

DETERMINATION OF THE EFFICIENCY OF INDUCTION MACHINE USING FIVE TESTED MACHINES.

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Abstract

Induction machines are mostly used as a motor but the manufacturer's catalogue only mentions the motor efficiency values with no mention of values for generator mode. The paper uncovers that nevertheless induction machines can be used either in motor or generator mode, the efficiency curves for these modes are not necessarily the same. Several high- and low-efficiency induction machines with different power rating are compared for motor and generator mode. These experiments show that depending on the machine's design, and thus also efficiency class, the efficiency for motor and generator mode can differ significantly. Special attention will be paid to differences between copper and aluminium rotors. In the paper the underlying phenomena causing this effect are elucidated. It can be concluded that the machines with lower stator and a non-saturated core, typical characteristics for high efficiency or machines with a high power rating, will have comparable efficiencies in both generator and motor mode. This is not the case for low power rated low efficiency machines, where the efficiency for generator mode can drop several percent. Whether for an induction motor or a generator, an efficiency increase of just one percent can represent a considerable economic benefit over the whole life-time.

Keywords: *Motor efficiency, induction machines, motor and generator mode, energy efficiency, motor and generator losses.*

1.0 Introduction

The work studies the standardized energy efficiency of induction machines in motor and generator mode. More specifically, the focus lies on how different design and material choices, intended to increase the energy efficiency, influence the performance in these two operating modes. In this context, four 7.5 kW and one 30 kW four pole, 50Hz, 230/400V, TEFC induction machines were tested. The first machine is a classical, commercial eff3 machine. It has a classical construction with an aluminium rotor cage and the laminations of stator and rotor are realised with standard steel. This machine is labelled SSAL (standard steel aluminum). For the second machine, the aluminum cage is replaced by a copper one. This machine has the same electrical steel, dimensions, winding, etc. it is labelled SSCU (standard steel copper). The third machine is labelled, PSCU (premium steel copper). For this machine, with respect to the second one, the standard steel is replaced by a premium steel.

The fourth machine is a commercial eff1 machine, labelled EFF1_7.5kW (high efficient). It is produced by a different manufacturer as the first three prototypes. This machine has a different design (e.g. a higher stack length), an aluminum rotor cage and different premium electrical steel. The fifth machine (EFF1_30kW) is produced by the same manufacturer as the fourth one. It is a premium efficiency 30 kW machine

In the context of the various worldwide efforts and initiatives towards a more efficient use of energy, there is an increased focus on energy efficiency. Therefore it is important to know the behaviour of the induction machine for each load condition in motor mode, as well as for generator mode. Not only for the idealized, standardized test conditions with specific voltage supply conditions and operating temperatures, but also for the distinct behaviour under practical operating conditions [1]. In this paper, the energy efficiency for both motor and

generator mode is assessed, though only for standardized conditions.

2.0 Energy Efficiency Determination

For the determination of the efficiency of induction machines, there exist different standards world wide. Different efficiency values are obtained for the same machine from the same test depending on which standard is taken as the basis of efficiency determination. These differences and other relevant aspects are well documented in literature [1-6]. It is the intention of this project to compare the motor and generator mode efficiency of induction machines and to assess the impact of material choice on this mutual relation. The results will only be compared relatively to each other, with focus on differences between motor and generator mode and not on differences between the separate machines. If each test would be performed for the same boundary conditions, such as atmospheric and supply voltage conditions, it would be sufficient to utilise the direct efficiency based on P_{out}/P_{in} .

In order to explain the different behavior of the machines in motor and generator mode for different design and material choices, the different loss components have to be determined. Therefore, the IEEE standard 112-B was adopted. The measurement equipment was in compliance with the standard and all parameters were recorded by a Labview[®] based data acquisition system.

