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Bronislav FIRAGO, Dmitry VASILYEV*

# SOFT STARTING AND BRAKING APPLICATION FOR SQUIRREL-CAGE INDUCTION MOTORS OPERATING IN INTERMITTENT DUTY

This paper deals with energetic aspects of soft starting and braking application for the squirrel-cage induction motors operating in intermittent duty with constant load. Energy losses in transients of an induction motor for different laws of voltage changing as well as induction motor stator winding temperature at the end of starting process are calculated and compared with the ones during full-voltage starting and plug braking. Energy losses calculation during induction motor soft starting and braking has been performed analytically and via the Matlab simulation models of equivalent two-phase induction motor in $\alpha - \beta$ coordinates. The results of both calculation methods are compared and a divergence between them is determined. Also the effect of total energy losses on the induction motor stator winding temperature at the end of the motor starting process and its allowable frequency of starting is analyzed. Analytical calculation and simulation of soft starting and braking have been performed with allow for the linear and exponential laws of the first voltage harmonic magnitude changing. The results of simulation and analytical calculations are given in the tables.

## 1. INTRODUCTION TO THE PROBLEM

Squirrel-cage induction motor full-voltage starting causes high impact torques damaging the motor shaft, reducer and couplings. High starting currents also invoke significant induction motor windings heat buildup which leads to an accelerated insulation ageing and accordingly to the induction motor service life decrease. Excessive windings heating limits the motor allowable frequency of starting. Moreover high starting currents may lead to supply voltage drops which cause contact breaking in power and control circuits. Also electromechanical processes during induction motor braking with residual magnetic field, e.g. plug braking, should be considered. Impact loads during squirrel-cage induction motor plugging are several

* Belarusian National Technical University, Belarus, 220027, Minsk, F. Skaryna 65, dmy@tut.by

times higher than the ones during its full-voltage starting certainly causing the mechanical gear untimely breaking. More detailed analysis of electromechanical processes in the induction motor transients during the motor direct starting and plugging is presented in [1].

To reduce high starting currents and limit impact torques soft starting and braking of a squirrel-cage induction motor can be applied [2]. During these starting and braking modes the induction motor supply voltage magnitude is changing in motor transients according to an appropriate law. In general, any voltage magnitude changing law can be used, however, often a linear law is applied. Previous research conducted by the authors shows the advantage of exponential voltage changing law compared to a linear law, which proves to be more effective in the reduction of starting currents and impact torques in squirrel-cage induction motor transients [1]. Also the effect of voltage ramp time $t_0$ on the reduction of impact torques and on the duration of induction motor transients has been examined. It has been found that voltage ramp time $t_0$ should be taken 2–3 times higher the induction motor direct starting time $t_{ds}$ to provide optimal reduction of starting currents and impact torques as well as minimum starting and braking time. In this paper the analysis and comparison of energy losses in the induction motor transients calculated analytically and via the Matlab simulation models for different laws of voltage magnitude changing is presented.

## 2. ENERGY LOSSES CALCULATION AND COMPARISON

Calculation of energy losses in the induction motor transients during soft starting and braking has been conducted with allow for the linear and exponential first voltage harmonic magnitude changing laws.

Linear first voltage harmonic changing law during induction motor soft starting can be defined as follows (Fig. 1a):

$$U_1 = U_{nom} \cdot \frac{t}{t_0}, \tag{1}$$

where:

$t_0$ – linear voltage ramp time;

$t$ – simulation time.

