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Transient Analysis of the Cage Induction Motor Start up

***Abstract**. The paper reports the detailed transient analysis of the cage induction motor (IM) at start up from the grid. Both start-off and run up stages are investigated to reveal the physical reasons of arising instantaneous torque surges. On the base of mathematical modeling the IM analytical expressions were derived and used at computer simulation of transient. The impact of rotor speed and character of transient currents on torque surges and electromagnetic transient time is determined.*

Keywords: induction motor, start up, transient analysis, torque surge

Introduction

High values of instantaneous toque surges and starting currents inrushes do not ensure energy saving and reliable work of both the cage induction motor (IM) and the AC drives as a whole [1, 2].

Unfortunately, in the scientific and technical publications the problems of the detailed transient analysis of the IM start-up are not enough worked out, that makes difficult the development of high effective soft starters for general purpose AC motor drives without of dangerous toque surges and starting currents inrushes.

The transients at an initial start-off stage and the consequent processes at a run up stage have a different character therefore the analysis of each stage has both methodological and physical peculiarities.

The purpose of the paper is to describe the theoretical transient analysis of the IM start up and to reveal the physical reasons of arising instantaneous torque surges. The outcomes of the analysis, executed with help of modeling tools and with an original method of constant speeds (MCS), can be interesting and useful at development and designing a new soft starter generation.

The IM start-off transient analysis

The transient analysis is executed with the help of a mathematical model at conventional assumptions, including a linear character of electrical and magnetic circuits. With phases segregation of the standstill IM for stator and rotor currents we have [2,3]:

$$\begin{aligned} \mathrm{i_s} &= I_{sm}\left[\sin(\omega t+\psi_u-\varphi_s)+D_{1s}\sin(\psi_u+\gamma_{1s})e^{p_1 t}+D_{2s}\sin(\psi_u+\gamma_{2s})e^{p_2 t}\right] \\ \mathrm{i_r} &= I_{sm}\left[\sin(\omega t+\psi_u-\varphi_r)+D_{1r}\sin(\psi_u+\gamma_{1r})e^{p_1 t}+D_{2r}\sin(\psi_u+\gamma_{2r})e^{p_2 t}\right] \end{aligned} \tag{1}$$

The analytical expression for an instantaneous torque is

$$\mathrm{T(t)} = 3\sqrt{3}/4 \cdot M\left[i_{ra}\cdot(i_{sb}-i_{sc})-i_{sa}\cdot(i_{rb}-i_{rc})\right] \tag{2}$$

Substituting (1) in (2) we get the solution with decomposed components for an instantaneous torque, consisting of a constant value and five time-dependent terms with a different time constants of damping:

$$\mathrm{T}(\mathrm{t}) = \tfrac{9}{4} \cdot M I_{sm} I_{rm} \begin{bmatrix} \sin(\varphi_r - \varphi_s) + e^{p_1 t} \cdot B \sin(\omega t + \alpha) + e^{p_2 t} C \sin(\omega t + \beta) + \\ + e^{2p_1 t} \cdot D_{1s} D_{1r} \sin(\gamma_{1s} - \gamma_{1r}) + e^{2p_2 t} \cdot D_{2s} D_{2r} \sin(\gamma_{2s} - \gamma_{2r}) + \\ + e^{(p_1 + p_2)t} (\cdot D_{1s} D_{2r} \sin(\gamma_{1s} - \gamma_{2r}) + D_{2s} D_{1r} \sin(\gamma_{2s} - \gamma_{1r})) \end{bmatrix} = T_{const} + \sum_{i=1}^{5} T_{\mathrm{var}.i} \tag{3}$$

On the base of analytical expression (3) the transient analysis of the IM starting torque was carried out and influence of time-dependent components on torque surges and transient time were revealed. High surges of oscillating instantaneous torque increasing 2Trated and a long transient time $3 \div 4|1/p_1| \approx 4{,}5$s (Fig. 1) is a result of multiplication of stator and rotor currents, each of them alongside with steady state components contains ones with long time damping constants.

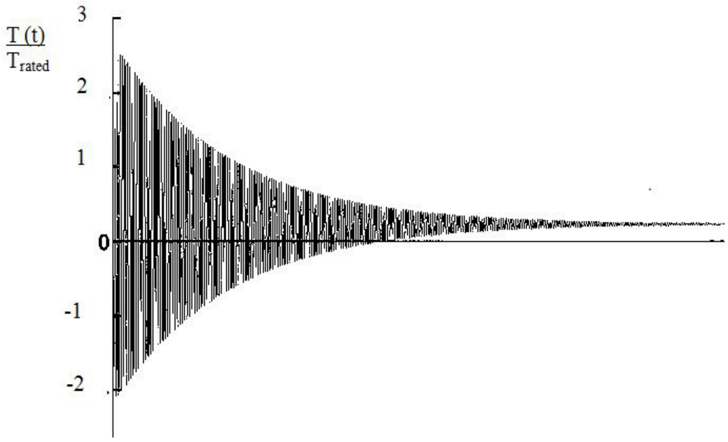

Fig. 1. A curve of transient torque in per units at direct switching on the standstill IM (series 4A180M4, P= 30 kW) to a grid.