2.1 Efficiency for motor and generator mode based on IEEE112-B

In IEEE 112-B the determination of the efficiency of an induction machine is based on the segregation of losses. The windage and friction ($P_{fr,w}$) and core losses (P_{Fe}) are considered to be constant for the whole working area and are determined by the practical no load test. These losses are assumed the same for generator and motor mode. The stator losses can be calculated by the same equation ($R_{stator} \cdot I_{stator}^2$). Rotor losses are equal to a slip fraction of the electromagnetic power that crosses the air gap. This air gap power can be calculated with (1) and (2):

$$\rightarrow \text{motor: } P_{airgap} = P_{el} - P_{stator} - P_{Fe} \quad (1)$$

$$\rightarrow \text{generator: } P_{airgap} = P_{el} + P_{stator} + P_{Fe} \quad (2)$$

The difference in stator and rotor losses for generator mode compared to motor mode are explained by the equivalent scheme and the assumption that the active electrical power is kept the same for motor and generator mode. In motor mode the core losses are supplied by the grid, in generator mode by the mechanical driver. However, the reactive power to magnetize the machine always comes from the grid. A SEIG (self excited induction generator) gets its reactive power from a capacitor bank. Here only grid-connected generators are considered.

For motoring (Figure 1), the stator current and thus the stator voltage drop, increase with load. Consequently, the air gap voltage (induced voltage or emf), i.e. the voltage determining the air gap flux, decreases a little and so do the magnetizing current and the core losses.

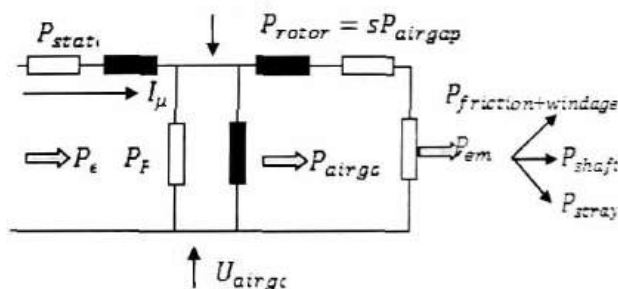


Fig. 1: Motor losses and IEEE based power flows indicated on equivalent scheme.

In generator mode (Figure 2) on the contrary, the air gap voltage will increase due to the stator voltage drop. This requires a higher magnetizing current and consequently core losses will increase. This increase can be significant when the machine is already in saturation at no load and the effect is more severe if the stator resistance is not negligible.

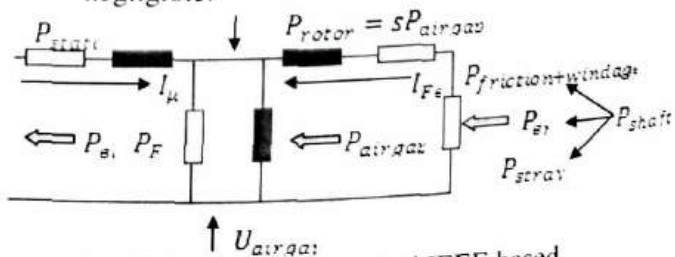


Fig. 2: Generator losses and IEEE based power flows indicated on equivalent scheme.

Based on the assumption of equal active electrical power (Figures 1 & 2), the stator losses in generator mode will be larger than in motor mode because the stator current will be more reactive due to the increase of the magnetization current. The rotor losses seem to increase due to the higher air gap power but the slip should also be considered. One could conclude that the efficiency in generator mode will always be smaller, but for generators the output power is $1/\eta$ motor higher compared to the output power of the motor since we assume equal electrical power. As a consequence the losses are allowed to rise with the same amount before the efficiency of the generator is indeed smaller than in motor mode.

In the context of induction machine efficiency measurement standards, this load dependency of the iron loss is very important. This is because of the fact that if losses are over or underestimated, this can be corrected by the influence this has on the determination of the additional losses. Standards that use an estimate, fixed value or percentage for the additional losses can not account for this. So that 'mechanism' is lost. This is especially the case for machines with non-negligible stator resistance and/or bad magnetic properties, i.e. small motors in general. This also explains why in general the standards based on indirect efficiency measurement overestimate the motoring efficiency for smaller machines and underestimate the efficiency of larger motors [6]. This would also have implications for the comparison between motor and generator mode and therefore, a direct method is applied here.

