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High power squirrel cage motors for heavy starting conditions

Streszczenie. *Prąd rozruchowy silników klatkowych dużej mocy załączanych bezpośrednio na sieć wywołuje naprężenia termiczne i dynamiczne, groźne szczególnie dla klatki wirnika. Właściwe rozwiązanie konstrukcyjne klatki ma zasadnicze znaczenie dla trwałości silnika. Pokazano przykłady, w których przez modyfikację konstrukcji wirnika uzyskano znaczącą poprawę trwałości silnika. (**Silniki dużej mocy dla trudnych warunków startowych**)*

Abstract. *High capacity induction squirrel cage motors used at different industrial drives are usually started by direct line starts. Starting current, several times higher than nominal load current, causes thermal and mechanical dynamic stresses posing hazard to motor construction. Both stator and rotor windings are endangered at starting period, but stresses in rotor cages are usually considerably higher, therefore rotor design (and its manufacturing process) is of high importance for motor's durability.*

Słowa kluczowe: silniki klatkowe, rozruch bezpośredni, prąd rozruchowy, naprężenia klatki
Keywords: cage rotor motors, direct line starting, starting current, thermal stresses

Introduction

Majority of medium and high power cage motors, rated at 6 kV or higher and operating in industrial plants are usually started by direct switching on of full line voltage (direct-on-line start - DOL start). Modern industrial plants are outfitted with power systems having short-circuit capacity high enough to be adequate to this type of start-up. Direct start-up is prevalent in all power plant drives, even those of maximum nominal power.
The direct start-up poses greatest threat to cage motors construction, and rotors especially. The starting current, which is several times higher than rated current (in electromagnetic steady-state) is related to thermal and dynamic effects, which cause damage to motor elements [1,2] and cage rotor winding in particular.

Thermal effects of starting current

The flow of starting current produces fast heating in windings. The start-up time is significantly less than windings thermal time constants and therefore the heating process in stator or rotor cage windings may be assumed to be adiabatic and no great error is committed; in case of stator windings this was proven by tests [3].
The rise in winding temperature Θ vs. time t, at constant current density j and adiabatic heating is equal to [3]:

$$\theta = \frac{e^{\frac{j^2 \cdot k \cdot t}{\gamma_0 \cdot c_v}} - 1}{k} \tag{1}$$

where: j – current density in wire, k – temperature coefficient of material's resistivity, γ_0 - specific conductance of the material for $t=0$ and $\Theta = \Theta_0$, c_v - specific heat capacity of the material per unit volume.

In case of predominantly used wire materials and if quantities c_v and γ_0 are approximated as constant (with values at 100^0C adopted here), the temperature rise time v in adiabatic heating process may be determined with the help of formula (1):
for copper winding:

$$V_{Cu} = \frac{j^2}{150} \text{ [K/s}\} \tag{2}$$

for brass winding:

$$V_{mos} = \frac{j^2}{44} \text{ [K/s]} \tag{3}$$

for aluminum winding:

$$V_{Al} = \frac{j^2}{54} \text{ [K/s]} \tag{4}$$

where: j – current density [A/mm^2].

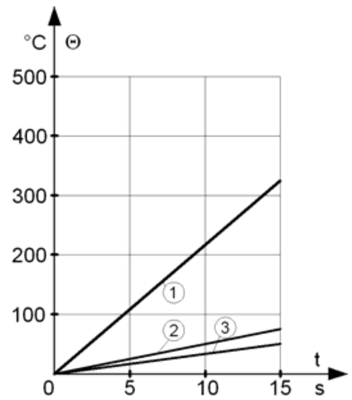

Fig.1. Windings temperature rise at slip s=1 (rotor is blocked) of 800 kW motor with single cage deep bar rotor, 1-rotor cage bar, 2-rotor end-ring, 3-stator winding