From the physical point of view the slow damping transient torque is a result of continuous transient of the IM magnetizing current.

The IM run up transient analysis

For transient analysis of the rotating IM the method of constant speeds (MCS) is suggested. The method is based on transient study arisen after connection the rotating IM with a given constant speed to a grid at zero initial rotor currents. To minimize number of differential equations up to 4 the d-q model of the IM is used within the MCS. The solution of these equations gives analytical expressions for the IM currents at given constant speeds [4]:

$$
\begin{aligned}
i_{sd} &= \sum_{n=1}^{3} I_{sn} e^{\psi_n t} \cos\left(\chi_n t - \varphi_{sn}\right) \\
i_{sq} &= \sum_{n=1}^{3} I_{sn} e^{\psi_n t} \sin\left(\chi_n t - \varphi_{sn}\right) \\
i_{rd} &= \sum_{n=1}^{3} I_{rn} e^{\psi_n t} \cos\left(\chi_n t + \varphi_{rn}\right) \\
i_{rq} &= \sum_{n=1}^{3} I_{rn} e^{\psi_n t} \sin\left(\chi_n t + \varphi_{rn}\right)
\end{aligned}
\tag{4}
$$

The values I_{sn}, I_{rn}, ψ_n, χ_n, φ_{sn}, φ_{rn} depend on the IM parameters, the amplitude of a stator voltage, its initial phase angle shift ψ_{usa} (an instant of the IM switching on to a grid) and rotor speed of rotation. As $\psi_{n=1}$=0, $\chi_{n=1}=\omega$, the stator and rotor transient currents are a sum of three components: a steady state current and two damping harmonic components with different frequencies. In case of an unmovable IM there were also two damping (free) components, but they were not harmonic, and exponential curves. Thus, the fact of rotation has led not only to a transient amplitude change, but also to the principled change of transient character, that significantly influences on magnetization process of the IM magnetic circuit.

Effect of speed influence on transient currents is clear visible from 3D set of transient digitally calculated with help of the MCS at $0 \le s \le 1$ and ψ_{usa}=0 (Fig. 2). With slip s decrease the oscillatory character of a slow component of i_{sa} results in emerging a nonlinear ravine on a surface of transient currents set, which separates a transient area (left-hand side) from steady state area (right-hand side) in Fig 2. The similar but deeper ravine exists on a surface of transient magnetizing currents set. It is very important to note that according to Fig. 2 all transients damp at $s \approx 0,5$.

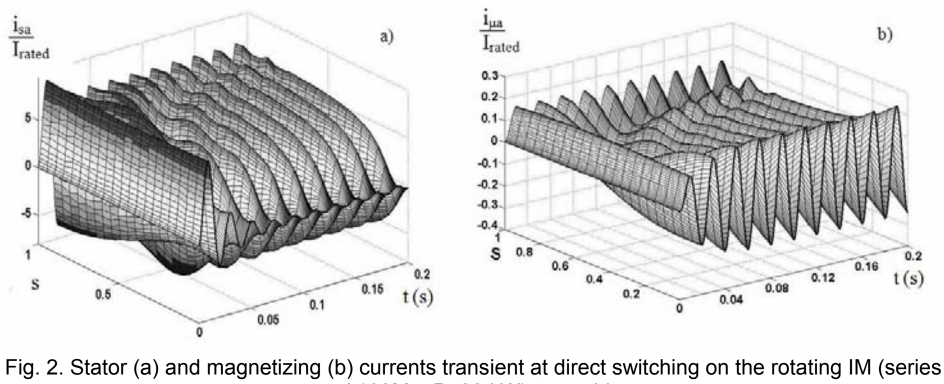

Fig. 2. Stator (a) and magnetizing (b) currents transient at direct switching on the rotating IM (series 4A180M4, P=30 kW) to a grid.

The executed analysis allows to conclude, that in the IM, connected to a grid with an initial speed of rotation about a half of synchronous value, practically neither transient

magnetization current nor surge of an instantaneous torque arise. It reflects the physical essence of the rotor speed influence on damping surges during the IM run up.
In the d-q model an electromagnetic torque is expressed as the following:

$$T(t) = k^2 M \left(i_{sq} i_{rd} - i_{sd} i_{rq} \right) \quad (5)$$

where i_{sd}=(3/2)i_{sa} and u_{sd}=u_{sa} at k=1, i_{sd}=i_{sa} and u_{sd}=(3/2)u_{sa} at k=3/2.

Substituting (4) into (5) we get the decomposed analytical solution for an instantaneous torque at a given constant speed of the IM. The total number of components in the solution received is equal six i.e. the same as in case with the standstill IM.

