Vagaries of Efficiency Measurement Methods for Induction Motors

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Abstract

This paper aims at demonstrating the need for a thorough scrutiny of induction motor efficiency measurement methods in current use. Moreover, it highlights the need for cognizance of many more factors that affect efficiency, such as unbalanced voltage supply conditions and power quality. After giving an overview of various different efficiency measurement techniques as embedded in standards the paper presents the results of efficiency tests performed in the laboratory according to a number of selected standard methods. It is shown that substantial discrepancies exist in results. The paper then discusses the effect of supply voltage unbalance on the performance of an induction machine and shows, on the basis of laboratory tests, that further discrepancies are introduced into the measured efficiency values.

1 Introduction

Against the backdrop of increasing (electrical) energy demand, diminishing resources accompanied by environmental concerns based on green-house considerations and increasing fossil fuel prices, efficiency has assumed paramount importance in recent years. More than 50% of the electricity consumption in the developed countries and approximately 65% of the electricity which is used in industry is consumed by electrical motors [de Almeida et al. 1997 / De Keulenaer et al. 2004 / Collard et al. 2004]. Therefore, the efficiency of motor driven systems is of major importance, especially in the case of induction motors which constitute the bulk users of energy in industrial societies. Evidently, even a modest increase in motor efficiency would yield considerable benefits in both environmental and economical terms. Governments, which have a responsibility to inform and to regulate, have been increasingly proactive in matters pertaining to device efficiency. There are numerous examples of national and international agreements, incentives and initiatives worldwide. For Europe, this is reflected in different ongoing programmes. For instance, 'The European Motor Challenge Programme' and the most recent classifications of industrial a.c. motors on the basis of their certified efficiency, e.g. EFF1, EFF2, EFF3 labels of the CEMEP (the European Committee of Manufacturers of Electrical Machines and Power Electronics) voluntary agreement [De Keulenaer et al. 2004].

Evidently these efficiency classifications presuppose that efficiency measurement methods are well established beyond reproach and agreed upon in national and international standards. A closer examination of standards, however, reveals that there are major discrepancies between the methods proposed by different standards. This has serious consequences both in terms of issuing certificates and credibility of the declared efficiency values for decision making when purchasing motors. The prescribed methods become all the more wanting for non-ideal operating conditions of a real application as opposed to the ideal test conditions of the standard methods. For instance, standards are conspicuously silent on matters pertaining to unbalanced supply or poor power quality. Also, the practice of certifying efficiency on the basis of a single efficiency value must be questioned.

This paper gives an overview of the most prevalent standards on efficiency measurement and of the different definitions of voltage unbalance. The effect of voltage unbalance on induction motors and their performance is addressed. Some standards concerning voltage unbalance and their consequences on induction machine performance are discussed. Throughout the paper, the discussion is backed up by results of efficiency measurements conducted in the laboratories of the Electrical Engineering Department at the KULeuven.

2 Efficiency Measurement

Motor efficiency is measured on the basis of standards and normally eludes to ‘energy efficiency’. Disturbingly, 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. Obviously, there are possible consequences of such discrepancies in measured efficiency values when they are used for the purpose of optimising the energy efficiency of motor driven systems.

2.1 Energy Efficiency of Induction Machines

Theoretically, the definition of energy efficiency is very simple:

$$\eta = \frac{Pout}{Pin} = 1 - \frac{Ploss}{Pin} \tag{1}$$

In practice however, a series of different standards, based on (1), lead to differences in efficiency values of several percent [Slaets et al. 2000 / Renier et al. 1999]. This theoretical definition (1) provides the licence for dividing the efficiency measurement methods into two categories: direct and indirect methods. For induction machines, this means that for the direct method the output power has to be determined. This necessitates a torque and a speed measurement. But, efficiency values obtained by this method also depend on ambient and motor temperature, which is not desirable for a transparent efficiency comparison. The second method allows the correction for these temperature values to a specified ambient and reference motor temperature. This is realised by correcting the individual loss components. Yet, the main difference between the standards emerges from the way in which the so-called stray load losses - as a part of the overall losses - are treated [Slaets et al. 2000 / Renier et al. 1999].

