Piotr Drozdowski, Zbigniew Szular
Cracow University of Technology, Cracow

ENERGY EFFICIENT TWO STAGE STARTING OF CAGE INDUCTION MOTORS

DWUETAPOWY ROZRUCH ENERGOOSZCZĘDNY SILNIKÓW INDUKCYJNYCH KLATKOWYCH

Streszczenie: „Dwuetapowy rozruch energooszczędny silników indukcyjnych klatkowych". W artykule zaproponowano rozruch silników indukcyjnych klatkowych kształtowany dwuetapowo: początkowo poprzez regulację częstotliwości i napięcia według odpowiedniego prawa sterowania zapewniającego żądana dynamikę a następnie poprzez regulację jedynie napięcia (od częstotliwości większej od ok. 20 Hz). Rozruch częstotliwościowy zapewnia zwiększenie strumienia skojarzonego wirnika a przez to zmniejszenie prądów fazowych i w efekcie zaoszczędzenie pobieranej przez silnik energii. Ponadto dynamika napędu w tym zakresie może być łatwo sterowana w zależności od celu i algorytmu sterowania. W drugim etapie rozruch jest kształtowany przy stałej częstotliwości i regulowanym napięciu. Jako urządzenie energoelektroniczne służące temu celowi zastosowano cyklokonwertor gwiazdowy pracujący w drugim etapie rozruchu jako trójfazowy sterownik mocy. Zaproponowaną metodę rozruchu uzasadniono teoretycznie oraz zilustrowano odpowiednimi przebiegami.

1. Introduction

Repeated starting of large-power cage induction motors is always a serious problem when the technological process demands it. During direct starting the motor draws about six times full load current. Hence, substantial damage to the motor and auxiliary equipment can occur as a result of this. The damages of the motor are usually not visible at once. At first the cage is weakened gradually causing local asymmetries. After this the degradation process increases. To protect the motor a few methods of starting are applied:

- double-cage and deep bar motors,
- inductive reactor starting,
- autotransformer starting,
- solid state soft-starters.

Additionally these methods decrease voltage drops in the mains. For the forth method the 3-phase ac. voltage regulators are applied consisting of two anti-parallel thyristors in each phase. These regulators reduce the supply voltage and the stator currents in result. The motor accelerates under current control until it reaches the region of operating speed. Additionally, power factor control is allowed and energy saving for weakly loaded induction motors. However, the regulators have one serious disadvantage: the motor torque is reduced proportionally to square of the stator voltage. Hence, starting of loaded motors (particularly one-cage motors) is difficult or sometimes impossible. Similar disadvantages are inherent to starting by autotransformer and inductive reactors.

Thus, as the solution an another method is proposed in this paper. It is based on two-stage starting. The first stage is the variable frequency starting and the second stage is the variable voltage starting. For both the stages one solid state converter is used. The device works at first as the cycloconverter and next as the ac. regulator. The topology of the device is changed only by appropriate sequence of signals controlling the thyristors. This system can be also used for speed control of the motor. The costs and complexity of the converter is not significantly greater than the standard ac. regulator, since the power switching elements are SCRs.

The proposed two stage starting is called further "Starting 1", whereas the starting shaped by controlled voltage (ac. regulator) "Starting 2".

2. Determination of control signals

To obtain two axis values of the signals representing stator voltages and the signal of stator frequency the mathematical model of the induction motor was expressed in *x-y* co-ordinates fixed to the rotor flux linkage vector $\underline{\psi}_r^r = \psi_{rx}^r + j\psi_{ry}^r$ (Fig. 1), where $\psi_{rx}^r = \psi_r^r$, $\psi_{ry}^r = 0$. The system of equations, presented below, describe the motor in per unit quantities – the upper index r denotes a “relative” or a “per unit” value.

