Comparative Analysis of Methods for Starting Squirrel-Cage Induction Motors

V. Petrushin, R. Yenoktaiev, J. Plotkin

***Abstract* -- Direct and soft starts of squirrel-cage induction motor are considered. Operation specificity due to nonsinusoidal supply voltage and equivalent circuit parameters changes due to variable voltage magnitude and frequency as well as magnetic circuit saturation and current displacement in rotor winding are studied. Consumed energy calculations show advantage of frequency converter start. Mathematical models are experimentally confirmed. Stator winding overheating during starts is analyzed. Analysis results of motor vibroacoustic indicators during start are given: vibrovelocity and –acceleration of magnetic origin, vibrovelocity of mechanical origin (radial and axial), ventilating and magnetic noises. Mechanical shaft stiffness indexes, shaft strength and dynamic bearing load are examined and compared at direct and soft starts. It was established that due to soft start at low intensities of the control parameters changes, dynamic bearing load surges can be excluded. Resulting shaft deflection at soft start reduces the stronger, the smaller is the control parameter change intensity.**

***Index Terms*-- Induction motors, motor drives, variable speed drives, electromagnetic transients, surges, energy consumption, vibrations, magnetoacoustic effects, acoustic noise, shafts, mechanical dynamics, mechanical strain, pulse width modulation converters.**

I. INTRODUCTION

FREQUENCY controlled induction motors (FCIM) are operated mainly in the intermittent modes with consecutive work periods changes with constant load on one rotational speed, operation periods on the other rotational speeds, with different, but also unchanged load, corresponding to this frequency. In this regard it is expedient to study dynamic characteristics of the FCIM, associated with the transition from one rotational speed to another. Special case of a dynamic mode is a start. A lot of works are devoted to questions of the induction motor (IM) start. Most have studied electromagnetic and electromechanical characteristics [1]-[2]. A number of studies analyzed an energy and heat indicators of a start [3]-[5]. At the same time, it is advisable to investigate all main physical processes types taking place in dynamic modes of IM, including vibroacoustic and mechanical processes.

Comparing aforementioned characteristics and indicators for direct and soft starts by a variety of semiconductor converters is necessary. The most common soft start converters are thyristor voltage converters (TVC) and transistor frequency converters (TFC).

Mathematical models (MM), describing dynamic modes should take into account motor operation specifics in drives with semiconductor converters, consisting in nonsinusoidal supply voltage and parameters changes of equivalent circuits due to variable voltage magnitude and frequency, saturation of magnetic circuit and current displacement in rotor windings. Therefore, joint consideration of all components included in the studied electric drive is necessary in the complex MM, which provides accounting of their interference at each other. Considerable experience in study of transient processes in the induction machines [6] can be used when analyzing the work of the IM in the dynamic modes.

Each higher time harmonic of motor supply voltage, creates a series of higher spatial harmonics (HSH). There are a number of articles that examines higher time harmonic account in the analysis of steady-state and dynamic modes of the frequency controlled induction motors (FCIM) [7]-[9]. Taking into account the cumulative effect of higher spatial-temporal harmonics (HSTH) provides adjustment of the mechanical characteristics of FCIM [10], refining of energy and thermal indicators under steady-state conditions [11].

Cumulative effect accounting of HSTH upon characteristics of the FCIM in transient modes can be realized using the approach described in [6], [12]. According to it, FCIM in the transformed coordinate system can be described by the equation system drawn up for each conditional motor, supplied by the voltage of corresponding HSTH, by a set of which the real motor is replaced for each accounted HSTH. For example, if spatial and temporal harmonics of 1, 5, 7, 11, 13 orders are taken into account, there would be 125 equations in the system. Induction machine equations in matrix form are given as follows:

$$\begin{aligned}
&\frac{d}{dt}\mathbf{\Psi}_{s\alpha\nu}(t) = \mathbf{u}_{s\alpha\nu}(t) - \mathbf{r}_{s\nu} \times \mathbf{d}_{\nu}(t) \times \\
&\quad \times [(\mathbf{x}_{r\nu}(t) \times \mathbf{\Psi}_{s\alpha\nu}(t) - \mathbf{x}_{M\nu}(t) \times \mathbf{\Psi}_{r\alpha\nu}(t)] \\
&\frac{d}{dt}\mathbf{\Psi}_{s\beta\nu}(t) = \mathbf{u}_{s\beta\nu}(t) - \mathbf{r}_{s\nu} \times \mathbf{d}_{\nu}(t) \times \\
&\quad \times [(\mathbf{x}_{r\nu}(t) \cdot \mathbf{\Psi}_{s\beta\nu}(t) - \mathbf{x}_{M\nu}(t) \cdot \mathbf{\Psi}_{r\beta\nu}(t)] \\
&\frac{d}{dt}\mathbf{\Psi}_{r\alpha\nu}(t) = -p \cdot \omega_r \times \mathbf{\Psi}_{r\beta\nu}(t) - \mathbf{r}_{r\nu}(t) \times \\
&\times \mathbf{d}_{\nu}(t) \times [(\mathbf{x}_{s\nu}(t) \times \mathbf{\Psi}_{r\alpha\nu}(t) - \mathbf{x}_{M\nu}(t) \times \mathbf{\Psi}_{s\alpha\nu}(t)] \\
&\frac{d}{dt}\mathbf{\Psi}_{r\beta\nu}(t) = p \cdot \omega_r \times \mathbf{\Psi}_{r\alpha\nu}(t) - \mathbf{r}_{r\nu}(t) \times \\
&\times \mathbf{d}_{\nu}(t) \times [(\mathbf{x}_{s\nu}(t) \times \mathbf{\Psi}_{r\beta\nu}(t) - \mathbf{x}_{M\nu}(t) \times \mathbf{\Psi}_{s\beta\nu}(t)]
\end{aligned} \tag{1}$$

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$$\frac{d\,\omega_r}{dt} = \frac{1}{J}\left\{\frac{3\,p}{2}\Big[\mathbf{x}_{M\nu}(t)\times \mathbf{d}_{\nu}(t)\times \right.$$
$$\times \boldsymbol{\Psi}_{s\beta\nu}(t)\times \boldsymbol{\Psi}_{r\alpha\nu}(t) - \mathbf{x}_{M\,\nu}(t)\times \mathbf{d}_{\nu}(t)\times$$
$$\left.\times \boldsymbol{\Psi}_{s\alpha\nu}(t)\times \boldsymbol{\Psi}_{r\beta\nu}(t)\Big] - M_c(\omega_r)\right\},$$

where included matrices are two-dimensional.

$\Psi_{s\alpha\nu}$ (t), $\Psi_{s\beta\nu}$ (t), $\Psi_{r\alpha\nu}$ (t), and $\Psi_{r\beta\nu}$ (t) – matrices of flux linkages of machine's stator and rotor windings on α and β axes; ω_r – angular speed of the shaft; p – number of pole pairs; J – total moment of inertia of the drive referred to motor shaft; $M_c(\omega_r)$ – dependence of mechanism resistance moment upon rotational speed; $\mathbf{r}_{s\nu}$, $\mathbf{r}_{r\nu}(t)$, $\mathbf{x}_{s\nu}(t)$, $\mathbf{x}_{r\nu}(t)$, $\mathbf{x}_{M\nu}(t)$ – matrices of rotor and stator winding resistances and reactances as well of mutual induction reactances, whereby all of them, except $\mathbf{r}_{s\nu}$, vary at each integration step; $\mathbf{d}_{\nu}(t)$ – matrices of auxiliary variables $\mathbf{d}_{\nu}(t) = = [\mathbf{x}_{s\nu}(t)\cdot\mathbf{x}_{r\nu}(t) - (\mathbf{x}_{M\nu}(t))^2]^{-1}$; $\mathbf{u}_{s\alpha\nu}(t)$ and $\mathbf{u}_{s\beta\nu}(t)$ – matrices of instantaneous voltage values along the α and β axes, which are determined by the voltage amplitudes $\mathbf{U}_{m\nu}$, (depending on the variable-frequency control law) and angular positions of the generalized vectors of voltages $\varphi_{1\nu}$:

$$\mathbf{u}_{s\alpha\,\nu}(t) = \mathbf{U}_{m\nu}(t)\cdot\cos(\boldsymbol{\varphi}_{1\nu}),$$
$$\mathbf{u}_{s\beta\nu}(t) = \mathbf{U}_{m\nu}(t)\cdot\sin(\boldsymbol{\varphi}_{1\nu}), \quad (2)$$

In the case of V/f start, the system is complemented by two differential equations:

$$\frac{d}{dt}\boldsymbol{\varphi}_{1\nu} = \boldsymbol{\omega}_{1\nu} \quad \text{è} \quad \frac{d}{dt}\boldsymbol{\omega}_{1\nu} = \boldsymbol{\varepsilon}_{1\nu}(t), \quad (3)$$

where $\boldsymbol{\omega}_{1\nu}$ – matrices of angular rotational speeds, and $\boldsymbol{\varepsilon}_{1\nu}(t)$ – matrices of angular accelerations of the generalized voltage vectors defined by the speed chart of drive motion.