2.2 Losses in Induction Machines

The losses in a three phase squirrel cage induction motor can be divided into five categories. These individual loss components and the methods for determining their values are now discussed briefly. An extensive discussion of these loss components can be found in literature [Nürnberg & Hanitsch 1987 / Renier et al. 1999].

The first four loss components are stator and rotor ohmic ($P_{stator,RI}{}^2$ & $P_{rotor,RI}{}^2$) losses, core losses (P_{Fe}) and the friction and windage losses ($P_{fr,w}$). The core and friction and windage losses are obtained from a no-load test. The ohmic losses are determined based on stator resistance, slip and input power measurements. Most standards also prescribe how to correct the ohmic losses for a specified ambient temperature and a reference motor temperature [Standards: IEEE and IEC].

The fifth loss component, the additional load losses, also known as stray load losses, is the most ambiguous of all the loss components, although it is simply defined as:

$$P_{addit} = \left(P_{in} - P_{out}\right) - \left(P_{Fe} + P_{stator} + P_{rotor} + P_{fr,w}\right) \qquad (2)$$

The stray load losses are caused by time and space harmonics and by the leakage flux near the winding ends. In the past, several methods have been proposed to measure these additional load losses, including the reverse rotation test at slip 2 or half frequency tests at slip -1 and 3. However, these methods have proved neither reliable nor practical for the determination of efficiency of induction machines.

2.3 Standards for Efficiency Measurement

World-wide, there exist several standards for determining the efficiency of induction motors. Of these the three most important are:

- IEEE Standard 112-1996
- IEC 60034-2 Ed.3
- JEC

2.3.1 IEEE Standard 112

The IEEE 112 standard defines several methods how best to test electric motors. Efficiency determination is only part of this standard, although it is an important one. Some of the key (there is a total of 10) test methods for efficiency are:

- Method A: simple input-output

- Method B: input-output with loss segregation (or separation)
- Method C: back to back machine test with separation of losses
- Method F: equivalent circuit (model) calculation

The other methods, E, E1, F1, C/F, E/F and E1/F1 are variations of these. Method A, which is only recommended for small machines, is a direct method. Method B is in fact an indirect method, but it uses a direct method to obtain a value for the additional losses. The measuring error is reduced by linearising the additional losses and correcting them for zero additional losses at no load. The correlation coefficient of the linear regression should be higher than 0.9. Method B is the recommended and the most popular method for testing of induction machines up to 180 kW.

2.3.2 IEC Standard 60034

Just as with the IEEE Standard 112, the IEC 60034 Standard defines how best to test electrical motors. The second part of this standard, IEC60034-2, describes how to determine the losses and efficiency from tests (excluding machines for traction purposes). This standard also provides different techniques to determine the different loss components, e.g. a breaking test with torque measurement, a back to back test, etc. Historically, due to difficulties of torque measurement, the current IEC standard for determining motor efficiency (IEC 60034.2 Ed. 3 (1972)) assumes a standard value for the additional load losses at rated load of 0.5% of the input power. Note that IEEE112-E1 sets the additional losses as 1.8% of the rated output power for motors between 0.75 kW and 90 kW. An intermediate proposed standard, the IEC 61972, gave two possibilities. The first was a method similar to IEEE112-B, the second attributed a fixed amount to every machine of the same rated output power. However, the latest proposed draft for the revised IEC 60034-2 (4th edition) recommends that for three phase induction machines between 1 kW and 150 kW the additional losses should be determined by the direct method as in the IEEE112-B standard. The approval of this proposal by the committee would be a significant improvement as already anticipated in literature [Slaets et al. 2000 / Renier et al. 1999 / Van Roy 2003] and supported by the experimental evidence below.

2.3.3 JEC Standard on induction motor efficiency

As far as it could be ascertained by the authors, the Japanese JEC Standard 37 still completely neglects the additional load losses.

2.4 Measurements

To illustrate the discrepancies that can exist in efficiency determination using different standards, a modern small 1.1 kW standard three phase squirrel cage induction motor was tested in laboratory, using the test setup shown in Fig.1.