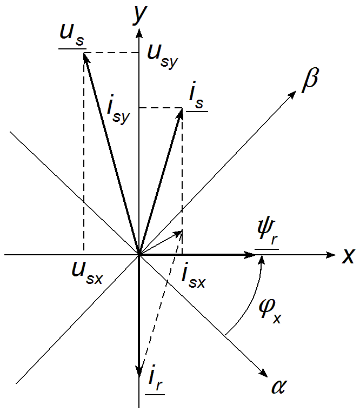

Fig.1. Vector diagram of the induction motor quantities in the stationary (α–β) and the rotating (x–y) reference frames

The motor model in *x-y* p. u. components is given below. The quantities correspond to Fig.1.

$$u_{sx}^r = R_s^r i_{sx}^r + \frac{1}{\Omega^o}\left(\frac{W^r}{L_r^r}\frac{di_{sx}^r}{dt} + \frac{L_m^r}{L_r^r}\frac{d\psi_r^r}{dt}\right) - \\ -\omega_x^r \frac{W^r}{L_r^r} i_{sy}^r \tag{1}$$

$$u_{sy}^r = R_s^r i_{sy}^r + \frac{1}{\Omega^o}\frac{W^r}{L_r^r}\frac{di_{sy}^r}{dt} + \\ +\omega_x^r\left(\frac{W^r}{L_r^r} i_{sx}^r + \frac{L_m^r}{L_r^r}\psi_r^r\right) \tag{2}$$

$$0 = R_r^r \frac{\psi_r^r - L_m^r i_{sx}^r}{L_r^r} + \frac{1}{\Omega^o}\frac{d\psi_r^r}{dt} \tag{3}$$

$$0 = -R_r^r \frac{L_m^r}{L_r^r} i_{sy}^r + \left(\omega_x^r - \omega^r\right)\psi_r^r \tag{4}$$

$$\frac{d\varphi_x}{dt} = \Omega^o \omega_x^r \tag{5}$$

$$T_e^r = \frac{L_m^r}{L_r^r}\psi_r^r i_{sy}^r \tag{6}$$

In the above equations: R_s, R_r - stator and rotor resistance respectively, L_m - main inductance (three phase magnetising inductance), L_s, L_r - total three phase stator and rotor inductance respectively, $W = L_s L_r - L_m^2$, Ω^o - reference angular frequency (usually for the rated stator frequency), T_e - electromagnetic torque.

When the greatest derivatives of any *x-y* current component $\frac{di_{sx}^r}{dt}$, $\frac{di_{sy}^r}{dt}$ cause signicantly lower voltage drops on the respective inductances than the lowest drops on resistances caused by the respective currents, the motor processes can be treated as quasi stationary. Additionally when the rotor flux linkage is stable $\psi_r^r = \text{const} = \Psi_r^r$, the motor equations take the form relevant to the steady state:

$$u_{sx}^r \approx U_{sx}^r = R_s^r I_{sx}^r - \alpha\, L_a^r I_{sy}^r \tag{7}$$

$$u_{sy}^r \approx U_{sy}^r = R_s^r I_{sy}^r + \alpha\, L_s^r I_{sx}^r \tag{8}$$

$$\psi_r^r \approx \Psi_r^r = L_m^r I_{sx}^r \tag{9}$$

$$R_r^r \frac{L_m^r}{L_r^r} I_{sy}^r = \beta \Psi_r^r \tag{10}$$

In the above equations: α - p. u. stator frequency ($\alpha = \omega_x^r$), $\beta = \alpha - \omega^r$ - p. u. rotor frequency or so called absolute motor slip.

Both equations (7) and (8) determine the control signals for the demanded run of the motor speed versus the time – here for required motor starting. So, taking $\omega(t)$, the appropriate electromagnetic torque in p. u. can be obtained from the mechanical equation

$$T_e^r = J\frac{1}{T^o}\frac{d\omega}{dt} + T_m^r \tag{11}$$

where: T^o - reference torque.

Considering eqn (10) in (6), for the given torque T_e^r, the rotor p. u. frequency

$$\beta = \frac{1+Q_\alpha}{2}(\alpha - \omega^r) + \frac{1-Q_\alpha}{2}\frac{R_r^r}{(\Psi_r^r)^2} T_e^r \tag{12}$$

where:

$Q_\alpha = 1$ for $\alpha = \text{const}$, $\Psi_r^r =$ var,

$Q_\alpha = -1$ for $\alpha = \text{var}$, $\Psi_r^r =$ const.