Expressions connecting the instantaneous values matrices of currents and flux linkages are as follows:

$$\mathbf{i}_{s\alpha\nu}(t) = \mathbf{d}_{\nu}(t)\cdot\left[\mathbf{x}_{r\nu}(t)\cdot\boldsymbol{\Psi}_{s\alpha\nu}(t) - \mathbf{x}_{M\nu}(t)\cdot\boldsymbol{\Psi}_{r\alpha\nu}(t)\right],$$
$$\mathbf{i}_{s\beta\nu}(t) = \mathbf{d}_{\nu}(t)\cdot\left[\mathbf{x}_{r\nu}(t)\cdot\boldsymbol{\Psi}_{s\beta\nu}(t) - \mathbf{x}_{M\nu}(t)\cdot\boldsymbol{\Psi}_{r\beta\nu}(t)\right], \quad (4)$$

where $\mathbf{i}_{s\alpha\nu}$, $\mathbf{i}_{s\beta\nu}$ – matrices of stator currents along the α and β axes. Effective value of the stator current

$$\mathbf{i}_{1\nu}(t) = \sqrt{\frac{1}{2}\cdot[\mathbf{i}_{s\alpha\nu}(t)^2 + \mathbf{i}_{s\beta\nu}(t)^2]}\,. \quad (5)$$

There are nonlinear coefficients in each of the equations - conditional motor parameters for the fundamental harmonic and HSTH, varying at each operating point due to the effects of the magnetic system saturation and the current displacement in the rotor winding. Proposed IM dynamic characteristics analysis approach suggests preliminary determination of these coefficients for required control range operating points. Therefore, calculations of the steady modes are conducted prior to analysis of transition process, in order to obtain values of all equivalent circuit parameters for fundamental harmonic and HSTH, taking into account currents displacement in the rotor windings and magnetic core saturation for the necessary control range operating points. MM of the established modes are used for this aim.

Conditional active power, consumed by the motor in dynamic mode, is calculated through the voltages and currents matrices, taking into account harmonic components order

$$P_1' = \frac{3}{2}\cdot\left[\mathbf{U}_{s\alpha\nu}\cdot\mathbf{I}_{s\alpha\nu} + \mathbf{U}_{s\beta\nu}\cdot\mathbf{I}_{s\beta\nu}\right]. \quad (6)$$

The real consumed active power P_1 is greater than the conditional by the amount of total unaccounted losses (magnetic core, additional and mechanical losses).

$$P_1 = P_1' + \Delta P_{Fe\ bas} + \Delta P_{Fe\ add} + \Delta P_{mech} + \Delta P_{add}\,. \quad (7)$$

Power at the motor shaft can be determined through matrices of flux linkages and currents using the rotor speed values

$$P_2 = \omega_r\,\frac{3p}{2}\left[\mathbf{I}_{r\beta\nu}\boldsymbol{\Psi}_{r\alpha\nu} - \mathbf{I}_{r\alpha\nu}\boldsymbol{\Psi}_{r\beta\nu}\right] - \Delta P_{mech} - \Delta P_{add}\,. \quad (8)$$

Instantaneous value of efficiency is determined by the ratio of instantaneous values of net power at the motor shaft $P_2(t)$ to the instantaneous consumed power $P_1(t)$.

II. Efficiency Parameters at Start

Theoretical and experimental studies of IM direct start as well as soft starts were conducted with a certain rate of parameter change (thyristor firing angle α for TVC, or respectively the motor supply voltage frequency and magnitude according to the control law for TFC). Motor of 4AH80A6U3-series (Table I) was fed during various experiments either directly by the grid or by TVC of type "Climatic" or by TFC of type ALTIVAR-28. Linear mains voltage during the experiment was 380 V. Active currents values were measured with a digital oscilloscope. The moment of inertia of the motor with a connected load mechanism was 0,1 kg·m². The load torque on the shaft had a linear dependence on the rotational speed, which was described by the following equation: $M(n) = 0{,}3 + 0{,}003\cdot n$. Investigations were carried out at the increase intensity of the TVC thyristor firing angle of 35 deg/s, which roughly corresponds to the motor voltage and frequency rise intensity of 54 V/s and 14 Hz/s in the case of TFC V/f = const operation. The intensities are selected in such a way that the soft start time was about the same at the start using TVC and TFC.

TABLE I
Rating of the Tested Motor for Star Connection

power	0,75	kW
voltage	380	V
current	2,2	A
frequency	50	Hz
speed	916	min^{-1}

Considered mathematical models formed the basis for simulation algorithms [13] in carried out theoretical studies. Fig. 1 shows simulated (solid lines) and measured (dashed lines) motor current, calculated electromagnetic torque, motor efficiency and consumed power P_1 at start.