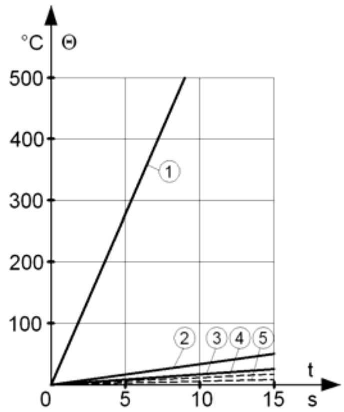

Fig.2. Windings temperature rise at slip s=1 (rotor is stopped) of 800 kW motor with double cage rotor, 1-rotor cage bar, 2-rotor end ring, starting (outer) cage, 3-stator winding, 4,5-bar and ring of inner cage

Adiabatic curves of winding temperature rise for slip s=1 (rotor stopped) are shown in Figs. 1 and 2. These curves were calculated for exemplary standard cage motor rated at 800 kW. Two different rotors were considered: single cage deep bar rotor, rectangular cage bars made of copper and double cage rotor with starting (outer) cage made of round brass bars and inner cage made of copper bars.
In double cage rotor the allowable maximum temperature is reached in very short time and this fact limits the use of these motors to drives with fast start-ups. The

rapid temperature rise during start-up results in generation of large mechanical stresses of thermal origin; these may pose serious threat to rotor structure.

Dynamic effects

Stator and rotor cage currents generate electrodynamic forces acting upon respective windings. The stator windings of modern high power motors are usually executed by VPI (Vacuum Pressure Impregnation method) and this makes them very resistant to surges and dynamic forces occurring either at start-up or in short-circuit states. However, the electrodynamic forces constitute a serious threat to rotor cage. The electrodynamic force in cage originates from interaction of current flowing in the cage bar and magnetic leakage flux (coupled with this current) in the bars. This is a pulsating force, with frequency doubled in relation to rotor current frequency and amplitude proportional to current squared. This force attains considerable values during initial stage of start-up, when aperiodic component is still present in starting current, see Fig.3.

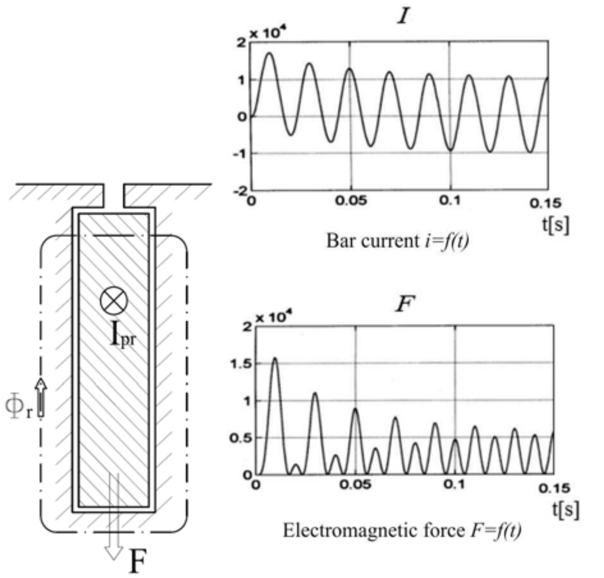

Fig.3. Electrodynamic force *F* excited in slot part of rectangular cage bar

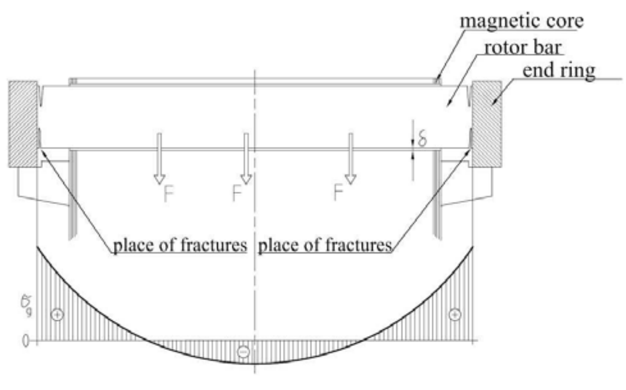

Fig.4. Distribution of bending stresses σ_g caused by electrodynamic force F, acting upon rotor cage bar if the radial clearance δ is big enough (the tolerance must be greater than deflection of the bar)

