Study on starting the high power induction motors with wounded rotor

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Abstract—The paper analyzes the energetic aspects at the rheostatic startup of the existing three-phase induction motors with wounded rotor, used in conveyor belts actuation, characterized by hard starting. The higher moment of inertia of the system significantly increases the startup time, so it results a higher power consumption and a higher operating cost. The study was made on customer request, which proposes a modernization of the start by using an electronically controlled rheostat at the rotor and a three-phase bridge. The paper makes a technical and an economical comparison between the known classic rheostatic starting and the version proposed by the beneficiary. The proposed modernization of the induction motor with wounded rotor that exists at the conveyor, means a controlled starting with lower current shocks, but it results an increased electricity consumption by 10.7% during the start.

Keywords—high power induction motors, startup optimizing.

I. INTRODUCTION

The basic components in all power systems are the electrical machines. Therefore, the progress in cutting-edge industries is conditioned by developments in electrical machines, so by their performance. It follows, as a necessity, that high power induction motors have to better operating characteristics, higher specific power, and lower overall dimensions and weight [1-4], [8].

These requirements are achieved through optimal designing of the motors, which have high energy efficiency, and through new experimental trials and product quality certification [10-12]. Designers should lay down in a short time an optimal asynchronous motor variant that meets the customer’s requirements, such as the producing company to gain marketplace and the investment to be effective [4], [6-7], [9], [12].

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The paper presents an energy analysis for the startup of the high power induction motors with wounded rotor, used in actuation of the machines with high inertia moment.

II. THE MATHEMATICAL MODEL AND THE OBJECTIVE FUNCTION

On a worldwide scale it is imposed an increase in energy efficiency, so that a rational use of electrical energy consumption in industry to be achieved [1-5], [8]. This results in a reduction of the operating expenses by minimizing losses of the active and reactive power at load operation and during the induction motors with wounded rotor startup.

A. Objective function

In the paper it is exposed a study of the rheostatic starting (k = 1, 2, ... n steps) for high power induction motors, considering the minimal startup costs criterion [3], [10-11], by using the objective function:

\[ f(\bar{x}) = C_{cp} + C_{cpr} = \sum_{k} T_{pk} (P_{lk,med} e_{el,a} + Q_{lk,med} e_{el,r}) \]

where: \(C_{cp}\) – total startup cost, \(C_{cpr}\) – active and reactive electricity costs at startup, \(T_{pk}\) – operating time at step k of the resistance, \(P_{lk,med}\), \(Q_{lk,med}\) – the average values of active and reactive power when running on step k, \(e_{el,a}\), \(e_{el,r}\) – the cost of a kWh for the active or reactive electricity.

The restrictive conditions are those for current limitation during startup: \(I_{min} = 0.9 I_{2N}\) – the lower limit and \(I_{max} = 1.2 I_{2N}\) – the upper limit. This limitation determines a sufficient starting torque, even at full load. This provides a lower dynamic torque in order to have a slow, longtime start of the conveyor belt, characterized by a high moment of inertia.

B. Rheostatic starting

In order to reduce the voltage between slip rings to an acceptable value, \(U_{200}=2745\) V, that doesn’t pierce the insulation, the designer opted for the Delta connection at the rotor’s winding. Because it is a high power induction motor with wounded rotor, was made a rheostatic starting for limiting the inrush current from the power network [3], [11].

Fig.1.a depicts the Delta connection of the rotor’s winding (with the additional resistance on phase included) connected in short-circuit during startup.

Knowing the total resistance for a phase of the rotor - \(R_{sp}\) (fig. 1.a), and \(r_2\) - own resistance for a phase of the rotor, one
computed the additional resistance $R_{\Delta p}$ mounted on a phase at Delta connection:

$$R_{\Delta p} = R_\Delta - r_2$$

(2)

In fig.1.b is depicted the switching from Delta to Star connection, and was made using the relationship:

$$R_{\Delta p} = \frac{R_\Delta + R_{\Delta p}}{3} = \frac{r_2 + R_{\Delta p}}{3}$$

(3)

In fig.1.c is highlighted the rotor’s phase resistance $R_3 = r_y/3$, supposing it was in Star connection and assuming the conservation condition of the engine operating mode.

Analysis was done on a specific case of a high power and high voltage three-phase induction motor with wounded rotor, used to drive long lengths conveyors.

The rated data of the engine are: $P_N = 3800$ kW – rated power, $U_N = 6$ kV – rated voltage, $I_{1N} = 410$ A, $I_{2N} = 1330$ A, $n_1 = 1000$ rot/min – synchronism speed.

The cost for a rheostatic starting of the engine was made for $c_{ela} = 0.132$ €/kWh - cost of an active electricity kWh, $c_{elr} = 0.036$ €/kVARh - cost of a reactive electricity kVARh.