During soft braking first voltage harmonic magnitude is reduced according to the following expression (Fig. 1b):

$$U_1 = U_{nom} \cdot \left(1 - \frac{t}{t_0}\right). \tag{2}$$

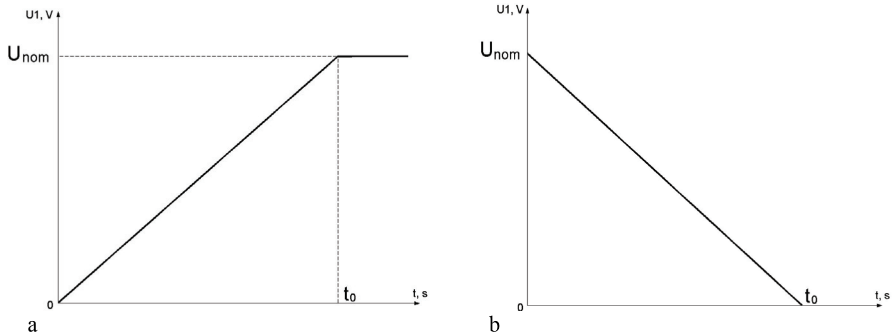


Fig. 1. Linear voltage magnitude changing during induction motor soft starting (a) and braking (b)

Exponential voltage changing law during induction motor soft starting has been applied in accordance with the following expression (Fig. 2a):

$$U_1 = U_{nom} \cdot \left(1 - e^{-t/T_1}\right), \tag{3}$$

where: $T_1 = t_0/4$ – time constant for the induction motor exponential first voltage harmonic increase; $t_0$ – exponential voltage ramp time.

For the induction motor soft braking with exponential voltage decrease the following law has been used (Fig. 2b):

$$U_1 = U_{nom} \cdot e^{-t/T_1}. \tag{4}$$

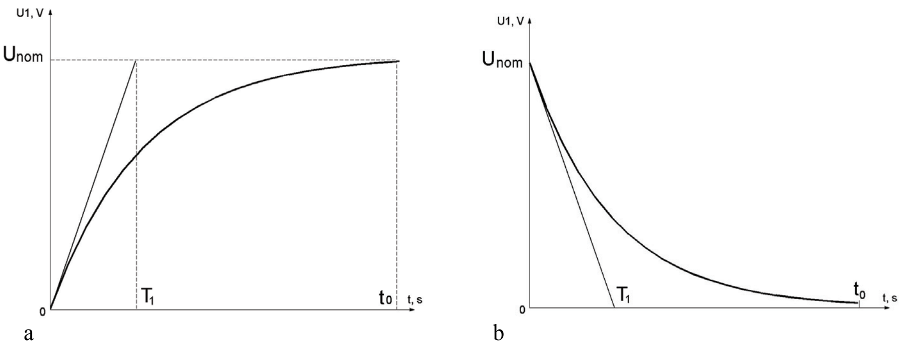


Fig. 2. Exponential voltage magnitude changing during induction motor soft starting (a) and braking (b)

For the calculation of energy losses during induction motor starting and braking a Matlab simulation model of equivalent two-phase induction motor in $\alpha - \beta$ coordinates has been used (Fig. 3).

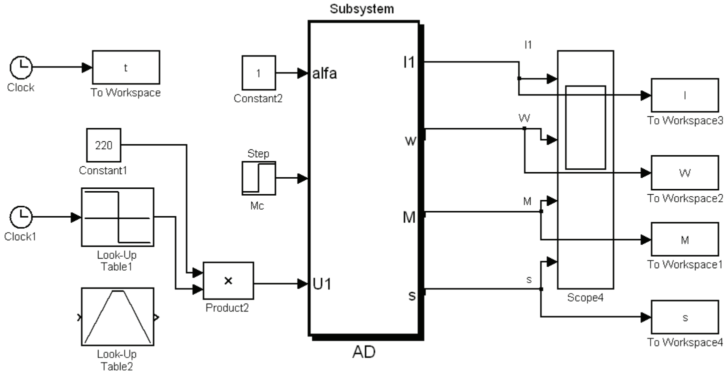


Fig. 3. Matlab simulation model used for the research of full-voltage starting, plugging, soft starting and braking of an equivalent two-phase induction motor in $\alpha - \beta$ coordinates