In the setup, the brake is a Vibrometer water-cooled Eddy Current - Powder Brake combination. The torque transducer (type T30FN of HBM) is used in combination with a

KMN913.C measurement amplifier of HBM. This combination allows the output power to be determined with an accuracy of better than 0.5%. This brake-torque transducer combination can be used to test machines up to 3 kW at 3000 rpm. The input power, input voltages and currents are directly measured using a Voltech PM3000A Power Analyser. The input power measurement accuracy is 0.4%. A LabVIEW® based data acquisition system was used.

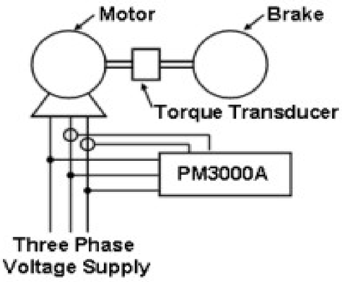

Figure 1: Measurement setup

Before the start of measurements, ambient temperature and the winding temperature are measured. Then, the motor is warmed up under rated load until thermal equilibrium is reached. This is checked by measuring the winding temperature again. Next, the load test is performed. Starting at 125% of rated load, about 20 load points are set and measured. And finally, the standard no-load test, with disconnected brake, is performed. During this test, the induction machine is run as a motor with different values of the stator voltage.

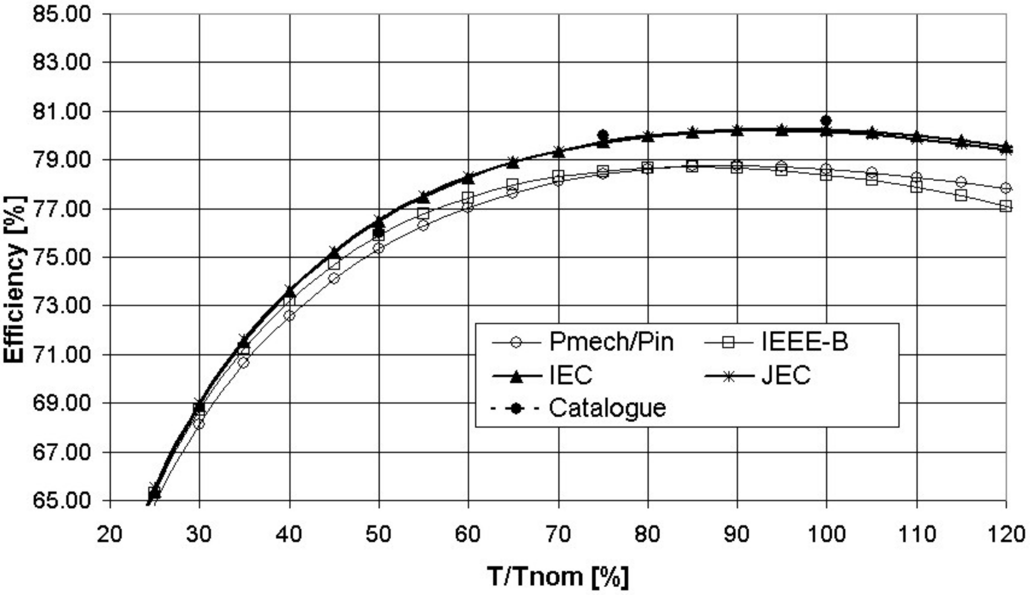

Figure 2: Efficiency values of a four pole three phase induction motor according to different standards

Based on these measurements, a spreadsheet automatically generates efficiency values in four different ways. The first is derived from the direct method as described by (1). The three other efficiency curves are those obtained according to IEEE standard 112 Method B, IEC 60034-2 standard (with the factor of 0.5% for the additional losses) and the JEC respectively. Fig.2. shows the efficiency according to these four methods as a function of normalised torque.

The difference between the measured efficiency and the catalogue value is 3.5% for the IEEE112B based efficiency and 1.1% for the IEC (0.5%) one at full load. The difference between the IEEE and the IEC efficiency is 2.44%. The calculated stray load losses are 2.09% of the rated output power. This clearly illustrates that the factor of 0.5% for stray losses is a serious underestimation and that the factor of 1.8% of IEEE Standard 112 Method E1 is more realistic. These conclusions are in agreement with findings based on measurements of 18 motors of 11 kW, 55 kW and 75 kW rating [Slaets et al. 2000 / Renier et al. 1999 / Van Roy 2003].

