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Induction Machine: Comparison of Motor and Generator Characteristics

***Abstract**. The aim of this paper is to present the difference of induction machine electromechanical characteristics in motor and generator operating modes. Firstly, the paper presents analytically derived equations, which are based on equivalent circuit and are used for calculation of induction machine breakdown torque. Secondly, a comparison of calculated and measured characteristics in motor and generator operating modes is presented. Results of torque characteristics measurements, temperature rise tests and load tests are also provided. Finally the difference between the calculated and the measured results is commented on and explained in detail.*

***Streszczenie.** Celem artykułu jest zaprezentowanie różnicy charakterystyk elektromechanicznych maszyny indukcyjnej pracującej w trybie silnika i generatora. W oparciu o model matematyczny i wyniki badań przedstawiono charakterystyki – momentu, temperatury i obciążenia. (**Maszyna indukcyjna – porównanie charakterystyk w trybie generatora i silnika**)*

Keywords: induction machine, motor, generator, analytical calculation, measurements
Słowa kluczowe: maszyna indukcyjna, silnik, generator

Introduction

In some electrical drives the induction machine can operate as a motor and as a generator (for example: elevators, electric vehicles, pumped storage power plants etc.). In such drives the key question is which nominal power of the induction machine is the right one. Namely, the nominal mechanical power written on the nominal plate of an induction motor is not the same as in a generator mode of operation. The reason lies in the shape of torque characteristics of the induction machine. Breakdown torque is not the same in motor and generator modes. Normally the generator breakdown torque is two to four times greater than the motor breakdown torque. The slope of torque characteristics is therefore also not the same in both modes. For the same torque value the generated rotor losses in the generator mode of operation are significantly lower than in the motor mode of operation. Consequently, the nominal power of the same induction machine in the generator mode of operation can be significantly higher than in the motor mode of operation.

Engineers and researches use different models and techniques for designing electrical machines which include magnetically nonlinearities of iron core [1, 2]. Ordinarily they use numerical or analytical approach, sometimes both of them [3-5]. This work provides an explanation of the analytical approach for the calculation of induction machine's characteristics in motor and generator modes of operation. This paper focuses on key equations for the calculation of breakdown torque based on induction motor's equivalent circuit [4, 6] and the calculation of all electrical and mechanical values at nominal power.

Induction machine torque characteristics – theoretical background

Induction machines can operate in different modes according to the torque characteristic. There are three known operating modes: breaking mode for slip values between ∞ and 1, motor mode for slip values between 1 and 0, and generator mode for slip values between 0 and $-\infty$. All three operating modes are as part of torque characteristic shown in Figure 1.

During the operation of the induction machine power losses generation is reflected in temperature rise, which can be different for motor and generator modes of operation. Direction of energy flow and the corresponding Sankey diagram, including power losses presentation, are shown in Figure 2.

In the process of designing an induction machine it is very important to calculate precisely the electrical and mechanical values in the breakdown torque point. The latter can be calculated with equation (1), which is deduced based on the equivalent circuit [6] of the induction motor (Figure 3):

$$T_b = \pm \frac{m_s\, p}{\omega} \frac{U_s^2}{2D} \tag{1}$$

where the operator $\pm$ enables the calculation of the breakdown torque in the motor mode (the + sign) and in the generator mode (the – sign), m_s is the number of stator winding phases, p is the number of pole pairs, U_s is the stator winding voltage, ω is the angular frequency and the denominator D represents:

$$\begin{aligned} D = &\pm\left((R_s - \chi_2 X'_{\sigma r})\chi_1 + (X_{\sigma s} + \chi_1 X'_{\sigma r})\chi_2\right) + \\ &+ \chi\sqrt{(R_s - \chi_2 X'_{\sigma r})^2 + (X_{\sigma s} + \chi_1 X'_{\sigma r})^2} \end{aligned} \tag{2}$$