Energy losses in the induction motor transients during the simulation process are calculated as follows:

$$\Delta A = \Delta A_1 + \Delta A_2 + \Delta A_{iron} = 3R_1 \int_0^t I_1^2(t)dt + +3R_2' \int_0^t I_2'^2(t)dt + \frac{\Delta P_{iron.nom}}{U_{1nom}^2} \int_0^t U_1^2(t)dt \,, \quad (5)$$

where: $\Delta A_1$, $\Delta A_2$ – energy losses in the stator and rotor of induction motor; $\Delta A_{iron}$ – energy losses of induction motor iron; $R_1$, $R_2'$ – phase resistances of stator and rotor of induction motor; $I_1$, $I_2'$ – stator and rotor current of induction motor; $\Delta P_{iron,nom}$ – nominal iron power losses of induction motor; $U_{1nom}$ – nominal stator supply voltage of induction motor.

Nominal iron power losses can be defined as follows:

$$\Delta P_{iron.nom} = \Delta P_{iron.1nom}(1 + s_{nom}^{1,5}) \,, \quad (6)$$

where: $\Delta P_{iron,1nom}$ – nominal iron power losses in induction motor stator, which can be considered (0,15–0,25) of nominal power losses $\Delta P_{nom}$ [3]; $s_{nom}$ – induction motor nominal slip.

Induction motor nominal power losses can be calculated according to the following expression:

$$\Delta P_{nom} = P_{nom}(1 - \eta_{nom}) / \eta_{nom} \,, \quad (7)$$

where: $P_{nom}$, $\eta_{nom}$ – induction motor nominal power and nominal motor efficiency.

Analytical calculation of energy losses in the induction motor transients during soft starting and braking has been performed according to the method introduced in [4]. This analytical method is based on the piecewise-linear approximation of an induction motor natural speed-torque characteristic and calculation of energy losses on each piece of this characteristic. According to this method total energy losses in the induction motor transient during soft starting include energy losses during the motor operation delay $\Delta A_{s1delay}$, energy losses during voltage ramp time $t_0$ depending on the applied voltage magnitude changing law $\Delta A_{s2ramp}$ and energy losses for each linear piece of an approximated natural speed-torque characteristic. The number of such linear pieces depends on the induction motor operation point location on its natural speed-torque characteristic at the end of voltage ramp time $t_0$ (Fig. 4).

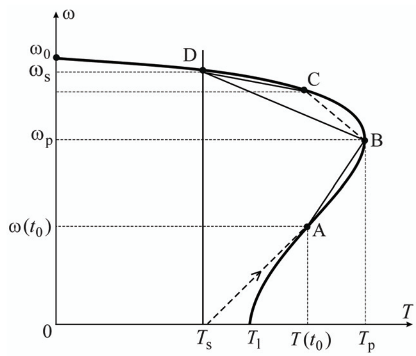


Fig. 4. Induction motor possible operation points on its natural speed-torque characteristic at the end of supply voltage changing during soft starting

According to Figure 4 the induction motor may operate at points A, B or C of its natural speed-torque characteristic at the end of the voltage ramp time $t_0$.

Provided that at the end of a linear or exponential voltage ramp time $t_0$ the induction motor speed $\omega(t_0)$ will reach point A of the natural speed-torque characteristic, i.e. $\omega(t_0) < \omega_p$, where $\omega_p$ is the motor speed corresponding to its pullout torque $T_p$, the remaining part of this speed-torque characteristic can be approximated with two linear pieces AB and BD. Therefore energy losses should be calculated for both of these intervals, i.e. $\Delta A_{s3AB}$ and $\Delta A_{s4BD}$.

If the induction motor speed at the end of voltage ramp time $\omega(t_0) > \omega_p$, meaning the induction motor operates at point C in Fig. 4, then the remaining part of its natural speed-torque characteristic can be approximated with only one linear piece CD. Thus calculation of the induction motor energy losses for this single interval $\Delta A_{s5CD}$ is required.