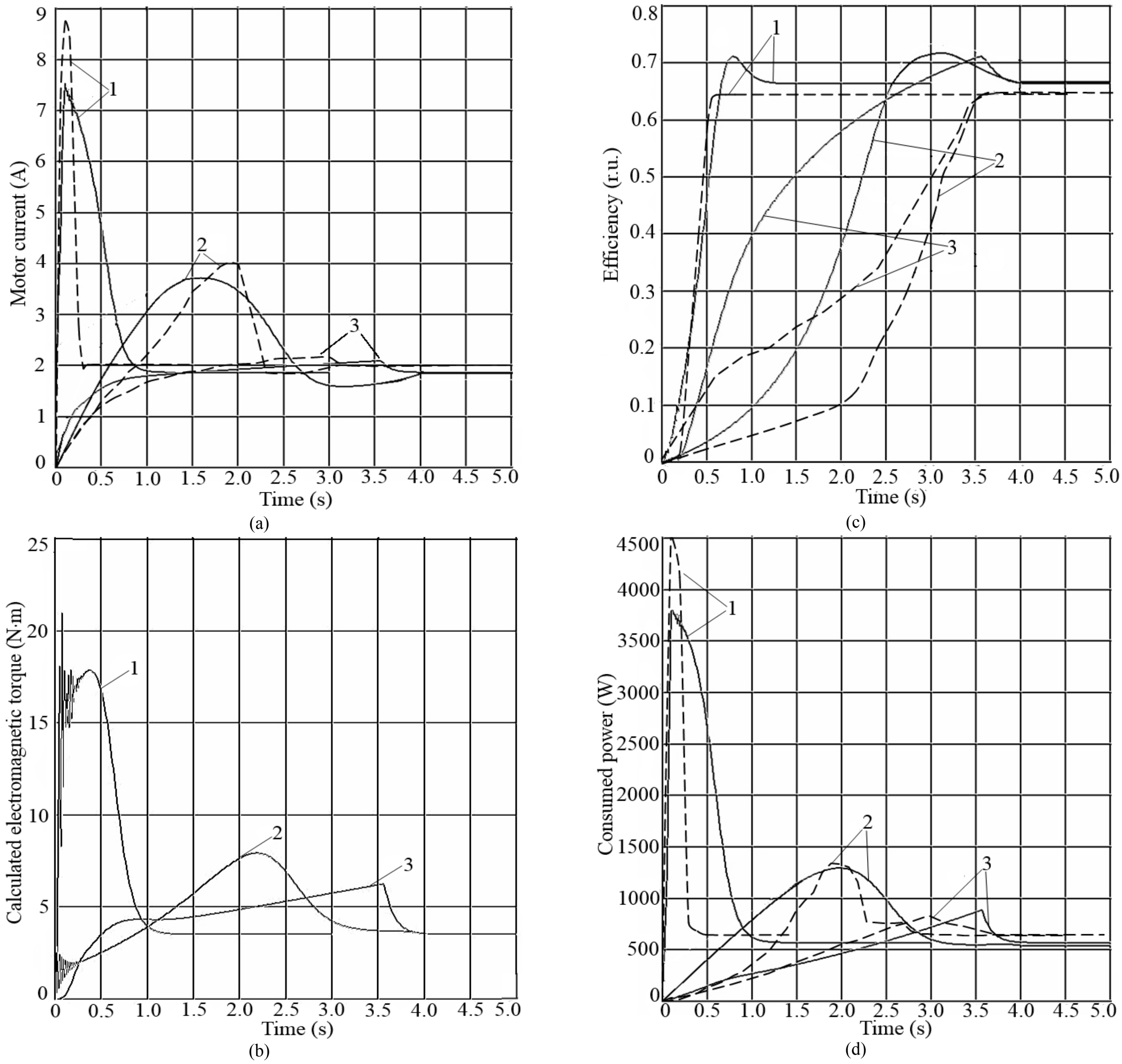


Fig.1 - Motor starting methods:
1 - direct start; 2 - soft start using TVC; 3 - soft start using TFC
a) motor current
b) calculated electromagnetic torque
c) efficiency
d) consumed power P_1

Obtained dependence of consumed power and efficiency (losses in power electronic devices were not considered) allows calculation of power losses at the start. Losses calculated on basis of simulation are given in Table II.

