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Parameters estimation using single phase measurement of three phase induction machine

Abstract. *In this paper a method for parameter detection through a single phase measurement in a three phase induction machine with broken rotor bars, is presented. Based on frequency response of the machine, the parameters can be obtained with only two measurements. In order to study the variation of these parameters with position of electrical rotor asymmetry a single phase measurement at standstill is proposed. Simulations and experimental measurements confirm the theoretical assumptions.*

Streszczenie. *W artykule przedstawiono metodę detekcji parametrów przez użycie jednofazowego pomiaru w trójfazowej maszynie indukcyjnej z pękniętym prętem wirnika. Wykorzystując odpowiedź częstotliwościową, parametry mogą być wyznaczone w dwóch pomiarach. W celu przebadania zmienności tych parametrów w zależności od elektrycznej asymetrii wirnika jednofazowy pomiar w stanie zatrzymanych jest przeprowadzany. Symulacje i pomiary potwierdzają założenia teoretyczne. (**Estymacja parametrów przy użyciu jednofazowego pomiaru trójfazowej maszyny elektrycznej**)*

Keywords: Broken rotor bars, Induction machines, Parameter measurement.
Słowa kluczowe: pęknięte pręty wirnika, maszyny indukcyjne, pomiar parametryczny

Introduction

The induction machine parameters are typically obtained from no-load, rated load and short circuit (locked rotor) measurements [1]. The drive is usually supplied with symmetrical three phase voltages that contain only first harmonic. Such measurements give precise machine's parameters only for symmetric machines. In case of machine's electrical asymmetry due to the broken rotor bars [2, 3, 4] the usual measurements do not give accurate machine parameters.

Many already developed mathematical models of induction machine with broken rotor bars are complex as they model the internal states of induction machine in great detail either by using high number of differential equations [5, 6] or even by finite element analysis (FEA) [7, 8] to correctly model the magnetic circuit of the machine. The parameters for these kinds of models can only be obtained either analytically or by FEA simulations.

Newly introduced simplified two axes model of induction machine with rotor fault [9], allows us to obtain the parameters either via FEA or through measurements. It has been designed based on the assumption that, in case of rotor asymmetry due to cracked or broken rotor bars, the rotor parameters in each coordinate differ, thus introducing some sort of saliency. Consequently, measured from the stator side, these parameters will vary with the rotor angle.

Traditional methods mentioned above can hardly measure this dependence with synchronously rotating field and rotor running at the mechanical speed. Therefore, a new approach that can effectively substitute a short-circuit and no-load test, has been proposed.

The method for parameter estimation presented in this paper supplies the drive with only one phase voltage keeping the rotor locked, without a need for outer stiffness. By changing the rotor alignment a dependence of the machine parameters on rotor angle can be obtained. Measured parameters are intended for a simplified induction machine dynamic model, which also considers electrical asymmetry of the rotor, thus proving the occurring saliency of the rotor.

Theory

Figure 1 shows the well-known single phase equivalent circuit of an induction machine. Usually the measurements are made at no-load when a slip value is practically zero and almost all of the stator current flows through the magnetizing inductance thus substitute inductance becomes $L \approx \sigma_s L_m + L_m$ and substitute resistance $R \approx R_s$. At standstill (short circuit) the slip equals one and most of the current flows through the rotor branch thus $L \approx \sigma_s L_m + \sigma_r L_m$ and $R \approx R_s + R_r$.

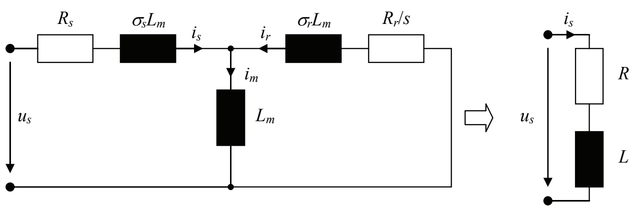


Fig. 1. Single phase equivalent circuit of induction machine.

As the rotor with broken rotor bars exhibits electrical asymmetry, measurement in a rotating magnetic field or with a rotating rotor in a non-rotating field cannot yield the dependence of machine parameters on rotor angle. The only way to obtain the parameters of the asymmetrical machine is with locked rotor and non-rotating magnetic field. In order to get enough data to calculate all the machine parameters two measurements must be made.