In equation (2) the sign $\pm$ dictates the solution of the quadratic equation and the local extremes of the torque characteristic, where elements χ_1, χ_2 and χ represent the correction factors for the calculation of the breakdown point:

$$\chi_1 = 1 + \sigma_s + d_1 \tag{3}$$

$$\chi_2 = a_1 - b_1 \tag{4}$$

$$\chi = \sqrt{\chi_1^2 + \chi_2^2} \tag{5}$$

In equation (3) σ_s is the factor of stator leakage, described by (6):

$$\sigma_s = \frac{X_{\sigma s}}{X_m} \tag{6}$$

and a_1, b_1 and d_1 are the corresponding proportions obtained from the equivalent circuit:

$$a_1 = \frac{X_{\sigma s}}{R_{Fe}} \tag{7}$$

$$b_1 = \frac{R_s}{X_m} \tag{8}$$

$$d_1 = \frac{R_s}{R_{Fe}} \tag{9}$$

Equation (1) and the corresponding formulas of elements from equations (2) to (9) enable an analytical calculation of breakdown torque values.

Tested induction machine

In this paper the small squirrel cage induction machine with nominal power 5.5 kW and shaft height of 132 mm according to IEC was used. The induction machine was designed for a small bio-gas power plant where a gas motor is used as a turbine. The tested machine works in power plant as induction generator and is water-cooled with the temperature of water between 50 and 60 degrees Celsius and a corresponding flow of approximately 8 l/min. The water cooling system is spiral shaped and built into the stator housing. The induction machine is designed and built for an F insulation class. Thus a standard stator and rotor lamination with a combination of 36/48 slots made by lamination manufacturer Kienle + Spiess GmbH (IEC 132-4 1248) is used as the basis for the construction. Figures 4a and 4b present the shapes of the stator slot and the rotor slot respectively. The stator and rotor lamination are made from steel material M700-50A, which has 5.7 W/kg of specific core losses at 1.5 T.