TABLE II
ENERGY INDICATORS OF DIFFERENT STARTING METHODS

Starting method of the IM / Indicators	direct	using TVC	using TFC
average power consumption, W	1605	985	521
average efficiency, p.u.	0,422	0,263	0,424
electrical power losses, W • s	928	725	300

III. ACOUSTIC PARAMETERS

Forces of magnetic, mechanical and aerodynamic origin are the reason for vibration and noise of electrical machines. Magnetic sources of vibration and noise are associated with higher magnetic field space and time harmonics, which are caused by teeth presence on stator and rotor, harmonic content of the supply voltage, eccentricity of air gap, nonsinusoidal distribution of the magneto-motive force of windings, saturation of the magnetic circuit of the machine and a number of other reasons. Mechanical sources include rotor unbalance, misalignment and skew of bearing seats, deviations in the form of their rings and separator size scatter, thermal deformation of the rotor, shaft deflection, etc. Aerodynamic noises are generated by fans and other parts placed on the rotor. Vibration and noises of the IM are studied by many authors [21], [23], [24].

Main features of vibroacoustic processes in FCIM is that in different operating points of the considered control range the intensity of all three sources mentioned above varies greatly and resonances are observed. In this regard, consideration of noise and vibration levels throughout the whole control range is necessary in order to compare them with the permissible levels. At the same time it should be noted that the intensity of magnetic origin noises is largely determined by the harmonic content of the motor supply voltage, i.e. it depends on the converter and control type, operation mode and drive load. A systematic approach, according to which all functional parameters, including vibration and noise, are determined by joint consideration of all drive components function, allows creating complex MM of vibroacoustic processes in FCIM, invariant to different converters and loads. Calculation of vibroacoustic indicators of magnetic origin taking into account voltage time harmonic can be performed by the method developed by Y.A. Shumilov and V.G. Gerasimchuk [23], according to which forces of magnetic origin are divided according to their direction on radial and tangential; vibration and noises are determined by these components. Linearity of the mechanical system is assumed: frequency of the magnetic vibrations and noises is equal to excitation frequency and the amplitude of deformation is calculated by dividing the force by the stiffness (taking into account the deformation amplification at resonances). The end result of calculations is a set of vibration amplitudes at respective frequencies (spectrum of vibration) and the overall level of magnetic noise. However it should be taken into account, that in each operating point of FCIM its equivalent circuit parameters and magneto-motive force in magnetic circuit segments are changing on each considered harmonic. This would increase the accuracy of the proposed MM [13]. Following parameters of vibration and noise are determined as a result of the vibroacoustic calculation: relative level of vibration speed and level of magnetic noise, depending on the vibration speed and the relative radiation power. Their values in different operating points depend on the load, converter and control type. For the calculation following values are used: geometrical dimensions and material properties of the IM; diameter of the stator core and housing; wall thickness and elastic modulus of stator and housing, etc.

This technique can be used to determine the vibroacoustic indicators for dynamic modes.

Figure 2 shows the calculated time course of vibration velocity S_v and magnetic noise S_n, obtained for various starting methods

Calculation methods of ventilation noise for serial IM are well established and confirmed by experimental data [21]. Centrifugal fans with blades of various designs are used in IM. Design features of blades are taken into account by considering fans geometric dimensions. Relative fan supply is the ratio of actual supply to the maximum supply and is determined by aerodynamic efficiency, which in its turn depends on design of centrifugal fan blades. Ventilation noise level is determined for different designs by different formulas using coefficients, those values are given in tables.