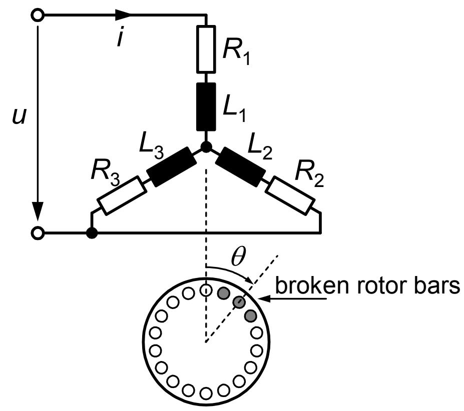


Fig. 2. Single phase measurement of machine parameters at standstill (assuming 2-pole machine).

As already mentioned, the only way to obtain the parameters of the asymmetrical machine is by measurement with a standstill rotor and a stationary sinusoidal magnetic field. This way, torque is not generated and locking of the rotor is unnecessary. The stator windings are supplied with one phase voltage only, where rotor angle (θ) is defined as the angle between the axis of stator field and the axis of rotor fault. Measuring of the parameters at different rotor angles should give the dependence of the parameters on rotor position (Fig. 2).

No-load measurement introduces a nearly zero slip into the impedance equation, thus isolating the parameters to only the stator side. At this operating point, the rotor and synchronous speed are almost equal. The idea of the presented approach is to supply the motor with a stationary field at a very low frequency assuming a fixed rotor. Thus, both the field and rotor speed become almost zero, yielding zero slip – corresponding to a no-load condition, with substitute parameters as defined above.

Since the machine in this case is already at standstill, when supplied with higher frequency voltage most of the current flows through rotor, thus emulating locked-rotor measurement. Therefore, the one-phase measurement at low- and high-frequency supply voltage subsitutes the usual no-load test and locked rotor test, respectively. Figure 3 shows the frequency response of the analyzed induction machine with a healthy rotor.

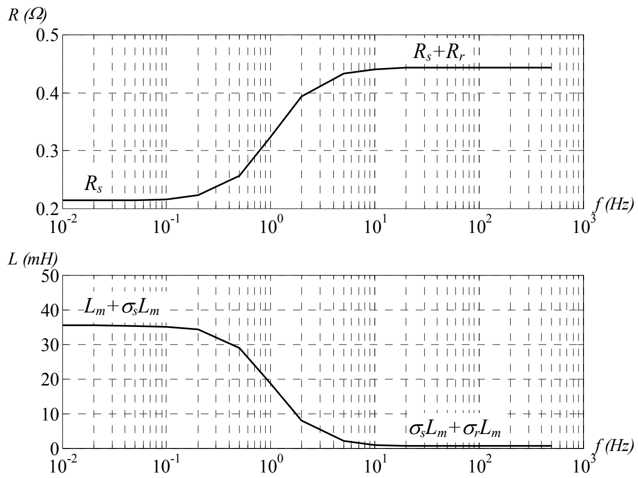
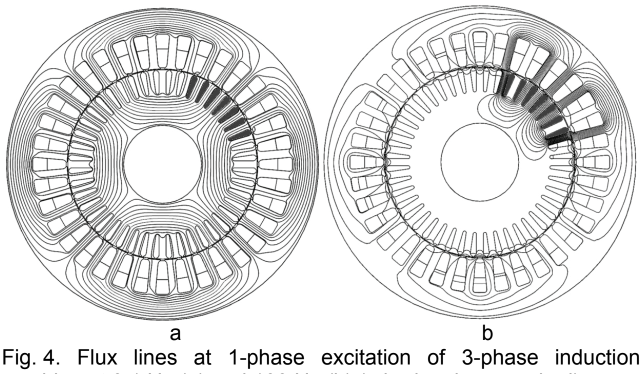


Fig. 3. Frequency response with single phase supply.

Simulations

Using a 2D FEA, a case study of different rotor asymmetries due broken rotor bars was analyzed and machine parameters were calculated at different rotor angles. Results of FEA were used for comparison with measured data and to compute parameters or investigate the operating conditions that cannot be achieved or measured on a real induction machine. Broken bars were modeled as non-conducting bars in a squirrel cage where all bars are connected in parallel.



a b

Fig. 4. Flux lines at 1-phase excitation of 3-phase induction machine at 0.1 Hz (a) and 100 Hz (b) (7 broken bars marked).

Due to a 2D model the stray inductances of windings' heads were neglected. A frequency domain solver was used to analyze this configuration, while stator windings were supplied by the same current as in measurements. As can be seen in Fig. 4 the impact of broken rotor bars is significant only at high frequency. In order to emphasize the effect, an almost exaggerated case of seven broken was considered.