For the vector of rotor current $\underline{i}_r^r = i_{rx}^r + j i_{ry}^r$ (Fig. 1) is always satisfied

$$i_{rx}^r = 0\,; \qquad i_{ry}^r = -\frac{L_m^r}{L_r^r} i_{sy}^r \tag{13}$$

Hence, the steady state rotor current

$$I_{ry}^r = \mathrm{sgn}(\beta)\sqrt{\frac{\beta}{R_r^r} T_e^r} \qquad (14)$$

allows for the stator current *x-y* components

$$i_{sx}^r \approx I_{sx}^r = -\frac{1+Q_\alpha}{2}\frac{R_r^r}{L_m^r \beta} I_{ry}^r + \frac{1-Q_\alpha}{2}\frac{\Psi_r^r}{L_m^r} \qquad (15)$$

$$i_{sy}^r \approx I_{sy}^r = -\frac{L_r^r}{L_m^r} I_{ry}^r \qquad (16)$$

these components together with the stator p. u. frequency

$$\alpha = \omega^r + \beta \qquad (17)$$

are necessary to determine signals of phase voltages from eqns (7) and (8)

$$\begin{bmatrix} u_U^r \\ u_V^r \\ u_W^r \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos\varphi_x & -\sin\varphi_x \\ \sin\varphi_x & \cos\varphi_x \end{bmatrix} \begin{bmatrix} u_{sx}^r \\ u_{sy}^r \end{bmatrix} \qquad (18)$$

where from (5)

$$\varphi_x = \Omega^o \int_0^t \alpha(t)dt + \varphi_{x0} \qquad (19)$$

Finally these signals of phase voltages can be used to control the supplying converter.

3. Analysis of motor starting

The simplified mathematical description of the induction motor was used to compare two method of starting:

1. "Starting 1" at two stages.
2. "Starting 2" at controlled voltage.

Results of calculations (Figs. 2, 3, 4 and 5) allow mainly for comparison of consumed energy for the same dynamics of both the starting methods and additionally the obtained waveforms illustrate quality of starting.

In Fig. 2 and the next figures the solid lines depict waveforms for the first method of starting (two stage starting), whereas the dashed lines depict waveforms for the second method (starting with controlled voltages).

Voltage and current *x-y* components are shown in Fig. 3. The voltage components state the control signals (18) for an appropriate converter, whereas the current components allow for effects of control for both the starting methods.

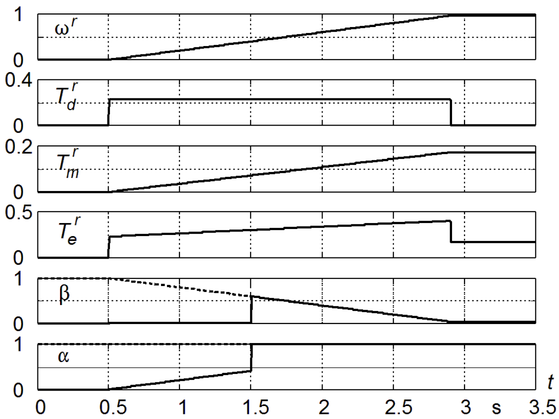

Fig.2. P. u. waveforms for the demanded dynamics of starting (ω^r – demanded run of the angular speed, T_d^r – dynamic torque, T_m^r – loading torque, T_e^r – electromagnetic torque, β – rotor p. u. frequency, α – stator p. u. frequency)

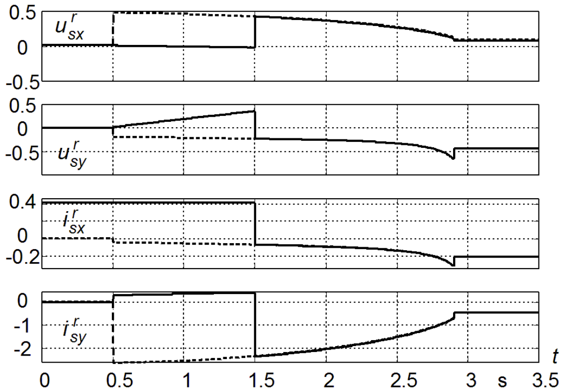

Fig.3. Waveforms of x-y voltage and current components for "Starting 1" and "Starting 2"

From Fig. 3 is visible that during the part of "Starting 1" at variable frequency the component i_{sx}^r is constant causing constant rotor flux ψ_r^r. At the same time interval for "Starting 2" the component i_{sx}^r is significantly lower causing low rotor flux and for the same electromagnetic torque T_e^r a lot greater component i_{sy}^r (see eqn (6)). Hence, this causes phase currents increased and greater consumption of input energy during "Starting 2". Comparison of power balances for both the starting methods is shown in Fig. 4.