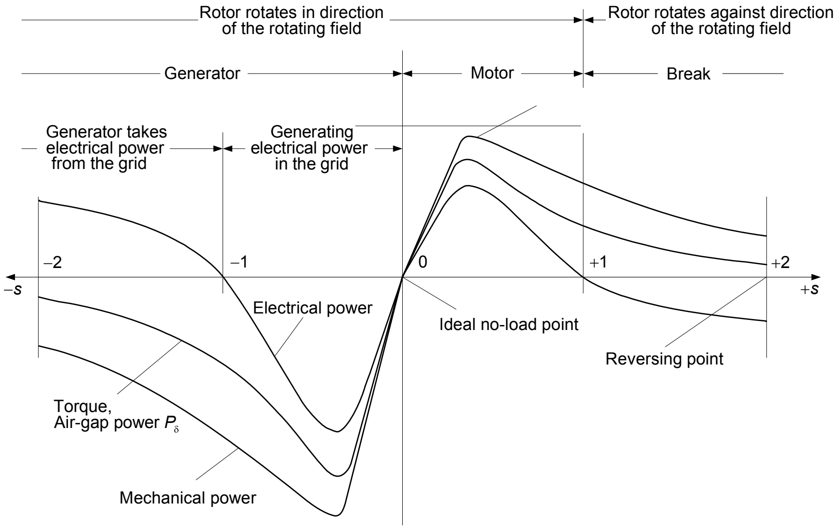

Fig.1. Induction motor torque and power characteristics

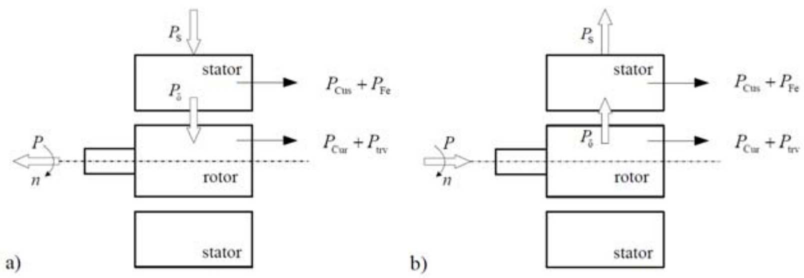

Fig.2. Energy flow Sankey diagram: a) motor mode, b) generator mode

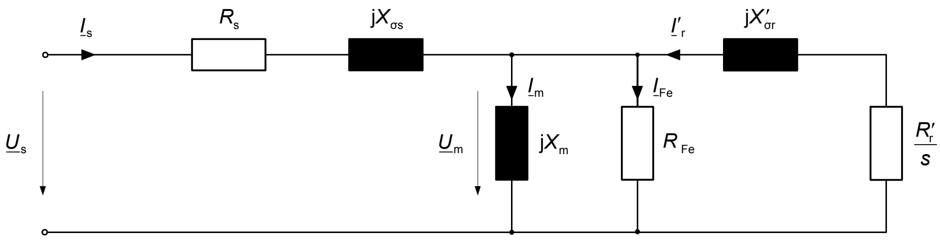

Fig.3. Induction motor equivalent circuit

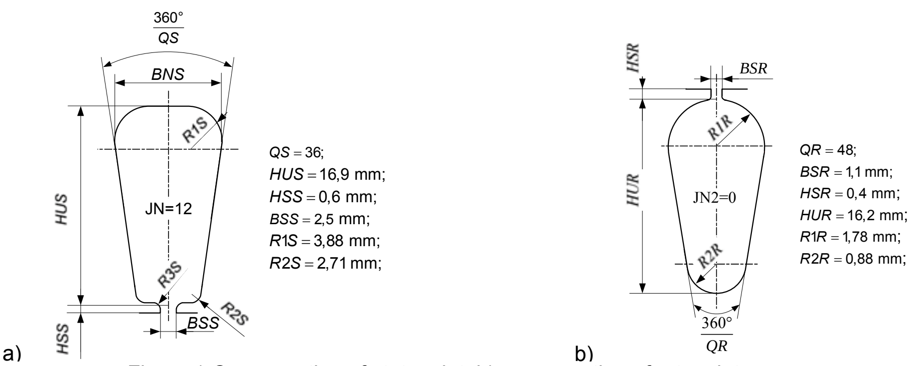

Fig.4. a) Cross-section of stator slot, b) cross-section of rotor slot

Table I. Values in the motor mode, power 5.5 kW, voltage Y 400 V and winding temperature 95 °C

I (A)	$\cos\varphi$	η	n (min^{-1})	T_N (Nm)	T_b (Nm)	P_{loss} (W)
11,18*	0,905	0,785	1420	37	88	1500
10,63	0,909	0,821	1419	37	89	1200

Remark: * measured results

Table II. Values in the generator mode, power 5.5 kW, voltage Y 400 V and winding temperature 95 °C

I (A)	$\cos\varphi$	η	n (min^{-1})	T_N (Nm)	T_b (Nm)	P_{loss} (W)
9,95*	0,801	0,825	1556	41,3	365	1140
9,49	0,845	0,864	1560	39,3	233	875

Remark: * measured results

Comparison of measured and calculated results

All presented measurements in this paper were performed by classical induction machine measurement system shown in Figure 5. It consists of tested induction machine mechanically connected by clutch with active load machine, which one is speed controlled by converter via position sensor. Tested induction machine torque is measured via force sensor by reaction method. All electrical and mechanical values of tested induction motor are measured by power analyzer which ones via GPIB interface send measured results to personal computer where analysis of measured data is performed.

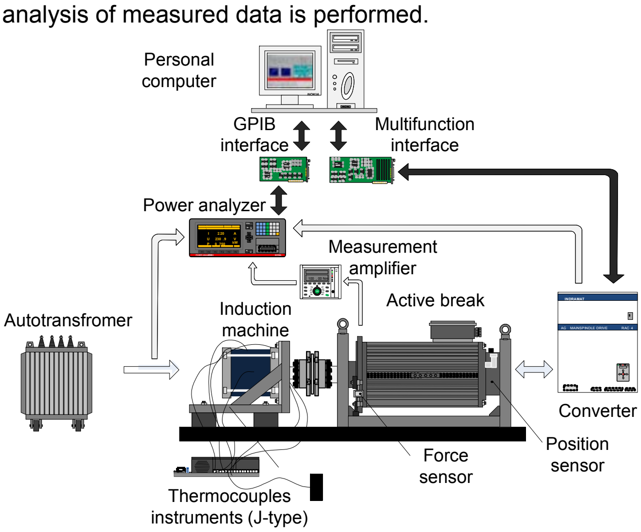

Fig.5. Measurement system

For temperature measurement the J-type thermocouples with corresponding instruments were used. Distribution of the thermocouples inside and on the surface of the induction machine housing is shown in Figure 6.