Calculated values of substitute resistance and inductance are shown in Fig. 5. In this case the windings are supplied with low frequency current (0.1 Hz). There is a slight variation of resistance due to rotor (fault) position, while the substitute inductance ($\sigma_s L_m + L_m$) is practically constant irrespective of rotor angle. We can deduce that total stator inductance (consisting of stator stray and magnetizing inductance) does not depend on the damage level of the rotor.

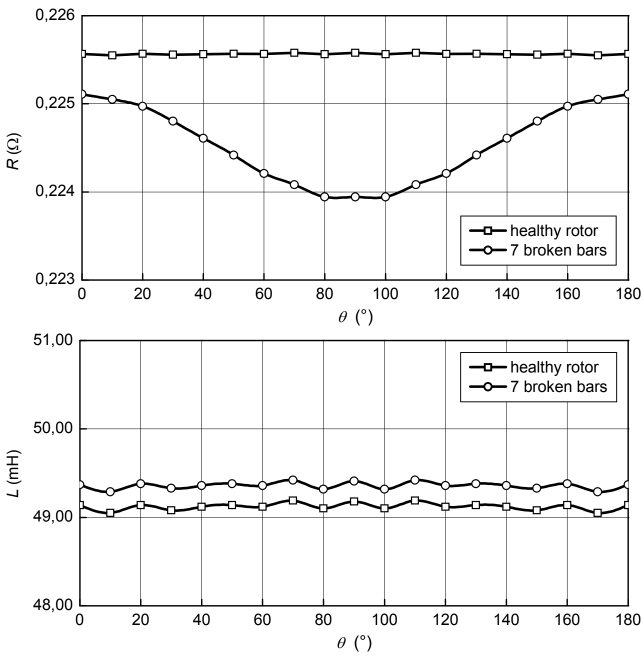


Fig. 5. Calculated resistance and inductance at 0.1 Hz versus rotor position for healthy rotor and rotor with 7 broken rotor bars.

When the motor is supplied with a high frequency current we can observe that the substitute resistance (in this case $R_s + R_r$) is constant for the healthy rotor, while for the rotor with seven broken bars the resistance variation has sinusoidal profile with a period which is half of a pole pair period (Fig. 6). Also, minimal substitute resistance of a motor with broken rotor bars is somewhat higher than with healthy rotor. The substitute inductance ($\sigma_s L_m + \sigma_r L_m$) is also constant for a healthy machine and has similar sinusoidal profile for the machine with broken rotor bars. Since we have concluded before that stator stray inductance is not affected by the rotor damage, the sinusoidal profile is owed only to rotor’s stray inductance.

The reason for the calculated resistance and inductance profile not beeing completely sinusoidal is the fact that, due to simplicity, a 2D FEA model was used and the effect of a skewed rotor was not taken into account. Rotor teeth and slots consequently form a magnetic saliency which has influence on the resultant profiles. Since the main goal was to show how and how much the rotor faults effect the motor parameters, the obtained results entirely cover our expectations.

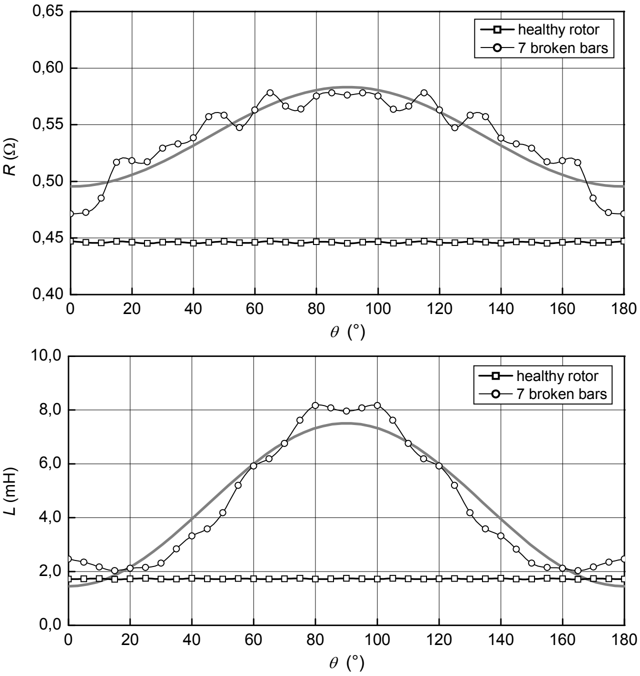


Fig. 6. Calculated resistance and inductance at 100 Hz versus rotor position for healthy rotor and rotor with 7 broken rotor bars.