Total energy losses during induction motor soft starting $\Delta A_{s\Sigma}$ can be defined in two ways:

1) in case of $\omega(t_0) < \omega_p$ : $\Delta A_{s\Sigma} = \Delta A_{s1delay} + \Delta A_{s2ramp} + \Delta A_{s3AB} + \Delta A_{s4BD}$, (8)

2) in case of $\omega(t_0) > \omega_p$ : $\Delta A_{s\Sigma} = \Delta A_{s1delay} + \Delta A_{s2ramp} + \Delta A_{s5CD}$. (9)

Energy losses during soft braking of a squirrel-cage induction motor $\Delta A_b$ are calculated in one expression depending on the applied voltage magnitude decrease law, i.e. linear or exponential.

The results of analytical ($\Delta A_{sa}$, $\Delta A_{ba}$) and simulation ($\Delta A_{sm}$, $\Delta A_{bm}$) energy losses calculation methods are given in tables 1–6. Calculations have been conducted for 11 kW and 30 kW squirrel-cage induction motors with allow for different inertia factors $k_J$ and the linear and exponential voltage magnitude changing laws. Energy losses during induction motor soft starting and braking are compared to the ones during full-voltage starting and plug braking but also to other simulated widely applied starting and braking modes, such as kick starting and starting by star-delta windings switching. To facilitate the analysis and comparison of energy losses calculation results for the linear and exponential voltage magnitude changing laws all energy losses are presented in relative units. The divergence between the results of both analytical and simulation methods is defined by the relative accuracy factor $\varepsilon$.

Table 1. Energy losses comparison for simulation and analytical calculation methods for the induction motor 4MTKF160LB8 (11 kW, 380/220 V, 40% duty cycle, $k_J = 1$, $T_s = T_{\text{nom}}$, $t_0 = 0.4$ s)

| Mode \ Parameters | $t_s$, s | $t_b$, s | $t_d$, s | $\frac{\Delta A_{sm}}{\Delta A_{sa}}$, p.u. | $\frac{\Delta A_{bm}}{\Delta A_{ba}}$, p.u. | $\varepsilon$, % |
|---|---|---|---|---|---|---|
| Full-voltage starting | 0.15 | – | – | 1 | – | – |
| Plug braking | – | 0.025 | – | – | 1 | – |
| Kick-start | 0.46 | – | 0.03 | 2.14 | – | – |
| Starting by star-delta windings switching | 0.38 | – | 0.204 | 1.87 | – | – |
| Linear voltage ramp soft starting | 0.5 | – | 0.28 | 1.996 / 1.89 | – | 5.3 |
| Linear voltage ramp soft braking | – | 0.35 | – | – | 0.58 / 0.55 | 5.1 |
| Exponential voltage ramp soft starting | 0.38 | – | 0.12 | 1.69 / 1.54 | – | 8.8 |
| Exponential voltage ramp soft braking | – | 0.22 | – | – | 0.21 / 0.197 | 6.2 |

Table 2. Energy losses comparison for simulation and analytical calculation methods for the induction motor 4MTKF160LB8 (11 kW, 380/220 V, 40% duty cycle, $k_J = 1.6$, $T_s = T_{\text{nom}}$, $t_0 = 0.75$ s)

| Mode \ Parameters | $t_s$, s | $t_b$, s | $t_d$, s | $\frac{\Delta A_{sm}}{\Delta A_{sa}}$, p.u. | $\frac{\Delta A_{bm}}{\Delta A_{ba}}$, p.u. | $\varepsilon$, % |
|---|---|---|---|---|---|---|
| Full-voltage starting | 0.25 | – | – | 1 | – | – |
| Plug braking | – | 0.047 | – | – | 1 | – |
| Kick-start | 0.8 | – | 0.03 | 2.07 | – | – |
| Starting by star-delta windings switching | 0.63 | – | 0.38 | 2.03 | – | – |
| Linear voltage ramp soft starting | 0.89 | – | 0.52 | 2.06 / 1.939 | – | 5.87 |
| Linear voltage ramp soft braking | – | 0.61 | – | – | 0.63 / 0.58 | 7.9 |
| Exponential voltage ramp soft starting | 0.69 | – | 0.22 | 1.85 / 1.716 | – | 7.2 |
| Exponential voltage ramp soft braking | – | 0.37 | – | – | 0.24 / 0.225 | 6.2 |