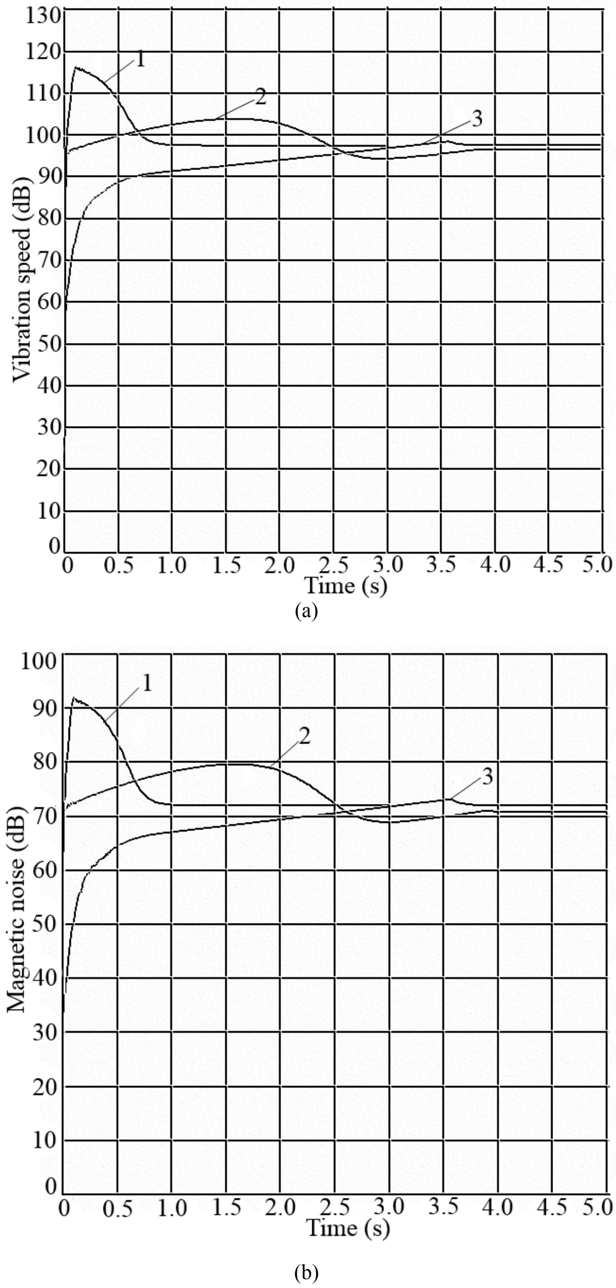


Fig. 2. Motor vibration speed (a) and magnetic noise (b) at different starting methods:
1 - direct start; 2 - soft start using TVC;
3 - soft start using TFC

Fan speed varies within the control range of FCIM, which leads to a change of aerodynamic noise. Total level of ventilation noise also depends on the fan type and its constructional dimensions. These noise values in a given range of regulation can be determined according to known method using software packages for the considered drive types [13]. In dynamic modes, particularly at start (Fig. 3), ventilation noise increases proportionally to the rotational speed reaching steady state values after starting.

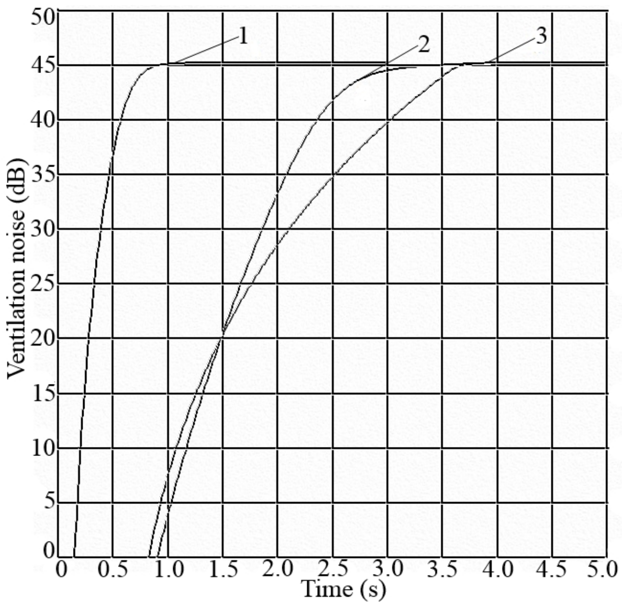


Fig. 3. Ventilation noise at start:
1 – direct start; 2 – soft start using TVC;
3 – soft start using TFC

Known technique of mechanical vibrations calculation for standard squirrel-cage IM [21] is intended for rigid rotors, which include IM rotors of unified series. Reasons for mechanical vibrations are residual imbalance at static and dynamic rotor balancing and presence of rolling bearings. For rolling bearings vibration calculation it is supposed, that at low-frequency vibrations reasons are imperfection of bearing manufacturing on the main dimensions and mounting inaccuracy, and at frequencies above the triple of rotational frequency - imperfection of bearings microgeometry, whereby vibration levels are maximal on rotor natural frequencies. Bearing vibrations underlie to a significant technological variation, determined by the quality of the bearings, as well as design and manufacturing technology of the motors. Mechanical vibrations indicators of FCIM vary within the control range. They depend on machine and rotor mass and on rotational speed. Mechanical vibration calculation delivers following values: general vibration velocity level due to unbalance and imperfections of bearings in the radial direction V_r and in the axial direction V_z. Maximal mechanical vibrations values for specific design variants can also be calculated using software package [13]. Values of mechanical vibrations are determined by motor rotating mass and rotor speed, they depend on the disbalance, imperfection of bearings manufacturing and mounting inaccuracies.