Analyses of motor with smaller number of broken rotor bars give following results (Fig. 7) where saliency diminishes with smaller number of broken rotor bars as expected.

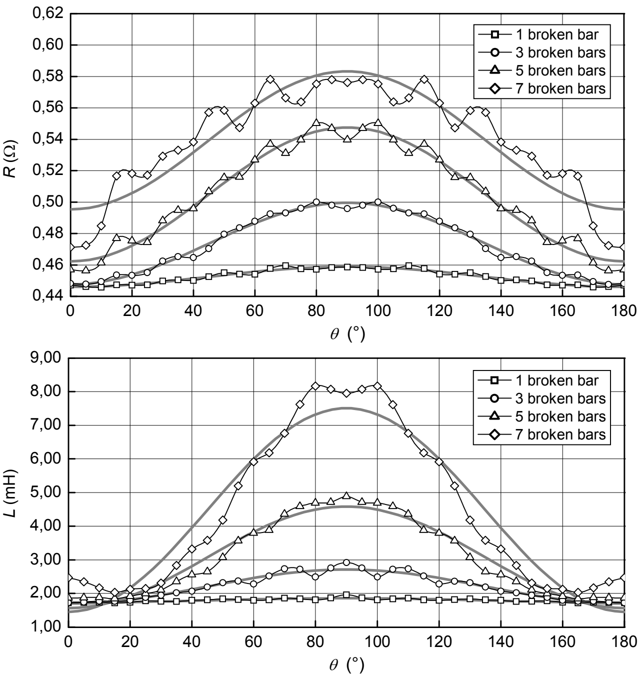


Fig. 7. Calculated resistance and inductance at 100 Hz versus rotor position for motor with 1, 3, 5 and 7 broken rotor bars.

For further use in dynamic models of induction machine both parameters can be decoupled into their components in a rotor reference frame. Observing the dependency of direct and quadrature resistance and inductance on the number of broken rotor bars (Fig. 8), we can see that direct and quadrature resistance increase approximately linearly, although direct resistance has much smaller slope. On the other hand quadrature inductance increases much faster while direct inductance remains the same.

From the presented results, a logical conclusion can be drawn. Namely, the sinusoidal dependence of inductances on the rotor position, being limited to rotor stray inductance only, doesn't have a significant impact on the motor behaviour (at least not in steady state). The main influence on the alteration of the behaviour of the motor with a damaged rotor is due to rotor resistance change.

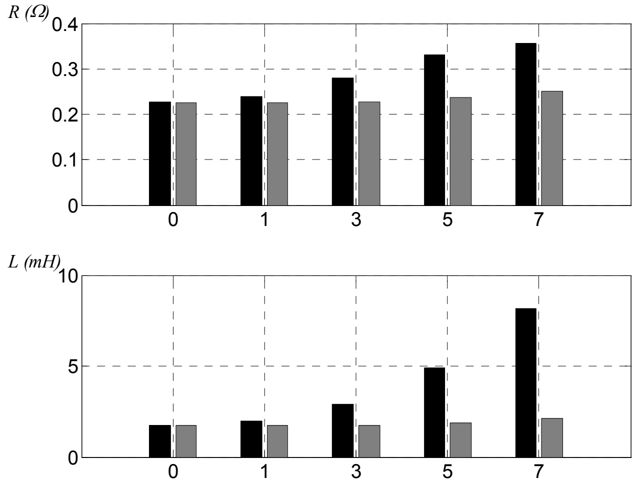


Fig. 8. Direct (grey) and quadrature (black) resistance and inductance depending on the number of broken rotor bars.

Experimental Result

Experimental measurements were made with variable frequency voltage/current source and oscilloscope. Measurement principle was already described in Fig. 2. Substitute resistances and inductances were calculated from phase angle between impressed phase voltage and phase current, and their amplitudes. As expected from simulation results, broken rotor bars do not have significant impact at low supply frequencies (Fig. 9).