A redesign of the engine (according to the literature) gave the following results: $\cos \phi_m = 0.92; \eta_m = 0.9665; \Sigma p_m = 127.3$ kW; $M_{max,m} = 2.60 * M_N; r_1 = 0.043 \Omega, r_2 = 0.014 \Omega, X_1 = 0.762 \Omega, X_2 = 0.27 \Omega, k_r = 3.621$ – reference factor.

A. Analysis of the classical rheostatic startup method

The phase current for the rotor [3], [11] is determined by the relationship:

$$I_{2p} = \frac{s_k U_{e20}}{\sqrt{(R_{\Delta p})^2 + (s_k X_2)^2}}$$

(6)

Using (6), the condition $I_{2p} = I_{pmax}$ and the slipping $s_k$, corresponding to the transition on the following step of the resistance, it gives the total phase resistance of the rotor $R_{\Delta p,k}$. From the condition $I_{2pk} = I_{pmin}$, equation (6) and resistance value $R_{\Delta p,k}$, results the slipping $s_k$, when switching on the next step. In this way the resistance steps of the starting rheostat are calculated.

For the current limits imposed by the beneficiary, $I_{pmin}$, $I_{pmax}$ resulted a starting rheostat with 14 steps, the related features being depicted in fig.2.

III. RESULTS, SIMULATIONS AND CONCLUSIONS

In the paper are analyzed some aspects regarding the startup optimization of the high power induction motors with wounded rotor, the rheostat sizing, the calculation of energy losses.
The rotor’s voltages on all three phases are sine waves. The equations that describe the motor operation on step \( k \) of the rheostat are:

\[
\begin{align*}
\tau \cdot \frac{d}{dt} i_a + \frac{R_{pk} i_a}{2} + R_{pk} i_b &= u_{eab} \\
\tau \cdot \frac{d}{dt} i_b + \frac{R_{pk} i_b}{2} + R_{pk} i_c &= u_{ebc} \\
\tau \cdot \frac{d}{dt} i_c + \frac{R_{pk} i_c}{2} + R_{pk} i_a &= u_{eca}
\end{align*}
\]

and from these relationships results:

\[
\begin{align*}
\tau \cdot \frac{d}{dt} i_a - \tau \cdot \frac{d}{dt} i_b &= \frac{u_{eab} - \frac{R_{pk} i_a}{2} - \frac{R_{pk} i_b}{2}}{L_2} \\
\tau \cdot \frac{d}{dt} i_b - \tau \cdot \frac{d}{dt} i_c &= \frac{u_{ebc} - \frac{R_{pk} i_b}{2} - \frac{R_{pk} i_c}{2}}{L_2} \\
\tau \cdot \frac{d}{dt} i_c - \tau \cdot \frac{d}{dt} i_a &= \frac{u_{eca} - \frac{R_{pk} i_c}{2} - \frac{R_{pk} i_a}{2}}{L_2}
\end{align*}
\]

Using these functions and the 4th order Runge Kutta method \([6], [10]\), it results the numerical solution of the problem (the time variation waveforms of the phase and line currents).

For current limitation imposed condition \( I_{2p} = I_{pmax} = 1.2*2N \), results the total resistance of the rotor \( R_{pk} = R_1 + R_2 + ... + R_{14} = 1.75 \Omega \) (fig.2 and fig.3).

B. Analysis of the startup for the proposed method

Fig. 4 depicts the modernization solution proposed by the beneficiary, where the rotor’s phase resistances are replaced with a single electronically controlled resistance, placed at the exit of the rectifier bridge, putting the condition to preserve the value of the line current in the rotor.

It will be noted with \( R_{ppk} = R_{sk} + R_{sk+1} + ... + R_{sk+14} \) – the load resistance of the rectifier bridge, corresponding to the starting resistance with step \( k \). The resulting emf, \( u_{dab} \), for the closed circuit containing the rotor’s phase \( ab \) (fig. 4), when the diodes \( D_{a1}, D_{b2}, D_{a2}, D_{b1} \) are conducting, is:

\[
u_{dab} = \begin{cases} 
0 & \omega = (0 \leq 60^\circ) \\
\omega & \omega = (60^\circ \leq 120^\circ) \\
0 & \omega = (120^\circ \leq 180^\circ) \\
\omega & \omega = (180^\circ \leq 240^\circ) \\
0 & \omega = (240^\circ \leq 300^\circ) \\
\omega & \omega = (300^\circ \leq 360^\circ)
\end{cases}
\]

The equations that describe the motor’s operation at step \( k \) of the rheostat are obtained from (8), where the phase voltages \( u_{eab}, u_{ebc}, u_{eca} \) are switching with the voltages that occur at the operation of the diode bridge \( u_{dab}, u_{dbc}, u_{dca} \):

\[
\begin{align*}
\tau \cdot \frac{d}{dt} i_a + \frac{R_{pk} i_a}{2} + R_{pk} i_b &= u_{eab} \\
\tau \cdot \frac{d}{dt} i_b + \frac{R_{pk} i_b}{2} + R_{pk} i_c &= u_{ebc} \\
\tau \cdot \frac{d}{dt} i_c + \frac{R_{pk} i_c}{2} + R_{pk} i_a &= u_{eca}
\end{align*}
\]

B1. The initial moment of the startup

In order to make a fair comparison with the rheostatic startup classical method, it will be analyzed the same starting time \( n = 0 \), (step \( k=1, s_k=1 \)). To comply with the current limitation imposed condition \( I_{2p} = I_{pmax} = 1.2*2N \), results the total resistance of the diode bridge \( R_{ppk} = R_{S1} + R_{S2} + ... + R_{S14} = 0.89 \Omega \) (fig. 4).