In dynamic modes, particularly at start (Fig. 4), mechanical vibrations are increasing proportional to the rotation frequency, reaching values corresponding to the steady state after start. Calculations of mechanical vibration indicators are performed specifying the inaccuracies of processing, balancing and bearings manufacturing imperfection of 1 micron.

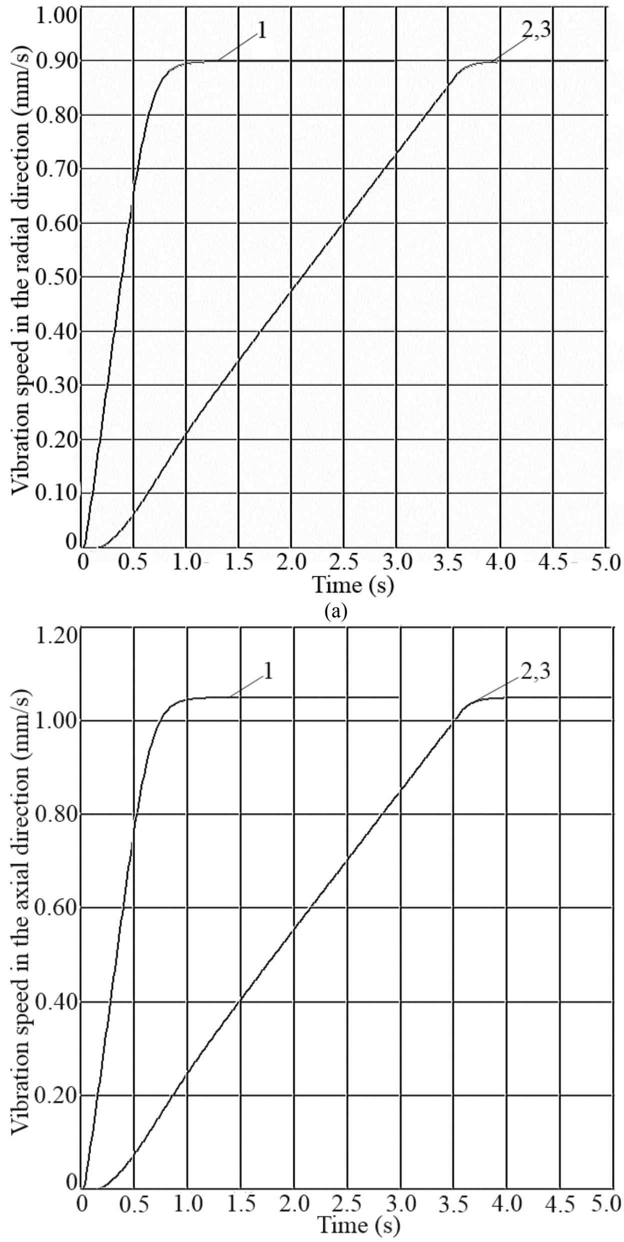
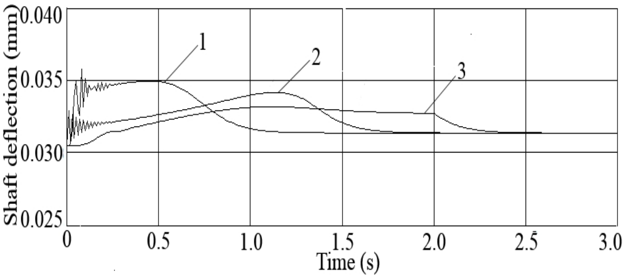


Fig. 4. Vibration speed in the radial direction V_r (a), vibration speed in the axial direction V_z (b) at different starting methods:
1 – direct start; 2 - soft start using TVC;
3 – soft start using TFC

IV. Mechanical Parameters

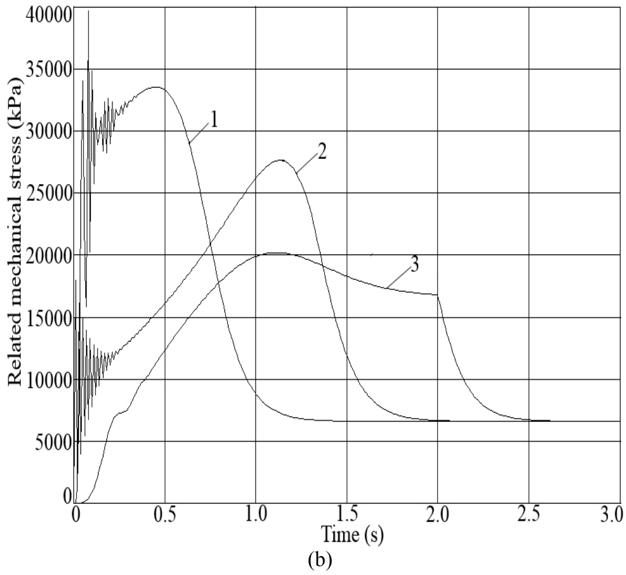
Motor and drive components are spared from mechanical overload at soft start. Protection degree is directly proportional to the start softness, which is determined by control parameter change rate. However, it is advisable to compare changes in mechanical indicators for direct and soft starts. Three factors characterizing mechanical condition are considered at IM mechanical calculations for steady state operation - shaft stiffness, shaft strength and dynamic load rate of bearings [15], [20]. To evaluate IM mechanical state at start, it is recommended to consider the same factors for transition modes.