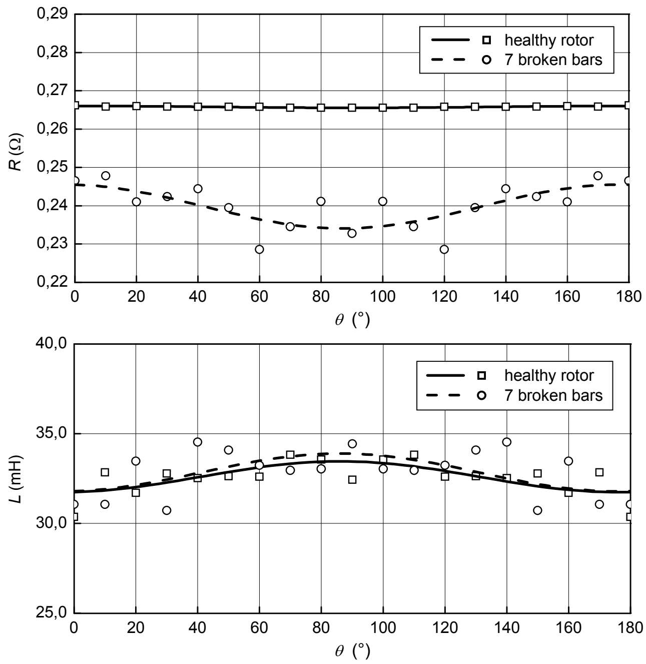


Fig. 9. Measured resistance and inductance at 0.1 Hz versus rotor position for healthy rotor and rotor with 7 broken bars.

The stator resistance is around 240 mΩ while stator inductance is around 33 mH. Note that measurement at 0.1 Hz is quite difficult and cannot be very precise (especially measurement of a phase angle). Dictated by the need for a zero slip measurement and yet by impressing sinusoidal stator quantities (needed for impedance determination) with extremely low voltage and current frequency, the phase angle measurement is subject to a lot of difficulties. Also note that for one period of supply voltage a minimum time for measurement is 10 s.

At higher frequencies we can observe the same sinusoidal profile that was evident from simulations (Fig. 10). While there are some discrepancies in the offsets as well as in magnitudes between simulations and measurements (Fig. 6, Fig. 10) they could be attributed to simplified simulation model (only 2D simulation, no skewing of rotor bars, neglected stray inductance, …).

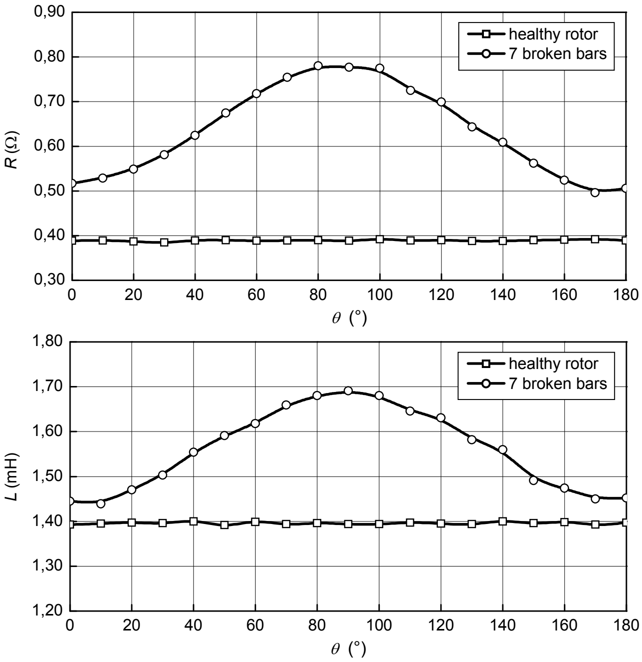


Fig. 10. Measured resistance and inductance at 100 Hz versus rotor position for healthy rotor and rotor with 7 broken rotor bars.

Conclusion

The paper showed that induction machine with broken rotor bars exhibit a sinusoidal distribution of inductance and resistance. Based on this knowledge, a simplified (linear) *dq*-axis model for observation of such machines under transient conditions could be derived.

Due to difficulties of traditional measurement methods in determining the above mentioned dependence of rotor parameters on the rotor angle, a new simple measurement procedure had to be developed. Comparison with data obtained through simulations show a good match between data obtained by measurement and simulation.

Appendix

Manufacturer's data of the applied induction machine is presented in Table 1.

Table 1. Rated parameters of induction machine.

P	3 kW	R_s	0.214 Ω
U_s	177 V	L_s	35.4 mH
I_s	14.8 A	R_r	0.231 Ω
n	1456 rpm	L_r	35.0 mH
T	20 Nm	L_m	34.1 mH

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