2.2 Test setup and Measurement Routine

A dc-machine is used to drive the induction machines in generator mode or to load it in motor mode. The torque is measured with a classic torque transducer. The electrical power, voltages and currents are directly measured using a Power Analyser. The measurement equipment is in compliance with the standard and all parameters are recorded by a Labview ® based data

acquisition system. The further processing of the data is automated, based on a Microsoft® Excel spreadsheet.

The IEEE standard 112-B recommends performing measurements at rated temperature and permits a temperature difference of 10K during the load test. Therefore, for every test the same measurement routine is followed. Each time, the temperature of the machine is stabilised by running the machine at rated conditions before the test starts. For almost the same boundary conditions, the surrounding temperature in the lab for each test was between 24 and 26 degrees Celsius, the end-winding temperature is monitored. When a generator test is to be performed, the machine is stabilised in this operating mode. For each run an equal number of load conditions are recorded in order to keep the test-run as short as possible and the temperature change limited.

3.0 Results

The standards for the determination of the efficiency of induction machines are based on the segregation of losses. The rotor losses are determined based on the airgap power, calculated from the electrical power. Therefore, in this paper, motor and generator mode (losses) are compared at the same electrical power. The efficiency characteristics of the five tested machines, based on the IEEE standard 122-B, for both motor and generator mode are shown in Figure 3.

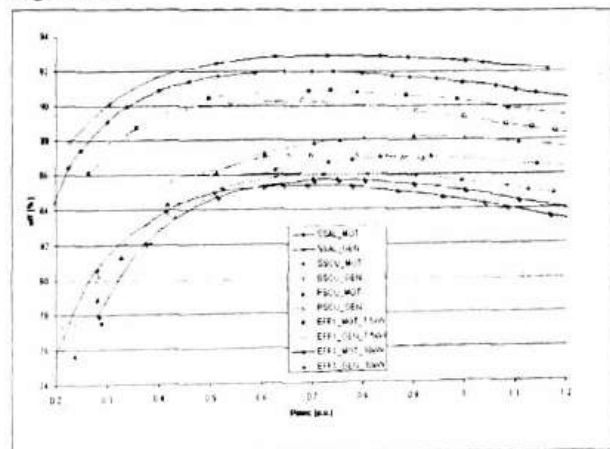


Figure 3: Motor and Generator Efficiency of the five machines according to IEEE 12-B.

However the conclusions are still valid since these two machines have a complete different design. First of all, the number of poles is different. Resulting in a different winding scheme and also the stator (and rotor) geometry, airgap length and stack length are different. This leads to a difference in stator resistance and magnetisation conditions. Indeed, the present machine has a higher stator resistance and also magnetically the machines are clearly different (Figures 4 & 5).

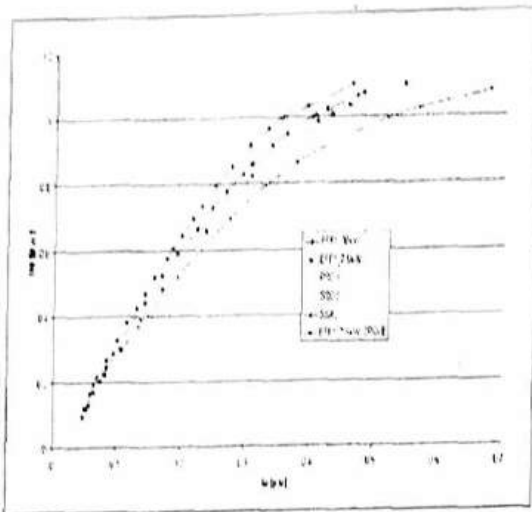


Figure 4: No load characteristics of the machines presented in this paper and of the two pole 7.5kW machine of [2]

