Energy Efficiency of small Induction Machines: Comparison between Motor and Generator Mode

Wim Deprez, Annick Dexters, Johan Driesen, Ronnie Belmans

Abstract—The market of small or micro electric energy generation units, often combined with local heat production, is becoming increasingly important. For these applications the classical asynchronous machine with cage rotor is an interesting generator. The grid-connected induction generator has some advantages over the synchronous generators; e.g. it is cheap, robust and maintenance-free. Since the induction machine is mostly used as a motor, the manufacturers’ catalogues only mention the motor efficiency values. The paper uncovers why nevertheless induction machines can be used either in motor or generator mode, the efficiency curves, based on IEEE 112-B, for these modes are not necessarily the same. We conclude that the machines with lower stator and rotor resistances 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.

Index Terms—Efficiency, grid-connected induction generators, induction machines, international standards

I. INTRODUCTION

The market of small or micro electric energy generation units, often combined with local heat production, is becoming increasingly important [1]. This growth is driven by several factors such as the increasing fossil fuel prices and Europe’s ambition to decrease its energy import dependency. Moreover, environmental protection and the ratification of the Kyoto Protocol make up an enormous challenge for the European energy industry. These drivers have evoked several European legislative initiatives, such as certificates and feed-in tariffs [2], stimulating consumers to look for alternative solutions properly. Therefore, in this paper, the energy efficiency of the induction machine when used as a generator is analysed. In order to discuss the induction generator

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efficiency, the difference in power flow between motor and generator mode is studied. This is necessary to explain the operational difference, and thus efficiency, and also to describe how standards concerning induction machine efficiency treat this problem. Some experimental results, recorded in order to illustrate the possible behaviour of the machine’s efficiency depending on the operating mode, are discussed. Other aspects that can influence the efficiency of induction generators are briefly discussed.

II. INDUCTION MACHINE AND ENERGY EFFICIENCY

Induction machines are mostly used as motors. Nameplate and catalogue data, such as power rating, power factor and efficiency, are generally only provided for motor operation. It should be noted that international research [11]-[13] reports that labeled efficiency values of induction motors are not unambiguous: they firmly depend on the standard used in determining the efficiency! In addition, these values can differ significantly for motor and generator mode depending on the size and the efficiency class of the machine. It is the intention of the following sections to provide an insight in energy efficiency issues of induction machines; especially related to differences between motor and generator mode.

Theoretically, the definition of energy efficiency is very simple:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \quad \rightarrow \text{mot} : \quad \eta_{\text{mot}} = \frac{P_{\text{mech}}}{P_{\text{el}}} = 1 - \frac{P_{\text{loss}}}{P_{\text{el}}} \quad (1)
\]

\[
\rightarrow \text{gen} : \quad \eta_{\text{gen}} = \frac{P_{\text{el}}}{P_{\text{mech}}} = \frac{P_{\text{el}}}{P_{\text{el}} + P_{\text{loss}}} \quad (2)
\]

Based on (1) and (2), the efficiency determination methods are categorized as either direct or indirect. For the direct method, the mechanical power has to be determined. This necessitates accurate torque and speed measurements. Efficiency values obtained by this method depend on ambient and motor temperature, which is not desirable for a transparent efficiency comparison. The indirect method based on the segregation of losses, allows the correction for these temperature values to a specified ambient and reference motor temperature. When examining losses of an induction machine, it is possible to identify the so-called “conventional losses’, including stator and rotor conductor losses, magnetic core losses, and friction and windage losses. However, induction machines also have an additional power loss component termed “stray load loss” caused by the non-ideal nature of a practical machine. The manufacturers provide efficiency data on the basis of measurements and calculation procedures prescribed by international standards, such as IEEE 112-B, IEC 34-2 and JEC 37. These standards recommend different measurement methods and calculation procedures, in particular, for the stray-load loss determination and the temperature correction of the copper losses. As a consequence, it is possible that a machine can be labeled with efficiency values that differ several percent [11]-[15].

III. EFFICIENCY FOR GENERATOR MODE AND MOTOR MODE BASED ON IEEE 112-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 (Pfr,w) and core losses (PFe) 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 (Rstator.Istator2). 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 (3) and (4):

\[
\rightarrow \text{motor} : \quad P_{\text{airgap}} = P_{\text{el}} - P_{\text{stator}} - P_{\text{Fe}} \quad (3)
\]

\[
\rightarrow \text{generator} : \quad P_{\text{airgap}} = P_{\text{el}} + P_{\text{stator}} + P_{\text{Fe}} \quad (4)
\]

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 the 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.

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.

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/ηmotor 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.

IV. MEASUREMENTS

A. Measurement Setup

To investigate the efficiency of induction machines in motor and grid connected generator mode, three standard squirrel cage induction machines with different efficiency classes and from different manufacturers are measured on a setup as shown in figure 3. The first machine is a high efficiency (eff1) induction motor with a rated power of 7.5 kW, the second and third machine both have a rated power of 5.5 kW and are of efficiency class 2 and 3 respectively. A dc-machine is used to drive the induction machines in generator mode or to load them in motor mode. The torque is measured with a classic torque transducer. The electrical power, voltages and currents are directly measured using a Power Analyzer. The measured electrical and mechanical data are captured by a data acquisition system. The further processing of the data is automated, based on a Microsoft® Excel spreadsheet.

