PARAMETER IDENTIFICATION FOR LARGE INDUCTION MACHINES USING DIRECT ON LINE STARTUP TEST

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Abstract: The paper introduces a convenient method for the electric parameters off-line identification in large induction machines, based on Direct On Line (DOL) starting, performed under no-load condition. Experimental results on a 6 kV, 4 poles, 7500 kW machine start-up are presented.

Key words: Testing, Large induction machines, Parameter identification.

1. INTRODUCTION

Parameter identification on large induction machines usually involves heavy efforts, in terms of manpower and equipment. Thus, simplified methods have been implemented, more or less successfully. The proposed paper deals with a deterministic type, off-line method for parameter identification for large induction machines.

2. NO-LOAD DOL START-UP ANALYSIS

The parameter identification of large induction machines problem has been extensively treated, and interesting results have been previously obtained. The main contribution of the present proposal is a feasible off-line method for determining these parameters using a simple Direct-On-Line (DOL) start-up. A complete procedure has been issued in order to “extract” the useful information from the electrical data \( U, I, P, n = f(t) \) recorded along a single start-up test. The method is thus a “one shot” type method.

Our proposal for identifying these parameters is based on the assumption that a large machine starting is a succession of steady-state mechanical and electric regimes, with all the inherent consequences.

These regimes are featured completely using \( U, I, P, n = f(t) \) which were reached through a data acquisition system. The proposed procedure is an off-line type one, and invokes the ordinary equivalent electric layout of the machine:

\[
R_1 \quad X_1 \quad X_m \quad X_2' \quad R_2'/s
\]

Further more, we have assumed that \( R_m = 0 \), and \( R_1, X_1, X_m = \text{ct.} \) all along the starting duration. The stator resistance was measured directly \( R_1 = 0.0174 \Omega \).

The stator reactance are to be determined using the short-circuit \( (s \equiv 1) \), immediately after connecting the machine to the power supply network) and the no-load \( (s \equiv 0) \), at the end of the starting duration, when the machine has reached it’s rated speed) regimes.

Assuming that \( Z_1 = Z_2' \), thus \( Z_k = 2Z_1 \), we come to:

\[
c_1 = 1 + \frac{Z_1}{Z_m} = 1 + \frac{Z_k}{2Z_m} \approx 1 + \frac{I_0}{2I_k} \\
X_0 = X_1 + X_m = \sqrt{\left(\frac{U}{I_0}\right)^2 - \frac{P_0}{3I_0^2}} \\
X_m = \frac{X_0}{c_1} = 29.085 \Omega \\
X_1 = \left(\frac{c_1 - 1}{c_1}\right)X_0 = 0.628 \Omega
\]

In order to identify the rotor parameters, we will use the standard phasor motor diagram, as follows:
\[ U_e^2 = U_1^2 + I_1^2 (R_1^2 + X_1^2) - 2U_1 I_1 \sqrt{R_1^2 + X_1^2} \cos \left( \frac{\pi}{2} - \varphi_1 - \alpha \tan \frac{R_1}{X_1} \right) \]

\[ I_{01} = \frac{U_e}{X_m} \]

\[ \sin \vartheta = \frac{I_1}{U_e} \sqrt{R_1^2 + X_1^2} \sin \left( \frac{\pi}{2} - \varphi_1 - \alpha \tan \frac{R_1}{X_1} \right) \]

\[ I_2^2 = I_{01}^2 + I_1^2 - 2I_0 I_1 \cos \left( \frac{\pi}{2} - \varphi_1 + \vartheta \right) \] (2)

\[ R_2 = \frac{M \omega_1 s}{pm I_2^2} \]

\[ X_2' = \sqrt{\left( \frac{U_e}{I_2} \right)^2 - \left( \frac{R_2}{s} \right)^2} \]

Basically, since we have already achieved or calculated (i.e. the electromagnetic torque by segregating the stator losses) the relevant numerical data, we are now able to reach the variation of the rotor parameters vs. rotor slip (fig.3).

The significant variation of the rotor parameters confirms the deep bar rotor construction (\( \phi/h = 1/10 \)). However, it also cumulates the errors born in the simplifying hypothesis previously assumed. How perfect does this newly “identified” machine matches the real one?

The availability of the electric equivalent parameters allows us to calculate \( M, I, \cos \varphi, P = f(s) \) (fig. 4), while applying the measured voltage \( U = f(s) \), thus simulating the behaviour of this ideal machine during start-up.
The comparison between the calculated and measured data was made for the whole set of values, using an average error defined as:

$$\varepsilon_Y = 100 \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Y_i - Y_{\text{calc}})_i^2} \%$$  \hspace{1cm} (3)

The error between the virtual and the real machines, indicates a very good match (fig. 5).

$$\varepsilon_M = 0.068 \% \quad \varepsilon_I = 0.022 \%$$

$$\varepsilon_{\text{cos}} = 0.158 \% \quad \varepsilon_p = 0.055 \%$$  \hspace{1cm} (4)

We point out that the mentioned procedures are of a deterministic type, not involving any regression techniques or so.

The data set covering the start-up duration consisted of 85 measuring points, at a sample rate of 5 measuring points per second. Each measuring point considered $U_{A,B,C}, I_{A,B,C}, n = f(t)$, along 50 msec "flashes", on 8 acquisition channels, at an average acquisition time of 50 \(\mu\text{sec/channel.}\)

The figure refers to an induction motor produced by U.C.M. Resita, type TIS 1520/1120-4, 7500 kW, 6 kV, 800 A, 1490 rpm, 50 Hz, Yo connection. The start-up was performed at reduced voltage ($0.6xU_n$), due to a weak supply network.