Instantaneous values of bar electrodynamic force F (assuming iron permeability to be infinite) are equal to [3]:
for rectangular slot:

(5) $$F = \frac{1}{2}\frac{\mu_0 l i^2}{d}$$

for round slot:

(6) $$F = \frac{1}{2}\frac{\mu_0 l i^2}{\pi d}$$

where: μ_0 - magnetic permeability of the air, $4\pi\cdot10^{-7}$ [H/m], i - wire current (instantaneous value) [A], l - stack length [m], d - width/diameter of rotor slot [m].

In case of even slight clearances existing between the bar and slot bottom, the electrodynamic force will produce dangerous and pulsating bending stresses in cage bars, causing material fatigue. The maximum stress occurs at the joint between the bars and end-ring, as seen in Fig.4.

Motors for frequent and brief start-ups

Frequent while brief start-ups in drives utilizing cage motors are often found in pump systems drives, when varying medium flow is attained by switching the pump on and off instead of controlling its speed. Cage motor operating in such drive must be characterized by rotor particularly resistant to dynamic effects of starting current flow. Double-cage rotor with starting cage made of round bars may be a natural solution to this problem. The electrodynamic force in slots, which acts upon the round bar during start-up is much less than in case of rectangular bar in deep-bar rotor (Eqs. (5) and (6)). Moreover, the round bar is characterized by considerably lower bending coefficient (it is more elastic) and therefore the electrodynamic force generates less stress in the joint between bar and end-ring. The starting cage of double-cage rotor must, however, be designed in such a way that it does not attain dangerous temperature levels during start-up. Appropriate rotor selection for drive with fast start-up and frequent switch-ons is illustrated by Example I.

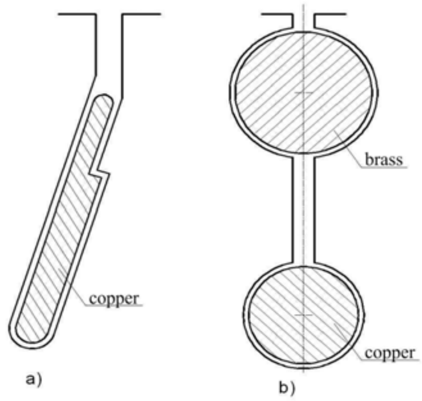

Fig.5. Slot shape, rotor, motor rated at 515 kW, 3000 rpm; a) original rotor slot, b) modified rotor slot [5]

Example I

Waste-heat boilers in one of Polish steel plants are supplied with water by pumps driven with cage rotor motors rated at 515 kW, 3000 rpm. The motor supplier (well-known European manufacturer) guaranteed start-up life span equal to 5000 start-ups (DOL). However, boiler mode of operation demanded frequent though brief switching on the pumps. Even though start-up time of motor driving the pump was very short (1.4-1.6 s), after 7000-8000 start-ups typical damages to rotor cage occurred due to electrodynamic forces generated at start-up, i.e. bar fractures at the joint between bars and end-ring (this was single cage deep bar motor). The user decided to modify the rotor design. Instead of single cage rotors with rotor slot shape as shown in Fig.5a, double cage rotors with slots shaped as in Fig.5b were specially designed and applied.
These rotors operated perfectly for over 20 years. Fig.6 shows a fragment of modernized rotor. The photo was

taken during motor overhaul after 25 years of operation; the inspection did not reveal any cracks, faults or deformations in rotor cages.