Table 3. Energy losses comparison for simulation
and analytical calculation methods for the induction motor 4MTKF160LB8
(11 kW, 380/220 V, 40% duty cycle, $k_J = 6.3$, $T_s = T_{\text{nom}}$, $t_0 = 2.5$ s)

| Parameters / Mode | $t_s$, s | $t_b$, s | $t_d$, s | $\frac{\Delta A_{sm}}{\Delta A_{sa}}$, p.u. | $\frac{\Delta A_{bm}}{\Delta A_{ba}}$, p.u. | $\varepsilon$, % |
|---|---|---|---|---|---|---|
| Full-voltage starting | 0.82 | – | – | 1 | – | – |
| Plug braking | – | 0.275 | – | – | 1 | – |
| Kick-start | 2.85 | – | 0.03 | 2.15 | – | – |
| Starting by star-delta windings switching | 2.4 | – | 1.25 | 2.05 | – | – |
| Linear voltage ramp soft starting | 3.1 | – | 1.72 | 2.09 / 1.952 | – | 6.6 |
| Linear voltage ramp soft braking | – | 2.15 | – | – | 0.43 / 0.407 | 5.3 |
| Exponential voltage ramp soft starting | 2.6 | – | 0.73 | 1.92 / 1.78 | – | 7.3 |
| Exponential voltage ramp soft braking | – | 1.35 | – | – | 0.17 / 0.158 | 7 |

Table 4. Energy losses comparison for simulation
and analytical calculation methods for the induction motor 4MTKH225M8
(30 kW, 380/220 V, 40% duty cycle, $k_J = 1$, $T_s = T_{\text{nom}}$, $t_0 = 0.5$ s)

| Parameters / Mode | $t_s$, s | $t_b$, s | $t_d$, s | $\frac{\Delta A_{sm}}{\Delta A_{sa}}$, p.u. | $\frac{\Delta A_{bm}}{\Delta A_{ba}}$, p.u. | $\varepsilon$, % |
|---|---|---|---|---|---|---|
| Full-voltage starting | 0.27 | – | – | 1 | – | – |
| Plug braking | – | 0.038 | – | – | 1 | – |
| Kick-start | 0.6 | – | 0.03 | 1.55 | – | – |
| Starting by star-delta windings switching | 0.48 | – | 0.251 | 1.29 | – | – |
| Linear voltage ramp soft starting | 0.68 | – | 0.38 | 1.925 / 1.83 | – | 4.9 |
| Linear voltage ramp soft braking | – | 0.44 | – | – | 0.47 / 0.44 | 6.4 |
| Exponential voltage ramp soft starting | 0.54 | – | 0.17 | 1.41 / 1.37 | – | 2.8 |
| Exponential voltage ramp soft braking | – | 0.208 | – | – | 0.185 / 0.17 | 8.1 |

Table 5. Energy losses comparison for simulation
and analytical calculation methods for the induction motor 4MTKH225M8
(30 kW, 380/220 V, 40% duty cycle, $k_J = 1.6$, $T_s = T_{nom}$, $t_0 = 1$ s)

| Parameters / Mode | $t_s$, s | $t_b$, s | $t_d$, s | $\frac{\Delta A_{sm}}{\Delta A_{sa}}$, p.u. | $\frac{\Delta A_{bm}}{\Delta A_{ba}}$, p.u. | $\varepsilon$, % |
|---|---|---|---|---|---|---|
| Full-voltage starting | 0.36 | – | – | 1 | – | – |
| Plug braking | – | 0.075 | – | - | 1 | – |
| Kick-start | 1.04 | – | 0.03 | 1.9 | – | – |
| Starting by star-delta windings switching | 0.82 | – | 0.5 | 1.61 | – | – |
| Linear voltage ramp soft starting | 1.26 | – | 0.75 | 1.857 / 1.77 | – | 4.7 |
| Linear voltage ramp soft braking | – | 0.81 | – | - | 0.585 / 0.56 | 4.3 |
| Exponential voltage ramp soft starting | 1.05 | – | 0.35 | 1.752 / 1.68 | – | 4.1 |
| Exponential voltage ramp soft braking | – | 0.49 | – | - | 0.238 / 0.22 | 7.5 |