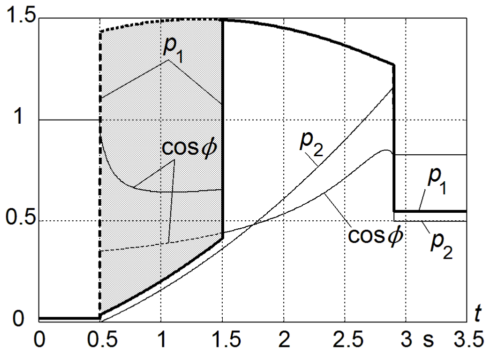

Fig.4. Waveforms of p. u. input power p_1, p. u. output power p_2 and cosϕ *for "Starting 1" and "Starting 2"*

From the waveforms p_1 for both the starting methods is clear that the darkened area in Fig. 4 shows the energy saved due to "Starting 1" in comparison with "Starting 2". The saved energy is about 31%.

For the obtained signals of voltages u_{sx}^r and u_{sy}^r (Fig. 3) and the signal α of stator frequency (Fig. 2) at "Starting 1" the simulation based on differential equations of the induction motor was done (Fig. 5).

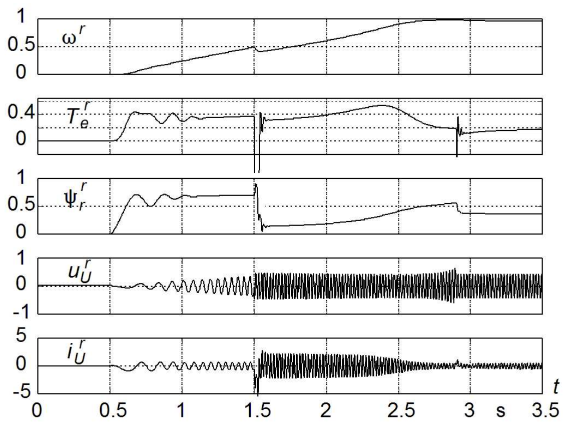

Fig.5. Waveforms illustrating the two stage starting ("Starting 1") obtained due to simulation at sinusoidal supply of the motor.

The reference base values for p. u. quantities in the above figures are $U^o = \sqrt{2} \cdot 220\,\text{V}$, $I^o = \sqrt{2} \cdot 6.5\,\text{A}$, $f^o = 50\,\text{Hz}$, $\Omega^o = 2\pi f^o$, $T^o = 27.3\,\text{Nm}$, $p = 2$ (pole pair number).

Comparing the speed and the torque waveforms from Fig. 5 with the corresponding waveforms from Fig. 2 it is clear that the signals of voltages from Fig. 3 are sufficiently correct in spite of simplified calculation. Additionally the simulation proved that "Starting 1" is significantly better than "Starting 2" with regard to energy consumption due to lower phase currents (in Fig. 5 only current i_U).

4. Practical application

The power electronic device allowing for the first method of starting "Starting 1" can be based on the star connected cycloconverter [2, 3] (Fig. 6).

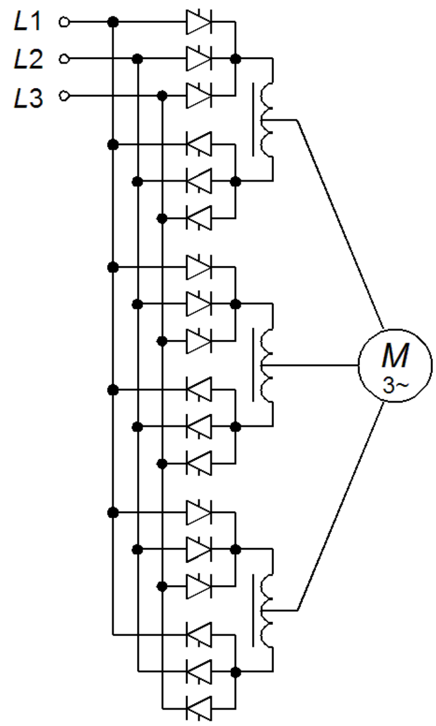

Fig.6. Three-pulse cycloconverter as the starting device for the cage induction motor

This converter can be controlled at variable and controlled output frequency and voltage up to 20 Hz. Beyond this region the converter can operate as the ac. power regulator at constant frequency 50 Hz and controlled voltage. In comparison with the typical ac. regulator composed of 3 pairs of anti-parallel thyristors the construction of the mentioned cycloconverter is practically not more complicated and expensive.