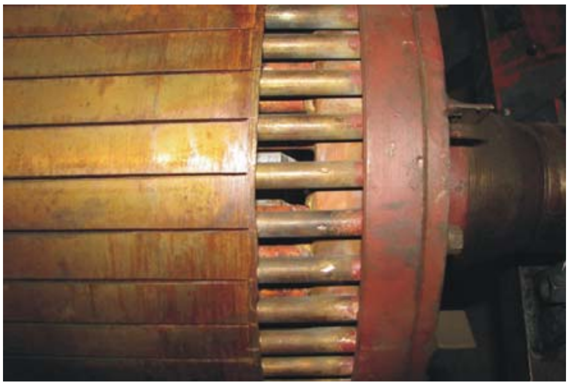

Fig.6. Fragment of modified rotor of 515 kW motor after 25 years of operation

Motors for long start-ups

Long start-up periods occur with high-inertia driven devices such as centrifugal fans, smoke exhaust fans and centrifuges. Cage motors used in these drives must possess rotor winding properly designed from the thermal point of view, since heat dissipated in rotor winding at start-up is equal to kinetic energy attained by mechanical system after start-up. Temperature in elements of rotor winding at start-up rises much more quickly than in stator winding - see Figs. 1,2. If long start-up will be repeated often, then the rotor must be properly protected against harmful effects of dynamic action of starting current.

In case of long start-up periods, single-cage deep bar rotors are usually applied. The bars in slots are fastened so that the dangerous radial clearance is kept at a minimum. However, the most appropriate design for long or very long start-ups (over 60 seconds) is the so-called *idle bar rotor.* The design and principle of operation of idle bar rotor motor type is given in [4] and design procedures are listed in [5]. Example II below demonstrates optimum selection of rotor winding for high power motor with long and frequent start-ups.

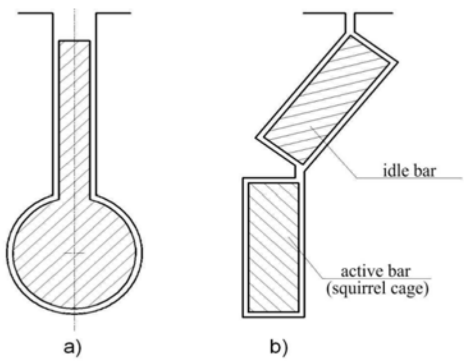

Fig.7. Slot shape, rotor, motor rated at 2000/500 kW, 1500/750 rpm; a) original rotor slot, b) modified rotor slot [5]

Example II

Smoke exhaust fans in one of steel plants are driven by two-speed cage motors rated at 2000/500 kW, 2*p*=4/8, 1500/750 rpm. Motors' mode of operation is continuous duty; the start-up takes place at lower speed (once a month at the average) and then once every hour motors are switched over to higher speed and operate for 20-25 minutes. The takeover time (i.e. when motor progresses from lower to higher speed) is equal to c. 16-17 s; during this period starting current flows in stator winding and rotor cage. When full speed is attained, the motor operates at rated load for *c*. 20 minutes and then stator winding is again switched to lower speed. Originally, the motors were equipped with single cage rotors with slots shaped as in Fig.7a.

During one year about 7000-8000 switchings and start-ups took place; on the average typical cage fractures occurred after 20000 switch-overs, due to action of electrodynamic forces in bar locations shown in Fig.4. Motors were modernized by introducing unique idle bar rotors with "idle" bars [5] and slots shaped as shown in Fig.7b. Major increase of motors operational durability was achieved. Fig.8 shows modernized rotor of 2000/500 kW motor after 70000 start-ups and speed switch-overs.

Fig.8. Modified rotor of 2000/500 kW, 1500/750 rpm motor, condition after 70000 start-ups [5]

Final remarks and conclusions

High power cage motors are standardized and usually manufacturers state their start-up durability as equal to 5000 start-ups, properly distributed over time. Technical specifications also state allowable time of single start-up for a given type of motor. If a particular drive is characterized by frequent starting and stopping of the motor or if the start-up period is long, then specialized designs are necessary. This is especially important in case of rotor winding, which must be designed in particular keeping in account starting time and start-ups frequency. Desired drive efficiency will be attained if the rotor is designed for a given drive and its anticipated mode of operation. Design and execution of dedicated rotor for high power motor is usually less expensive than purchase of new motor, while operational durability of special design is many times higher.

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