Table 6. Energy losses comparison for simulation
and analytical calculation methods for the induction motor 4MTKH225M8
(30 kW, 380/220 V, 40% duty cycle, $k_J = 6.3$, $T_s = T_{nom}$, $t_0 = 4.5$ s)

| Parameters / Mode | $t_s$, s | $t_b$, s | $t_d$, s | $\frac{\Delta A_{sm}}{\Delta A_{sa}}$, p.u. | $\frac{\Delta A_{bm}}{\Delta A_{ba}}$, p.u. | $\varepsilon$, % |
|---|---|---|---|---|---|---|
| Full-voltage starting | 1.5 | – | – | 1 | – | – |
| Plug braking | – | 0.43 | – | – | 1 | – |
| Kick-start | 4.8 | – | 0.03 | 2.32 | – | – |
| Starting by star-delta windings switching | 3.8 | – | 2.25 | 1.97 | – | – |
| Linear voltage ramp soft starting | 5.6 | – | 3.4 | 2.18 / 1.97 | – | 9.6 |
| Linear voltage ramp soft braking | – | 3.47 | – | – | 0.57 / 0.535 | 6.1 |
| Exponential voltage ramp soft starting | 4.7 | – | 1.55 | 1.609 / 1.57 | – | 2.4 |
| Exponential voltage ramp soft braking | – | 2.05 | – | – | 0.23 / 0.215 | 6.5 |

It can be seen from tables 1–6 that maximum divergence between the results of both methods of energy losses calculation, analytical and simulation, does not exceed 9% that proves these methods to be effective and useful for the research of energy aspects of an induction motor soft starting and braking. Also it should be noted that during simulation the induction motor iron energy losses $\Delta A_{iron}$ have been considered while the analytical method does not provide their calculation. Therefore, the divergence between the results of both methods would be less noticeable with allow for iron energy losses for the analytical method.

From tables 1–6 it can be concluded that total energy losses during induction motor full-voltage starting are the lowest if compared to other examined starting modes. There is a significant increase of energy losses during induction motor soft starting and their noticeable decrease during soft braking if compared to energy losses during full-voltage starting and plug braking correspondingly. For soft starting and braking of a squirrel-cage induction motor it is best to apply exponential voltage magnitude changing law than a linear law due to lower energy losses in motor transients.

## 3. ALLOWABLE FREQUENCY OF STARTING AND STATOR WINDING TEMPERATURE CALCULATION

Due to very low energy losses during soft braking and relatively high energy losses during soft starting it is reasonable to evaluate the effect of total energy losses in transients of squirrel-cage induction motors operating in intermittent duty on their allowable frequency of starting (Table 7).

Table 7. Allowable frequency of starting of 11 kW and 30 kW induction motors for different starting/braking modes and inertia factors $k_J$

| Induction motor starting and braking mode | Induction motor allowable frequency of starting $Z$, starts/h | | | | | |
|---|---|---|---|---|---|---|
| | $k_J = 1$ | | $k_J = 1.6$ | | $k_J = 6.3$ | |
| | 11 kW | 30 kW | 11 kW | 30 kW | 11 kW | 30 kW |
| Direct starting & plugging | 665 | 330 | 414 | 219 | 103 | 58 |
| Kick-start & plugging | 383 | 239 | 248 | 138 | 63 | 33 |
| Star-delta windings switching & plugging | 425 | 274 | 252 | 156 | 65 | 37 |
| Linear voltage ramp soft starting & soft braking | 470 | 292 | 271 | 161 | 77 | 38 |
| Exponential voltage ramp soft starting & soft braking | 570 | 329 | 332 | 185 | 91 | 44 |

The analysis of table 7 shows that exponential voltage changing law gives the highest allowable frequency of starting of all the examined reduced and soft voltage starting and braking modes. Therefore it is best to apply this law for soft starting and braking of the induction motors operating in intermittent duty.