For the time domain waveforms of signals u_{sx}^r and u_{sy}^r given in Fig. 3 and the stator frequency α given in Fig. 2 the two-stage starting was checked practically using the power electronic device from Fig. 6. The waveforms illustrating this starting are shown in Fig. 7.

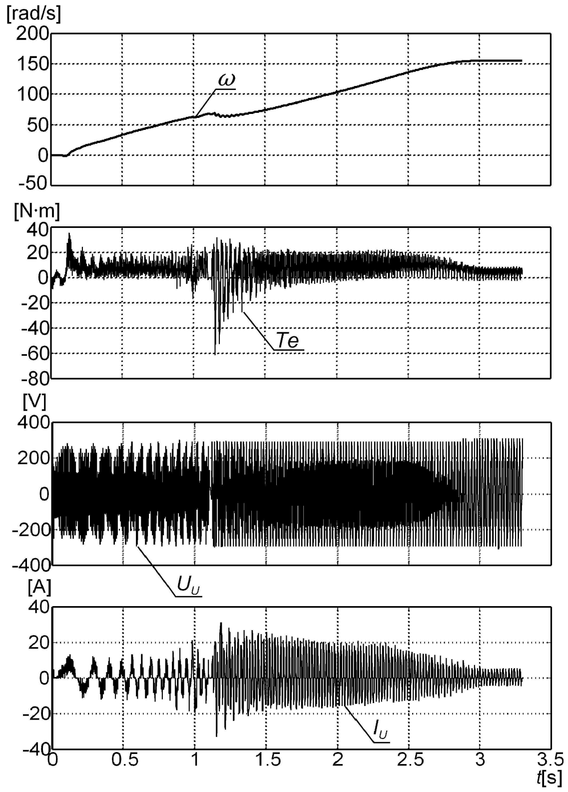

Fig.7. Waveforms illustrating the two-stage starting of the cage induction motor supplied by the cycloconverter

Comparing the above waveforms with the waveform from Fig. 5 it is seen that the proposed converter and its control satisfies the settled requirements for starting.

5. Conclusions

Applying the two stage starting of the cage induction motor the consumed energy is lower than for direct starting and starting controlled only by variable voltages (ac. regulator, inductive reactors, auto-transformer etc.). An appropriate frequency control at the beginning increases the starting torque by the increased magnetic flux keeping the motor current on the demanded low level. So, this is the reason for energy saving during the proposed two stage soft starting.

At the region of variable frequency the control law can be based on field-oriented control, the scalar control or direct torque control. Additionally the motor speed can be controlled for low levels. Thus, the proposed method can be an attractive alternative in relation to the traditional ac. regulators.

Additionally one can notice that application of inverters only for starting, without necessity of speed control, is not advantageous because of greater costs of the device particularly for motors of large power.

Bibliography

[1]. Nowak M., Barlik R.: *Poradnik inżyniera energoelektronika*. WNT Warszawa 1998.

[2]. Drozdowski P., Mazgaj W., Szular Z.: Zgłoszenie patentowe *Sposób rozruchu trójfazowego indukcyjnego silnika klatkowego*. Nr P-371071. Politechnika Krakowska 0.8.11.2004.

[3]. Szular Z.: *Dwuetapowy rozruch silnika indukcyjnego klatkowego z zastosowaniem układu tyrystorowego*. Czasopismo techniczne „Elektrotechnika” ISSN 0011-4561, nr 5E/2005. Kraków 2005.

Authors

1. Prof. Piotr Drozdowski
2. MSc. Zbigniew Szular
   Cracow University of Technology
   Institute of Electromechanical Energy Conversion

Address:
ul. Warszawska 24
31-155 Kraków, Poland
e-mails:
1. pdrozdow@usk.pk.edu.pl (P. Drozdowski)
2. aszs@poczta.fm (Z. Szular)