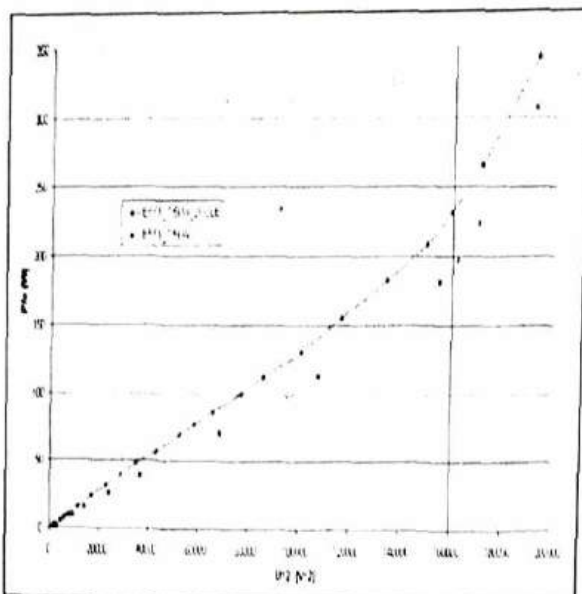


Figure 5: Comparison of the Iron Loss Characteristics for the 7.5kW motor of this test and that of [2]

Figure 4 shows the no-load characteristics of the five four pole machines that were tested in the context of this paper and also that for the 7.5kW two pole motor for which the generator efficiency was higher than the performance in motor mode. From this figure, it is not so clear yet that the magnetic situation in both machines is that different. Therefore, in Figure 5, the iron losses are plotted as a function of voltage squared. From this figure, it is clear that the rated airgap voltage of the machine studied in this paper is located before a pronounced bend in the characteristic. If the airgap voltage increases, the iron losses will increase more than proportionally. This is not the case for the other 7.5kW machine. This effect, combined with the different stator windings, makes that the efficiency situations for motor and generator mode do not correspond.

3.1 Large Machines

Machines of higher power ratings are said to have negligible stator resistance and also magnetisation problems would not be an issue. The efficiency of large induction generators should therefore be comparable with the efficiency they have in motoring mode [2]. From the results depicted in Figure 3, this can be confirmed. The efficiency in generator mode is even more than one percentage point higher than the motor efficiency. Taking into account the power rating, this is a considerable benefit.

This positive effect is based on the same mechanisms as described above and can be confirmed by taking a look at the different loss components. Therefore, the friction and windage losses are given in Table 1; the stator -, rotor - and additional losses of the machines tested in the context of this paper are depicted in the Figures 6 to 8 respectively.

Table 1: Friction and Windage Losses of the five motors

	SS	SS	PS	HE_7.5	HE_30
	AL	CU	CU	kW	kW
$P_{fr,w}$	32	39	41	19	207
[W]					

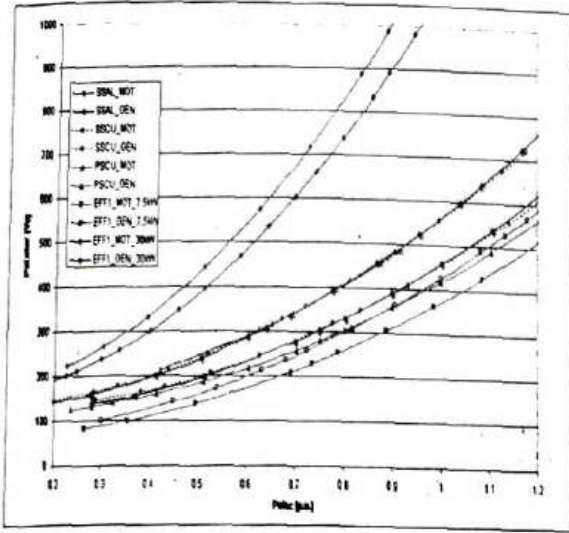


Fig. 6: Stator Losses for both motor and generator mode of the five tested machines.

For the 30kW machine, the combination of the 'magnetic advantage' and the negligible stator resistance make that relatively spoken, the stator losses are only 0.4% higher, whereas for the other machines, it is at least 1%.

The rotor losses are depicted in figure 7. For the 7.5 kW machines, these losses are significantly larger in generator than in motor mode.