The determining mechanical indicator for shaft stiffness calculation is the resulting shaft deflection. Besides the main shaft deflection, which is dependent on active rotor steel and short-circuited winding mass, there is an additional shaft deflection, which value is proportional to IM torque. Shaft deflection is also caused by unilateral magnetic attraction forces, which appear by rotor displacement. Shaft deflection on IM start can be calculated applying starting torque values to known algorithms [15], [20]. These values can be obtained when considering the transient electromechanical calculations by solving a system of differential equations [25]-[27]. Related mechanical stress, which takes into account combined effect of bending and torsional stresses, is determined when calculating the shaft strength. Related mechanical stress at start is determined using IM torque values during start. Determination of bearings dynamic load at start is carried out similarly according to the type of bearing and character of the motor load. The developed mathematical models used in the software package [13], by which studies of the mechanical IM condition at start were carried out. Elastic motor coupling to actuator and moderate load surges were adopted for the analysis, overload factor of 2.5 is set for reversive machines. Investigated IM contains ball bearings.

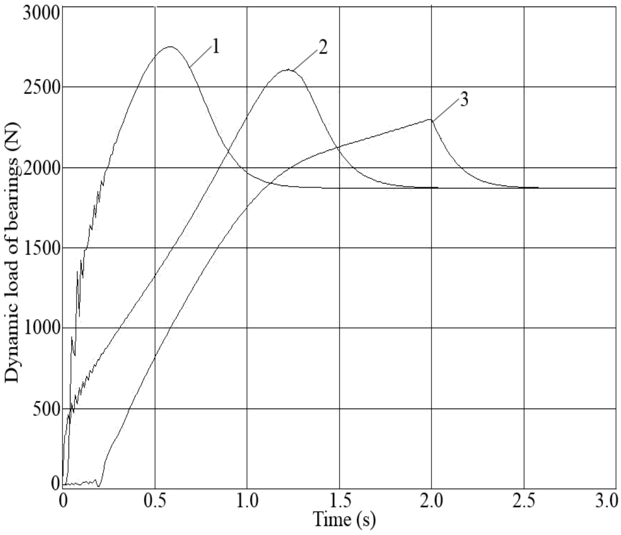


(a)

In Fig. 5 calculations results of the above mentioned mechanical parameters at starting of the motor 4AH80A6U3 are shown.



(b)



(c)

Fig. 5. Mechanical parameters at start:
1 – direct start;
2 – soft start using TVC, control parameters change intensity 25 Hz/s.
3 – soft start using TFC, control parameter change intensity 50 V/s;
a) shaft deflection
b) related mechanical stress
c) dynamic load of bearings

V. CONCLUSIONS

Study of motor parameters at start showed following results. Inrush currents are significantly reduced at soft start: ratio of inrush current at TVC start is 2.05, at TFC start is 1.22 compared to 4.16 at direct start. Values of starting torque surges decrease with soft start as follows: at TVC start ratio of starting torque is 2.42, at TFC start - 1.88 compared to 5.45 at direct start. Dependencies of motor consumed power during the start are defined by the electromagnetic torque dependencies. According to conducted studies the most energy efficient start is done by TFC.

Maximal vibration speed S_v, vibration acceleration S_a and magnetic noise S_n values at direct start are exceeding those at soft start. Ventilation noise increases in proportion to rotational speed. Mechanical vibrations are increasing in proportion to the rotational speed. Their values are identical at various soft start methods. The resulting shaft deflection is reduced at soft start compared to direct start, whereby the reduction is the more substantial the less the control parameter change intensity. Dependencies of related mechanical stress repeat dependencies of the electromagnetic torque and similarly depend on control parameter change intensity. Estimated bearing dynamic load surges may be excluded due to soft starting at low control parameters change intensities.

Similarly, the investigated parameters can be calculated for other starting conditions (various loads on the shaft, moments of inertia, control parameter increase intensity etc.)

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VII. Biographies

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