Stray losses due to inter-bar currents of skewed cage induction motors at no-load

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Contents  In accordance with present-day efforts to reduce power losses in electrical machines, an analytical approach to estimate the influence of contact resistances between the skewed rotor cage and its laminated iron core on the amount of stray losses of induction motors is made in this paper.

Equations for calculation of resistances of the rotor iron core, with which the stray losses due to inter-bar currents are taken into account, are presented.

Querstrom Zusatzverluste im Rotor von Asynchronmaschinen mit geschraegetem Käfigläufer im Leerlauf

Übersicht  In Übereinstimmung mit neuzeitlichen Bemühungen, die Verluste von elektrischen Maschinen zu vermindern, ist in der vorliegenden Arbeit eine analytische Lösung zur Bewertung des Einflusses der Kontaktwiderstände zwischen dem geschraegten Käfig und Blechpaket des Rotors auf die Zusatz und indirekt auf die Gesamtverluste von Asynchronmaschinen angegeben.

Es werden die Gleichungen zur Berechnung des Blechpaket-Widerstandes des Rotors angegeben, mit denen man den Anteil der Zusatzverluste berechnet die, der von Querströmen im Rotor verursacht wird.

List of symbols

\[ L_{\text{obsi}} \quad \text{rotor bar leakage inductance} \]
\[ L_{\text{ori}} \quad \text{rotor end ring leakage inductance} \]
\[ Q_s, Q_r \quad \text{stator and rotor slots respectively} \]
\[ R_{\text{ori}} \quad \text{rotor bar resistance}[6] \]
\[ R_{\text{eri}} \quad \text{rotor end ring resistance}[6] \]
\[ m \quad \text{number of stator phases} \]
\[ k_{\text{CR}}, k_{\text{CR}} \quad \text{stator and rotor Carter factor respectively:} \]
\[ k_{\text{C}} = k_{\text{CR}}, k_{\text{CR}} \]
\[ N \quad \text{series-connected stator turns per phase} \]
\[ a_s \quad \text{number of stator parallel paths} \]
\[ k_{\text{wax}} \quad \text{stator winding factor} \]

Z_{\text{eri}} \quad \text{rotor end ring impedance:} \]
\[ Z_{\text{eri}} = R_{\text{eri}} + j \omega L_{\text{eri}} \]
\[ k_{\text{R}} \quad \text{skin effect factor for the resistance} \]
\[ d \quad \text{air-gap middle diameter} \]
\[ d_{\text{ri}}, d_{\text{te}} \quad \text{rotor inner and yoke diameter respectively} \]
\[ h_{\text{r}}, h_{\text{y}} \quad \text{rotor slot and yoke height respectively} \]
\[ l_{\text{Fe}}, l_e \quad \text{iron core and equivalent core length respectively} \]
\[ b_{\text{dav}} \quad \text{rotor average tooth width} \]
\[ 1/n_{\text{sq}} \quad \text{sweeping of rotor bars} \]
\[ \gamma \quad \text{pole pair number of a harmonic} \]
\[ \gamma_{\text{v}} \quad \text{electrical angle:} \]
\[ \gamma_{\text{v}} = \frac{\gamma_{\text{sa}}}{\omega} \]
\[ \xi_{\text{v}} \quad \text{rotor reaction damping factor (Taegenaus) \}
\[ \gamma_{\text{v}} \quad \text{contact resistance (has to be determined experimentally)} \]
\[ \rho_{\text{Fe}} \quad \text{resistivity of the iron} \]
\[ s_{\text{v}} \quad \text{slip of the vth harmonic} \]
\[ P_{\text{st}} \quad \text{stator input power} \]
\[ P_{\text{w}} \quad \text{stator winding losses of the fundamental harmonic (frequency f)} \]
\[ P_{\text{w,C}} \quad \text{stator core losses of the fundamental harmonic (frequency f)} \]
\[ P_{\text{pm}} \quad \text{mechanical output power of the auxiliary motor} \]
\[ P_{\text{dav}} \quad \text{total no-load stray losses} \]
\[ P_{\text{m}} \quad \text{mechanical losses (friction and windage losses)} \]
\[ P_{\text{dav}} \quad \text{rotor cage and inter-bar currents stray losses} \]
\[ \text{(frequencies other than f and }sf\text{ respectively) \}
\[ P_{\text{dav}} \quad \text{rotor core hysteresis losses} \]
\[ P_{\text{dav}} \quad \text{stator core stray losses} \]
\[ P_{\text{dav}} \quad \text{rotor core stray losses} \]
\[ P_{\text{dav}} \quad \text{total no-load losses} \]

1 Introduction

Results of analyses, undertaken by the U.S. Department of Energy (USDOE), together with studies by the European Council for an Energy Efficient Economy, warn that the greatest part of the total energy consumption in industrial applications is used by industrial systems in which electrical motors are included, most frequently cage induction motors. The latter also decisively effect the efficiency of those systems.