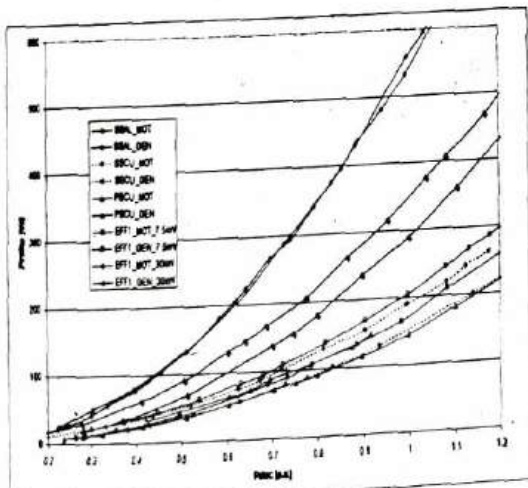


Figure 7: Rotor Losses for both motor and generator mode of the five-tested machines

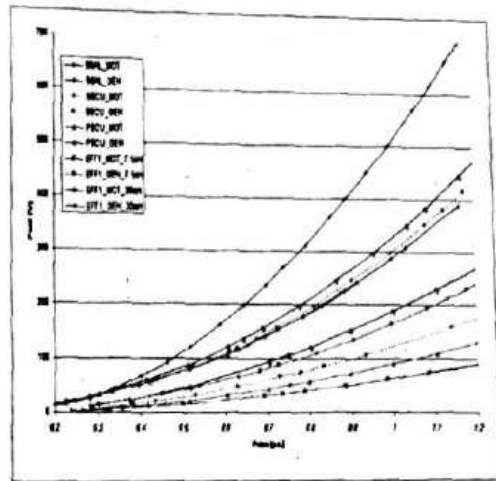


Figure 8: Additional Losses for both motor and generator mode of the five tested machines.

This is not only because stator and core losses must cross the airgap, but mainly due to the fact that these losses are much higher in generator than in motor mode due to saturation. But for the large machine, the rotor losses in generator mode are comparable. This has to be attributed to a decreasing slip: rotor losses are not only determined by the airgap power (equations 1 and 2; the airgap power in generator mode is higher), but also by the slip. Apparently, the stator resistance is not (yet — for large machines it would be —) negligible, causing a higher air gap voltage in generator mode; the flux in the machine increases. As a consequence, the required rotor current to produce the same electromechanical torque decreases, resulting in a lower slip. For machines with non-negligible stator resistance, the pull-out torque in generator mode is slightly higher than the pull-out torque in motor mode [7], again the same electromechanical torque can be produced at a lower slip. For the 30kW machine, there is a decrease of the slip due to the two preceding effects which seems to

compensate the increase of the airgap power. For the other machines, this is not the case.

On figure 8, the stray-load losses calculated according to IEEE 122-B are plotted. Stray load losses tend to decrease with rated power, but for the same rated power, a deviation of a few percent is found [1,4-6]. The determined stray load losses for the examined machines in motor mode are according to the results reported in [6,8]. In generator mode the large machine shows much lower stray load losses. Schwarz defined eight different stray load loss components. The origin of these different components are mainly airgap leakage (harmonic) flux and slot leakage flux and three of them are located in the rotor as extra rotor $1^2 R$ loss [9]. As was indicated above, for this machine, the electromechanical torque can be produced with a lower rotor current and a decreased slip, contributing to the lower value of additional losses.

4..0 New Materials

From Figure 3, it can be noticed that by applying copper rotor technology and premium electrical steel, the overall efficiency can be significantly improved, even without changing the design of the machine [3].

As with the other 7.5kW machines with aluminium rotor cage, the generator efficiency is worse than the motor performance. Also for these machines; the stator resistance and the (consequent) different magnetisation condition in generator mode make that the stator and the rotor losses are higher (Figures 6 and 7) compared with motoring condition.