3. Rotor Circuit Decomposition

Instead of using several data sets $R'_2, X'_2=s(f(s))$, especially for simulation purposes, it is sometimes more suitable to work with rotor models consisting of multiple elementary rotor cages with constant parameters vs. slip (fig. 3).

Invoking these models (eq. 5), and using the already known parameter variations vs. slip (see fig. 3), we aim to identify the resistances and reactances for each cage, so we could finally get a good match between the model and the real machine.

$$N = 1$$

$$R_{2e}', X_{2e}' = ct(s)$$

$$N = 2$$

$$R_{2e} = \frac{(X_{21}^2 + X_{22}^2)R_{22} + R_{22}X_{21}^2 + R_{21}'R_{22} + R_{22}'R_{21}'}{\left( X_{21} + X_{22} ' \right)^2 s^2 + \left( R_{21}' + R_{22}' \right)^2} = \frac{as^2 + b}{cs^2 + d}$$

$$X_{2e} = \frac{(X_{21}^2 + X_{22}^2)R_{22} + R_{22}X_{21}^2 + R_{21}'X_{22} + X_{22}'R_{22}'}{\left( X_{21} + X_{22} ' \right)^2 s^2 + \left( R_{21}' + R_{22}' \right)^2} = \frac{es^2 + f}{cs^2 + d}$$

$$N = 3$$

$$R_{2e} = \frac{as^4 + bs^2 + c}{ds^4 + es^2 + f}$$

$$X_{2e} = \frac{gs^4 + hs^2 + k}{ds^4 + es^2 + f}$$  \hspace{1cm} (5)
where $a, b, c, d, e, f, g, h, k$ are constants:

$$a = R_1^2 R_2^2 R_3^2 + R_2^2 R_2^2 R_3^2 + R_2^2 R_2^2 R_3^2$$

$$b = R_1^2 R_2^2 R_3^2 + R_2^2 R_2^2 R_3^2 + R_2^2 R_2^2 R_3^2 + R_2^2 R_2^2 R_3^2 + R_2^2 R_2^2 R_3^2$$

$$c = R_1^2 R_2^2 R_3^2 (R_2^2 + R_2^2 + R_2^2)$$

$$d = X_1^2 X_2^2 + X_2^2 X_3^2 + X_3^2 X_3^2$$

$$e = X_1^2 R_2^2 + 2X_2^2 R_2^2 R_2^2 + X_2^2 R_2^2 + 2X_2^2 R_2^2 R_2^2 + 2X_2^2 R_2^2 R_2^2 + R_2^2 R_2^2$$

$$f = \left[R_2^2 R_2^2 + R_2^2 R_2^2 + R_2^2 R_2^2\right]^2$$

$$g = X_1^2 X_2^2 + X_2^2 X_3^2 + X_3^2 X_3^2$$

$$h = R_2^2 X_2^2 R_3^2 + X_2^2 X_2^2 R_3^2 + R_2^2 X_2^2 R_3^2 + X_2^2 X_2^2 R_3^2 + X_2^2 X_2^2 R_3^2$$

$$k = X_1^2 R_2^2 R_2^2 + R_2^2 R_2^2 R_2^2 + X_2^2 R_2^2 R_2^2$$

Based on these known type models, by using a standard Levenberg-Marquardt regression tool, we have assessed these constant parameters, for each model.

In order to find out the relevant $R_2, X_2, R_1, X_1$ parameters, we have then succeeded in solving the equivalent non-linear equation systems. A certain number of refining criteria were used along the numerical process.

The results are presented in graphical and numerical format (see fig. 6, table 1).
4. DISCUSSION AND CONCLUSION

The presented method shows reasonable results, both for 2 and 3 cage models. The errors listed in table 1 can be explained by the fact that the considered simplified models have disregarded the influence of the mutual reactances between the cages (fig. 7), thus influencing the accuracy of the results. Regarding the rotor reactance, the errors are strongly affected by the fact that we went with the slip as low as the critical slip, where the procedure proves it’s limitations.

These influences mostly affect the reactance of the upper cage, which apparently has a “mathematical” meaning, especially for the model with 3 cages. However, the model presented in fig. 7 cannot be used due to mathematical complications introduced.

Finally, as a conclusion after performing similar tests for machines rated at 1000, 2200, 2800, 3200 kW, for most practical applications in the large machines area, the use of the 2-cage model is more appropriate for simulation purposes.

All the introduced procedures have been implemented on MathCAD & MatLab support, as universal tools nowadays available in the hand of any testing engineer. Moreover, since computer data acquisition measuring sets are a common today, the practicality of the introduced method is obvious.

Tab. 1. Comparative results for multiple cage electric parameters.

<table>
<thead>
<tr>
<th></th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
<th>( X_M )</th>
<th>( \epsilon_I )</th>
<th>( \epsilon_{cos} )</th>
<th>( \epsilon_P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cage, variable parameters</td>
<td>0.0174</td>
<td>0.0174</td>
<td>0.6287</td>
<td>29.085</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 cage, constant parameters</td>
<td>0.0894</td>
<td>0.0894</td>
<td>0.1729</td>
<td>416</td>
<td>31.47</td>
<td>10.99</td>
<td>35.26</td>
<td>28.6</td>
</tr>
<tr>
<td>2 cages, constant parameters</td>
<td>0.257</td>
<td>0.052</td>
<td>6.5</td>
<td>31.1</td>
<td>5.78</td>
<td>1.56</td>
<td>10.95</td>
<td>5.27</td>
</tr>
<tr>
<td>3 cages, constant parameters</td>
<td>1.22</td>
<td>0.173</td>
<td>10.57</td>
<td>26.9</td>
<td>15.72</td>
<td>2.83</td>
<td>13.09</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Fig. 7. Realistic equivalent circuit for the rotor cages.
5. ACKNOWLEDGEMENTS

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6. REFERENCES