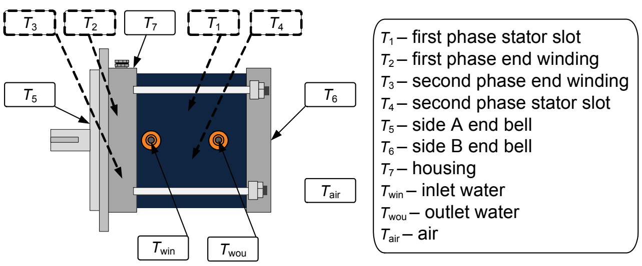

Fig.6. Measurement of temperatures on motor's housing

Figure 7 shows the measured and the calculated torque and current characteristics of the tested induction machine with nominal power 5.5 kW. From the presented characteristics it is evident that the breakdown torque in the generator mode is greater than the breakdown torque in the motor mode. From the measurements we obtain 88 Nm (at ≈ 1050 rpm) breakdown torque of the machine in the motor mode and in the 365 Nm (at ≈ 2170 rpm) breakdown torque in the generator mode, i.e. with slip $s = 0{,}3$ or $s = -0{,}47$. It turned out that the measured breakdown torque in the generator mode is about 4 times larger than in the motor mode.

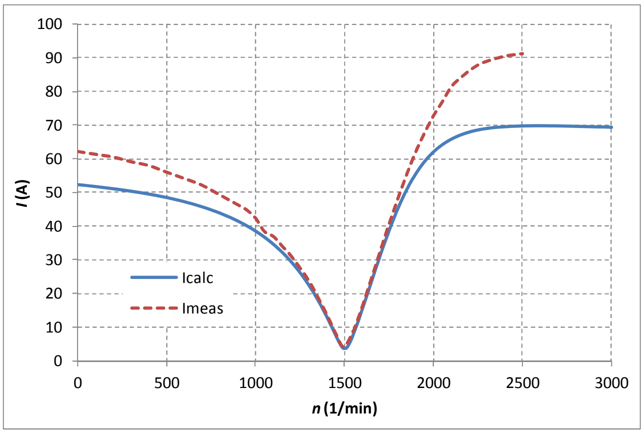

Fig.7. Measured and calculated current characteristics

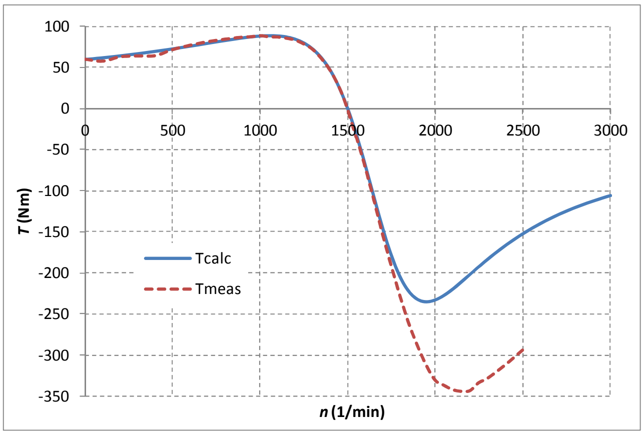

Fig.8. Measured and calculated torque characteristics

To calculate the characteristics of the three-phase induction machine, we used the emLook software, which enables "click calculation" of characteristics. The calculation software package uses a standard equivalent circuit (Figure 3) stated in IEC 60034-28 as a basis. The measurement and the calculation (with emLook) results for the machine are provided in Table I for the motor operation mode and in Table 2 for the generator operation mode.