The digital calculation of the transient torques was executed with the MCS for the IM of a series 4A180M4, P=30kW. The results are depicted in Fig. 3 with a 3D set of transient torques in per units at different slips s. Black colored area corresponds to electromagnetic steady states.

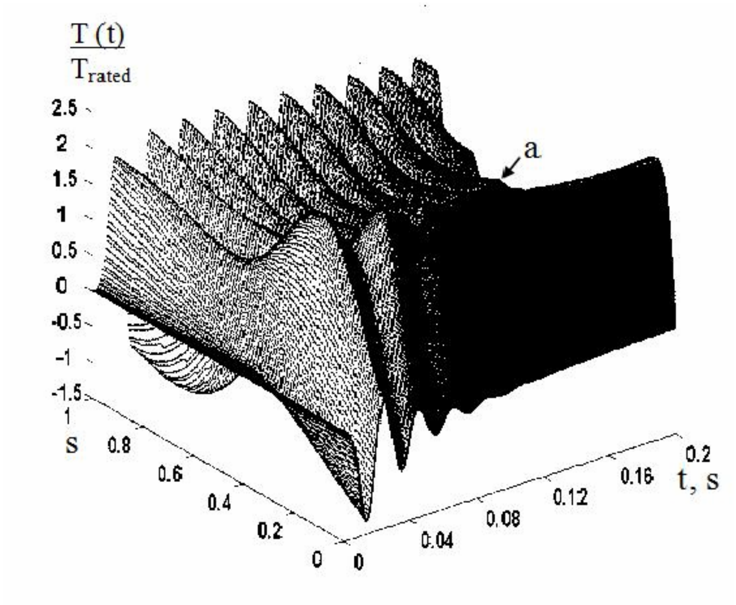

Fig. 3. Calculated the IM transient torques.

Summarizing outcomes of the analysis with the help of MCS, it is possible to conclude:

- At direct start-up of the IM with the zero initial conditions the duration of toque surges does not exceed time of what the motor runs up to a half of synchronous speed irrespectively of a load;
- The MCS and d-q model based analysis clarified the reasons of transient currents and toque variations during the IM run up;
- The obtained set of transient torque curves allows with acceptable for practice accuracy to determine a character and parameters of the IM start-up transients within any given time;
- The adequacy of the analysis with help of the MCS is verified by the presented below results of computer simulations of the IM dynamic performances at run up stage.

To analyze the IM run up transients the computer simulation was carried out with taking into account the motor load and the rotor moment of inertia in the motion differential equation. The results are depicted in Fig.4.

Test points "a" in Fig.3 and Fig.4 correspond to time instants of full damping of electromagnetic transient. Very close their coordinates at t=0,2s (T(t)/Trated ≈0,8; s ≈ 0,5), indicate good agreement between the MCS calculation and computer simulation.

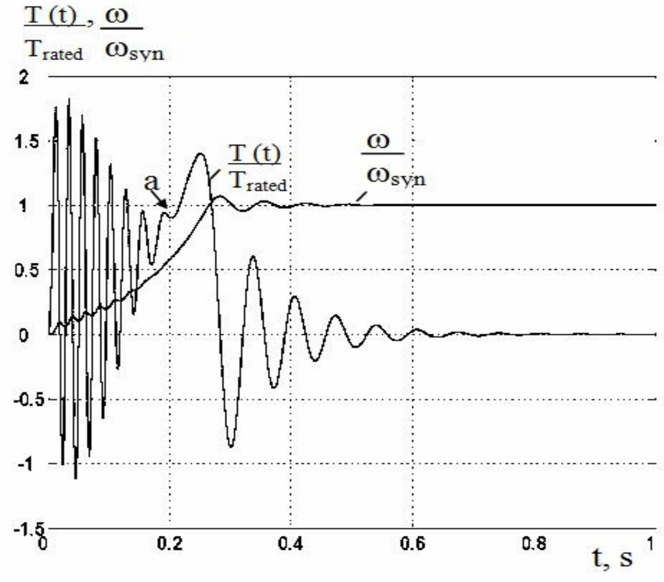

Fig.4. PC simulations of the no-loaded IM run up transient.

Conclusions

1. The method of constant speeds and d-q model allowed to provide a detailed transient analysis of the IM start up and to reveal that a speed of rotation exerts a damping impact on instantaneous torque surges.
2. Originated at start-off stage electromagnetic transient practically do not bring any delay in formation of average starting torque but at the same time these transient become a major reason of arising instantaneous torque surges during the IM start - off and run up.
3. At direct start-up of the IM with zero initial conditions the toque surges are heavily damped with rotor speed growth and the electromagnetic transient time never exceeds time of the IM run up to a half of synchronous speed irrespectively of the motor load.
4. The practical significance of the analysis consists of an opening possibility to use the obtained results for development and designing a new generation of soft starters.

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