Due to an increase of energy losses during soft starting it is important to define the induction motor winding temperature at the end of starting process (Table 8) which should not exceed the maximum allowable temperature $\theta_m$ for its winding insulation class.

Provided that the electric drive soft starting time is less than the induction motor heating time constant its heating process during soft starting can be considered adiabatic allowing stator winding temperature $\theta_1$ calculation in accordance with the following expression:

$$\theta_1 = \theta_0 + \frac{\Delta A_1}{m_1 c_1}, \tag{10}$$

where: $\theta_0$ – ambient temperature; $\Delta A_1$ – energy losses in induction motor stator at the end of its starting process; $c_1$ – specific heat capacity of stator winding material; $m_1$ – stator winding material mass.

Table 8. Stator winding heating temperature at the end of starting process of 11 kW, 30 kW and 160 kW induction motors with allow for different inertia factors $k_J$

| Induction motor starting and braking mode | Induction motor stator winding temperature $\theta_1$, °C | | | | | | |
|---|---|---|---|---|---|---|---|
| | $k_J = 1$ | | $k_J = 1.6$ | | $k_J = 6.3$ | | $k_J = 10$ |
| | 11 kW $t_0 \approx 3t_{ds}$ | 30 kW $t_0 \approx 2t_{ds.}$ | 11 kW $t_0 \approx 3t_{ds}$ | 30 kW $t_0 \approx 3t_{ds}$ | 11 kW $t_0 \approx 3t_{ds}$ | 30 kW $t_0 \approx 3t_{ds}$ | 160 kW $t_0 \approx 3t_{ds}$ |
| Full-voltage starting | 40,49 | 40,5 | 40,75 | 42,4 | 42,65 | 48,1 | 86 |
| Kick-start | 41 | 40,75 | 41,56 | 44,5 | 45,69 | 58,8 | 167 |
| Starting by star-delta windings switching | 40,9 | 40,63 | 41,51 | 43,9 | 45,42 | 55,9 | 128 |
| Linear voltage ramp soft starting | 40,92 | 40,7 | 41,55 | 44,2 | 45,52 | 57,7 | 160 |
| Exponential voltage ramp soft starting | 40,82 | 40,6 | 41,38 | 44 | 45,12 | 56,8 | 148 |

Although stator winding heating temperatures of low and medium rated power induction motors (11 kW and 30 kW) driving light ($k_J = 1.6$) and average ($k_J = 6.3$) inertial mechanisms do not exceed the maximum allowable temperature of their insulation class (155 °C for F-class insulation) it can be seen that final stator winding temperature of 160 kW induction motor driving a highly inertial mechanism ($k_J = 10$) for a linear voltage changing law is higher the maximum allowable F-class insulation temperature. Therefore, in this case exponential voltage changing law for soft starting of a squirrel cage induction motor is appropriate.

## 4. CONCLUSIONS

The divergence between the results of both energy losses calculation methods, analytical and simulation, is relatively small (<9%). It means that any of these methods is appropriate for energy losses calculation in the induction motor transients.

The research proves that together with the reduction of high starting currents and impact torques there is an increase of energy losses during induction motor soft starting and their decrease during soft braking if compared to full-voltage direct starting and plugging. Less energy losses during soft starting and braking of an induction motor can be achieved by the application of exponential voltage magnitude changing law instead of a linear law.

Also the application of exponential voltage changing law provides higher allowable frequency of induction motor starting than the use of a linear law while the induction motor stator winding temperature at the end of starting process does not exceed its maximum allowable value. Therefore it is recommended to apply this law for soft starting and braking of the induction motor electric drives operating in intermittent duty.

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