A comparison of the measurement and the analytical calculation data shows a significant difference between the two in the generator breakdown torque. The measured breakdown torque in the generator operating mode is about 4 times larger than in the motor operating mode. An analytical calculation of the breakdown torque with equation (1) for equivalent circuit (Figure 3) however returns only a

2.6 times higher value for the generator than for the motor. There are several reasons for the much higher measured value of the breakdown torque T_b than the calculated value (Table II). The main reason is that the analytical calculation (emLook) in generator mode does not correctly take into account the real reduction of leakage reactance for the basic harmonic of the magnetic field. This is due the higher current in the rotor, which has as a consequence higher local saturation in slot bridges. The motor thus has the measured current in the breakdown point $I_b \approx 36$ A, and the generator $I_b \approx 96$ A; the increase is about threefold. The leakage reactance is the same in the analytical calculation for motor and for generator both in the nominal and the breakdown operation points. This is the main reason for the difference between the measured and the calculated results. Another increase of the breakdown torque in generator operation mode is the consequence of the influence of higher harmonics, which are being deduced in generator operation, i.e. added to the negative torque of the basic harmonic for the generator, thus absolutely increasing it.

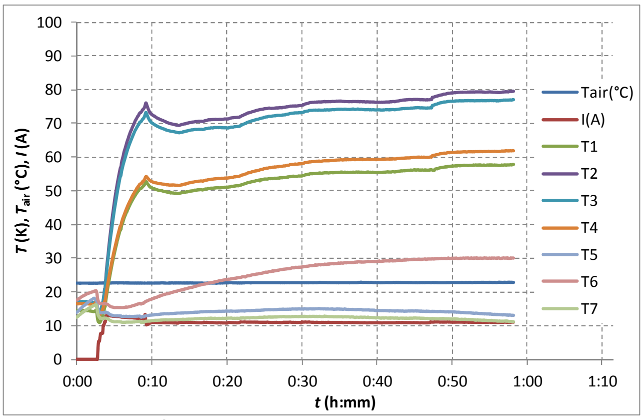

Fig.9. Results of temperature rise test in motor operation mode: nominal power 5,5 kW (mechanical output power)

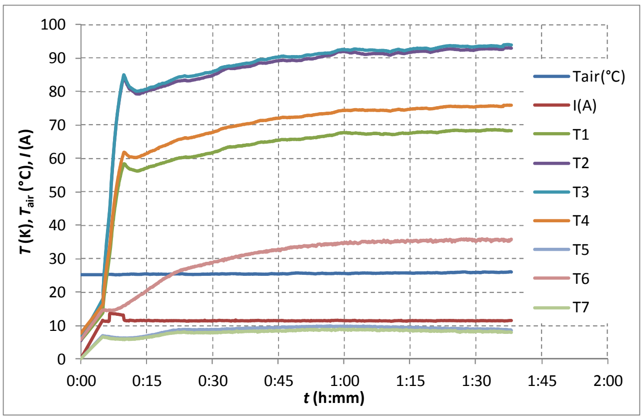

Fig.10. Results of temperature rise test in generator operation mode: thermal power 6,6 kW (electrical output power)

Because of a much higher torque characteristic in generator operation mode the losses of the machine are lower at the same output power. At the same load current and the same cooling conditions the output power in generator operation mode is for the presented machine 6.36 kW or by 15.6% higher than in the motor operation mode with 5.5 kW of power. The thermal power was approximately 6.6 kW at the incoming water temperature 50 ºC and flow of 8.3 l/min for F insulation class. Results of temperature rise tests for motor and generator operating mode are presented in Figure 9 and 10.

Conclusion

The paper presents an analytically equation for calculation of induction machine breakdown torque in motor and generator operating modes. Special emphasis is given to the comparison of machine characteristics in motor and generator modes, including a comparison of calculated and measured results for load conditions and torque characteristics. The differences between the calculated and the measured results are commented on and explained in detail. From calculated and measured results is obviously seen that the induction machine is able to operate in generator mode with much higher power than in motor operating mode. Reason lies in higher efficiency and lower power losses of generator which is reflected as lower heating in comparison with motor.

The main focus of future research will be the calculation of torque characteristics and magnet circuit and equivalent circuit parameters of an induction machine with finite element method in order to improve the analytical approach.

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