From an economical and environmental protection point of view efforts for improving the efficiency and
reduction of energy consumption expenses for these kinds of motors are quite understandable. This also justifies why time and again the same questions and researches are being carried out.

Notwithstanding the comprehension that the large majority of new era authors [1] direct their attention to numerical methods, thus avoiding some hypotheses and achieving better quantitative results, it has many times been proven that the analytical approach to the analysis of processes in electrical machines is more practical. The latter enables analysis of effects of practically all important construction parameters on performance characteristics of machines.

In addition to the stray load losses, the substantial amount of stray losses could also depend on the voltage. Therefore, the voltage dependent stray losses, which are basically investigated at no-load operation, should not be underestimated nor ignored.

2 Sample motor

To estimate the influence of the contact resistance between rotor bars and the iron core on stray losses due to interbar currents, a water-cooled 3-phase 4-pole skewed cage induction motor, type 1MB160H-4A produced by Indramat [9], was used. The motor has the following rated data:

It has 36 stator and 44 rotor slots and is designed with a relatively big borehole in the rotor package, big enough to build in a bush and a spindle. The motor is used as the direct drive of the main spindle in the CNC machine tool, and due to the need to be built into a CNC machine its outer diameter is strictly limited.

Because of the skewed rotor slots, i.e. cage bars and definite value of contact resistance, it is necessary to take the rotor inter-bar currents and related stray losses into account. Particularly because the ratio between stator and rotor slots, regarding stray losses [2], is inconvenient i.e. \( Q_s < Q_t \).

3 Influence of rotor inter-bar currents on equivalent circuit parameters

It is well known that the stray losses of cage induction motors, in the case of an uninsulated skewed cage, can be many times higher than the same losses in the case of an insulated skewed cage [3-5].

In analyses performed so far it is assumed that inter-bar currents flow only between two adjacent rotor bars [4, 5] or in direction from bars to the shaft of the motor [3].

In fact the flow of inter-bar currents in the rotor is much more complex than it is taken into consideration in general [5]. Definite values of contact resistances namely allow inter-bar currents in the rotor, which are the result of higher magnetic induction harmonics in the air-gap, to flow between adjacent cage bars as well as between the bars and the shaft of the motor. This leads to a change of rotor parameters for all harmonics, including the fundamental, and with that to an additional increase of the stray and therefore the total losses of the motor. The way one should calculate the cross resistances is shown later in this paper.

By defining the voltage equations and by the recognition of equivalent circuit parameters in the general way, where the ideal insulated cage rotor and indefinite value of contact resistance between the rotor bars and the iron core is assumed respectively, in the analyses of voltage dependent stray losses it is simply not possible to achieve proper results. Therefore, it is supposed that by defining parameters (resistances and leakage reactances) for the unskewed and insulated cage of the rotor, apparent power of which are the same as for the real, in particular the skewed and uninsulated cage, the real cage equivalent parameters are obtained, which are suitable for the calculation of stray losses.

It is necessary to emphasise that the parameters of the rotor iron core, by which the surface losses in teeth and pulsation losses in teeth and yoke were taken into account, are not defined. The latter can be considered separately, with a subsequent definition of suitable expressions.

In the given procedure only resistances of the rotor iron core, with which a part of stray losses due to inter-bar currents in the iron core are taken into account, are included.

3.1 Determination of inter-bar currents

The currents, which are induced in the uninsulated skewed rotor cage by the magnetic induction harmonics

\[ b_r = B_r \cos(\nu x_r - s_r \omega t - \varphi_r) \]  \hspace{1cm} (1)

the source of which is unknown, are defined according to the known procedure [3]. The magnetic induction amplitude of each stator harmonic at no-load is calculated as follows

\[ B_r = \frac{\mu_0 m_i N k_{sw} v}{\pi a_s} C_{sv} \sqrt{2} I_s \]

where stator slotting factor is

\[ C_{sv} = k_{sa} \frac{\sin \frac{\pi}{k_{sa} Q_s}}{\sin \frac{\pi}{Q_s}} \]

Figure 1 shows the position of the coordinate system for calculation of rotor currents.

The rotor inter-bar currents can be expressed in the form

\[ I_{b_r}(y_r) = -\frac{E_r e^{j\varphi_r}}{Z'_{sw}(s^2 + d_{sw}^2)} \times \left[ e^{-j\nu x_r} - C_{sw} \text{ch}(d_{sw} y_r) + j C_{sw} \text{sh}(d_{sw} y_r) \right] \]  \hspace{1cm} (2)

where \( E_r \) is the voltage induced in the non-skewed loop of the rotor cage.