is stronger (starting torque is high) and the current values are slightly higher due to the variation of rotor parameters. Rotor current variation mode i_{ra} it is explained in a similar way to the variation of the stator current. The current values do not differ significantly in the two situations, because the rotor leakage inductance is much lower than the magnetization inductance. It is found, as it is known, that the rotor frequency at low resistive torque has a small value and increases as the resistive torque increases. The form of variation of the rotor speed n2, for the two cases, is explained similarly to the form of variation of the mechanical rotor pulsation at the shaft. From the variation curves of the electromagnetic torque *m* as a function of time, for the two cases, it is found that at start-up, for constant rotor parameters, the starting torque is small and therefore the rotor accelerates more slowly (when the rotor parameters are constant). For variable rotor parameters, the starting torque is high and therefore the rotor accelerates much faster. In a stabilized regime, the electromagnetic torque follows the resistant torque according to the principle of conservation of powers. From the variation curves of the rotor pulsation at the axis depending on the electromagnetic torque m it can be seen that the value of the maximum torque is approximately the same in both cases, because the motor parameters have the same values in the range [0; ω_{rx}] but the starting torque differs substantially in the two cases as it results from the relations analyzed previously. At the junction point the derivative is discontinuous. As noted above, the studied asynchronous motor operates on the characteristic of electromagnetic torque - slip corresponding to the case when it is considered that the electrical parameters of the rotor vary with the rotor frequency, from start (s = 1, f_r = 0 Hz) until slipping s_1 = 0.215 ($\omega_r = \omega_{rx}$ = 81.0 rad/s, fr = 12.9 Hz), then the electromagnetic torque-slip characteristic is switched on when the electrical parameters of the rotor are constant. In this way, an active torque higher than the rated torque is ensured at start-up and the motor can start at rated load, and at critical slip a maximum torque to ensure an appropriate overload factor.

The originality of this paper stands in the fact that ACAP, SYSEG and CSAP can analyze analogue circuits in an completely symbolic, numeric-symbolic or numerical way which allows that certain parameters from the equivalent circuit of the asyncornous motor to be considerd as symbols. This way analysis can be made, in different work regimes for the motor, for the work performances related to these parameters. In order to integrate the liniar or non-linear differential equations MATLAB routines were used which are very efficent in solving this type of equations.

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