For the SSAL and the SSCU machines, the stator losses for motor mode as well as for generator mode coincide; they have the same stator. For the PSCU motor, which has premium steel, in motor mode the stator losses are slightly lower, as was expected. However, in generator mode this is not the case, but this can be explained by the slightly worse permeability of the premium steel for induction levels over 1.2 Tesla [3]. The rotor losses (Figure 7) for the copper rotor machines are in general, also for generator

mode, significantly lower than for the machines with aluminium rotor.

Also in generator mode, the copper rotor cages seem to have a positive influence on the additional losses. They are still lower than the stray load losses for the generator mode of the SSAL machine. It should be noted that, as was explained above, the not constant part of the iron losses (that are treated as a constant part in equations 1 and 2) shows up in these additional losses. Compared with the aluminium rotor machines, the relative increase of the stray load losses from motor to generator mode for the rotor cage machines is slightly higher. This could explain the relative difference in motoring and generator efficiency.

5.0 Conclusion

The motor as well as the generator efficiency of five induction machines was determined according to the IEEE standard 112-B. This was with the intention to confirm earlier findings, and to investigate the effects of the application of copper rotor technology and premium electrical steel, especially with a focus on the different conditions between the two operating modes. Therefore, two commercial premium efficiency machines with aluminium rotor, one of 7.5 and one of 30 kW, and three prototypes of 7.5 kW, with different steel and/or rotor conductor material, were tested.

It can be concluded that machines with a low stator resistance and a non saturated core have comparable or even better efficiencies in both generator and motor mode. The measurements show that for premium efficiency machines, these conditions are not necessarily fulfilled. Depending on their design, they still can have a light saturated core and/or a non-negligible stator resistance.

For copper rotor machines, the efficiency for motor as well as for generator mode in general is higher than for aluminium rotor motors. Nevertheless, the difference in efficiency between motor and generator

mode is larger than for aluminium rotor motors and will be investigated further.

The efficiency value indicated on the nameplate of a machine doesn't say anything about the behaviour at partial loads, under practical operating conditions and for generator mode. In order to know the efficiency of specific operating conditions, it is recommended to indicate more machine parameters on the nameplate or even better, run a test for the specific circumstances.

References

- [1] W. Deprez, O. Gol, R. Belmans "Vagaries of Efficiency Measurement Methods for Induction Motors" (Energy Efficiency in Motor Driven Systems (EEMODS) Heidelberg, Germany, Sept.5- 8, 2005)
- [2] W. Deprez, A. Dexters, J. Driesen, R. Belmans, 2006, "Energy efficiency of small induction machines: comparison between motor and generator mode", ICEM 2006.
- [3] E. Chiricozzi, F. Parasiliti, M. Villani: "New Materials and Innovative Technologies to Improve the Efficiency of Three-phase Induction Motors. A Case Study". *International Conference on Electrical Machines (ICEM 2004)*, Krakov, Poland, September 2004.
- [4] A. Boglietti, A. Cavagnino, M. Lazzari, M. Pastorelli, "International Standards for the Induction Motor Efficiency Evaluation: A Critical Analysis of the Stray-Load Loss Determination," *IEEE Trans on Industry Applic.*, vol 40, No 5, Sept-Oct 2004.
- [5] B. Renier, K. Hameyer, R. Belmans "Comparison of Standards for Determining Efficiency of Three Phase Induction Motors" (*IEEE Trans on Energy Conversion* 14 (1999) No. 3, pages 512-517)
- [6] H. Aulinger "Determination and designation of the efficiency of electrical machines" (*Power Engineering Journal*, Feb 1999 pages 15— 23)
- [7] H. Jordan, V. Kilma, K. Kovács, *Asynchronmaschinen: Funktion Theorie, Technisches*, Braunschweig: Vieweg, 1975.
- [8] A. Nagorny, A. Wallace, A. Von Jouanne, "Stray load loss efficiency connections," *IEEE Industry Applications Magazine*, vol. 10, issue 3, pp. 62 — 69, May-Jun 2004.
- [9] K. K. Schwarz, "Survey of Basic Stray Losses in Squirrel-Cage Induction Motors," *Proc. IEE*, 111, pp: 1565-1 574, 1964