B. 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.

Figure 4 shows the practical no-load characteristics of the tested induction machines. One can observe that the saturation level at rated voltage is more significant when the machine is of a lower efficiency class. For instance, the eff3 machine shows a higher saturation level at rated voltage. A small variation in airgap voltage will significantly change the magnetization current. This pronounced saturation effect is caused by the lower relative quantity and/or quality of the used magnetic steel in cheaper eff3 machines. Saturation causes the stator current in generator mode to be much more reactive than in motor mode as can be noticed in figure 5.

The displacement of the no-load characteristic of the eff2 machine is caused by significantly higher friction and windage losses.

Figure 6 shows that the stator losses for the high efficiency machine in motor and generator mode are comparable. The stator losses for generator mode are slightly higher. For the eff2 and eff3 machine the stator losses in generator mode are significantly higher than in motor mode. This has two reasons: the voltage drop in the stator and the saturation level at rated voltage. The first induces a larger airgap flux, the latter gives rise to a higher magnetization current and increased core losses. Both result in higher stator losses. For the high efficiency machine, the stator resistance is low and there is hardly saturation at rated voltage (Figure 4). Thus the difference in stator losses between motor and generator mode is limited.
The rotor losses are depicted in figure 7. For the eff2 and eff3 machine, these losses are significantly larger in generator than in motor mode. 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. For the eff1 machine, the difference is less pronounced because the stator and core losses are comparable in motor and generator mode. But this does not explain that the losses in generator mode are somewhat smaller. This has to be attributed to a decreasing slip: rotor losses are not only determined by the airgap power, but also by the slip.

Due to the higher airgap 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 [16], again the same electromechanical torque can be produced at a lower slip.

For the high-efficiency machine the decrease of the slip due to the two preceding effects seems to over-compensate the increase of the airgap power. For the eff2 and eff3 machines, this is not the case. The effect of the slip decrease is obviously rather small.

For the sake of completeness, it should be noted that the rotor losses in motor mode of the eff2 machine are lower than those of the eff1 machine. This is due to the fact that the slip of the eff2 machine is significantly lower.

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 [11]-[15]. The determined stray load losses for the examined machines in motor mode are according to the results reported in [14], [15]. In generator mode the machines show much higher stray load losses as their efficiency class descends. This can be allocated to the saturation effect, giving rise to higher harmonic currents but especially to the rising core losses themselves since the IEEE 112-B does not account for changes in the core losses in the first place [17], [18]. The core losses are kept constant at the level of no load and rated voltage.

The efficiency according to IEEE 112-B referring to the same electrical power for both generator and motor mode is visualized in figure 9. Assuming the same efficiency and the same electrical power in generator and in motor mode, the mechanical power and the losses for the generator are $\frac{1}{\eta_{\text{motor}}}$ times those of the motor [19].

As long as the air gap flux doesn’t change much, which is the case in the lower load area, the losses in motor and generator mode do not differ much. Because of this, the efficiency of the generator for the same electrical active power
is higher than the motor efficiency. For machines with non-negligible stator resistance a further load increase causes the airgap flux to augment and consequently, the core losses increase in proportion with the saturation level at rated voltage. From a certain level of loading, the motor efficiency becomes higher than the generator efficiency. As one can conclude from figure 9, the generator efficiency stays higher for the eff1 machine for all loads, the losses for generator mode stay below \(1/\eta_{\text{base}}\) times those for motor mode. This can be assigned to the combination of unsaturated iron and limited stator and rotor resistances. For the eff2 machine the motor efficiency is a little higher but is of the same size as the fault tolerance. For the examined eff3 machine the difference in efficiency between generator and motor mode is significant and drops several percent in generator mode.

Attention must be paid when using this chart. The 1 per unit point for generator mode is an overload condition, as the current in generation mode is far more reactive. Thus, in order to supply the same active power, the current has to be higher. In order to compare efficiencies in a more practical way, they are plotted as a function of the stator current on figure 10.

Fig. 10. Efficiency according to IEEE 112-B referred to the same stator current for both generator and motor mode.

VI. OTHER EFFICIENCY ASPECTS

For completeness, it should be noted that there are other aspects that can influence the overall generator system efficiency. For induction motors, literature states the importance of partial load and the detrimental effects of harmonics, power electronics and voltage unbalance [11], [13], [20], [21]. These effects also influence the performance in generator mode.

VI. CONCLUSIONS

Induction machines of different efficiency classes and similar power ratings are compared for motor and generator mode. One can conclude that a machine with a lower stator and rotor resistance and a non saturated core, typical characteristics for high efficiency machines or machines with a high power rating, have comparable efficiencies in both generator and motor mode. This is not the case for low efficiency machines, where the efficiency for generator mode can drop several percent.

When using catalogues for induction motors, efficiency values differ according to the standards the manufacturers use. One should also consider that the efficiency curves for motor and generator mode are not necessarily the same.

REFERENCES