By solving the differential equations system with the 4th order Runge Kutta method, the numerical solution is obtained and results the time variation waveforms for the phase and line currents. Through numerical methods also, are determined the
The effective value of the phase current I_{ph}=960 A, the fundamental harmonic value I_{h1}=916 A, the distortion factor k_{th}=30.1% and the harmonic spectrum.

The effective value of the line current is I_{l}=1670 A, and for the rectified current it results I_{ct}=4318 A. Fig. 5 depicts the phase currents i_{ab}, i_{ac} and the resultant line current i_{l}.

The version proposed by the beneficiary presents a high deformed regime with a rich harmonic spectrum.

C. Energy balance at startup

It will be analyzed, in terms of energy efficiency, the starting rheostatic methods (the classical rheostatic starting, and the one proposed by the beneficiary).

Since the conveyor belt has a high moment of inertia, results a lasting startup with a high consumption of electricity.

C1. Energy balance at the rheostatic startup

In this case all sizes are sinusoidal and a detailed analysis can be made for the motor operation on each step of the starting rheostat R_{pk} (k=1, 2, 3, ... 14), using the variable s=(0;1) and the relationships:

\[
I_{k}^{2}(s) = \sqrt{I_{10a}^{2} + I_{2ak}^{2} + I_{1k}^{2} + I_{2k}^{2}}
\]

\[
\cos \varphi_{I_{k}}^{2} = \frac{I_{10a} + I_{2ak}}{I_{k}}
\]

\[
P_{k}^{2}(s) = \sqrt{3} U_{N} I_{k} \cos \varphi_{I_{k}}
\]

where I_{10a}, I_{1k}, I_{2ak}, I_{2k} represents the active and reactive components for the current at no load operation, respectively of the related rotor current, determined according to the literature [3], [10-11] for the variable s=(0;1).

At the rheostatic starting the rotor current must be within the limits I_{pmin}=0.9*I_{N}= 1197 A and I_{pmax}=1.2*I_{N}= 1596 A. When it reaches the minimum value of the current, is given the command to close the contactor C_{1} (fig.2, fig.3), corresponding to the operation step.

For the step resistance R_{pk} and the imposed limits (I_{pmax}, I_{pmin}) results the proper slidings s_{k,1} si s_{k} respectively the speeds n_{k-1}, n_{k}. Using the equation motion, the relationship (14) is obtained which allows us to calculate the operating time on the step resistance R_{pk}, having the speed as variable.

\[
T_{pk} = \sum_{i=n_{k-1}}^{n_{k}} \frac{2\pi j_{c}}{M_{k}(s_{i}) - M_{k}(s_{i-1})}
\]

The total duration of the startup will be:

\[
T_{p} = \sum_{k=1}^{14} T_{pk}
\]

The average value of the active power from the grid when running on step R_{pk} is:

\[
P_{pk_{med}} = \sum_{i=n_{k-1}}^{n_{k}} \frac{P_{k}(s)}{N}
\]

N - is the number of points of the range (s_{k,1}, s_{k}). The energy costs during start up will be:

\[
C_{p} = \sum_{k=1}^{14} P_{pk_{med}} T_{pk \leq el.a}
\]

C2. Energy balance at the proposed rheostatic startup

Because we have a deformed regime during startup, for the proposed rheostatic starting method, all determinations are made through numerical methods by using the previous relationships.

In fig. 4 we have the rotor winding in Delta connection, the three-phase rectifier bridge, the 14 resistances used at startup and the thyristors that take out of circuit the step resistances.

During the operation at step resistance R_{pk} with corresponding slides s_{k,1} and s_{k} (and speeds n_{k-1}, n_{k}), the powers P_{pk} are determined by numerical calculation using the relationships (11), (17).

D. Conclusions

The study performed on customer’s demand, aimed to compare functionally and energetically the two methods of rheostatic starting (classical with three-phase rheostat and the proposed method with single-phase electronically controlled rheostat).

In terms of energy, the classical rheostatic startup means a lower cost of energy consumption by 10.7% and a reduced process time by 10.6%. The solution proposed by the beneficiary, with the single-phase electronically controlled rheostat, means a reduction in the amount of the fundamental harmonic for a imposed value of the rotor current. This explains the increased startup time and increased energy consumption for the new method.

REFERENCES