2.5 Discussion

The above shows that measured efficiency values of induction motors are not unambiguous: they just depend on the standard used in determining the efficiency! This underlines the expectation that the only correct way to determine the efficiency of an induction motor is by the direct determination of the additional losses: all other methods overestimate the efficiency. This could pose problems when issuing certificates. For instance, the voluntary agreement of CEMEP concerning the efficiency labels issues an EFF3 label for 4 pole 1.1 kW motors with an efficiency below 76.2%, an EFF2 label if the efficiency is above or equal to 76.2% and an EFF1 label if the efficiency is above 83.8%. For the measured motor, this means that according to IEEE standard 112-B, the motor does not qualify for an EFF2 label, whereas according to the IEC standard (estimating the stray load losses as 0.5% of rated input power) the motor gets the EFF2 label comfortably. This has serious ramifications in the context of improving the efficiency of motor driven systems.

There are further aspects that influence efficiency determination in motor driven systems. Firstly, there is the problem of issuing efficiency certificates on the basis of a single load condition. Since the shape of the efficiency curves (see Fig.2.) can differ from manufacturer to manufacturer and from motor type to motor type, as was demonstrated in [Slaets et al. 2000 / Renier et al. 1999], the use of efficiency labels can be misleading from the point of view of the motor purchaser and unfair from the motor manufacturers' point of view. It seems not unreasonable that manufacturers ought to be required to declare partial load efficiency values also, at least for 75% and 50% of the rated load. It is not clear how or whether this problem should be solved. But possible solutions would be the revision of the efficiency labels or the introduction of an extra penalising factor reflecting the shape of the efficiency curve.

A second issue concerns the effect of power supply quality on efficiency. IEC standard 60034-1 for efficiency measurements allows for a certain total harmonic distortion factor and a certain maximum unbalance for the supply voltage. However, these conditions do not always correspond to real life situations. It is shown that unbalanced supply voltages considerably affect induction motor efficiency [Pillay et al. 2002 / Wang 2001 / Lee 1999]. This issue is addressed in more detail in the next section.

3 Voltage unbalance and induction machines

In a three-phase system, voltage unbalance is the phenomenon in which the rms values of the voltages or the phase angles between consecutive phases are not equal. This can occur due to incomplete transposition of power lines, uneven distribution of single-phase loads, open delta transformer connections, blown fuses on three phase capacitor banks and so on. Voltage unbalance can negatively influence the efficiency of three phase induction motors and even shorten their service life.

3.1 Definitions and Standards

3.1.1 Definitions

There are several definitions of voltage unbalance in standards and the literature [Pillay et al. 2002]:

- NEMA uses the line voltage unbalance rate (LVUR) given by

$$\%LVUR = \frac{\text{Max Voltage Deviation from Avg Line Voltage}}{\text{Avg Line Voltage}} \cdot 100 \tag{3}$$

- IEEE defines voltage unbalance as the phase voltage unbalance rate (PVUR) as

$$\%PVUR = \frac{\text{Max Voltage Deviation from Avg PhaseVoltage}}{\text{Avg Phase Voltage}} \cdot 100 \tag{4}$$

- IEC defines the voltage unbalance factor (VUF) expressed as

$$\%VUF = \frac{V_2}{V_1} \cdot 100 \tag{5}$$

In equation (5) V_1 and V_2 are the positive and negative sequence voltages respectively, which can be obtained by symmetrical component transformation. This is the only definition which includes information of both magnitudes and phase angles. V_1 and V_2 are phasor quantities although often only the magnitude of VUF is considered. To avoid the use of complex algebra, it is proposed [Pillay et al. 2002] to use equation (6) which provides a good approximation to the 'true' IEC definition of unbalance:

$$\%\text{voltage unbalance } = \frac{82 \cdot \sqrt{V^2{}_{abe} + V^2{}_{bce} + V^2{}_{cae}}}{\text{Avg Line Voltage}} \cdot 100 \tag{6}$$

with V_{abe} being equal to the difference between the line voltage V_{ab} and the average line voltage, etc.

Not surprisingly, the above three definitions provide different values to characterise the unbalance. For instance, one value of VUF can correspond to different unbalanced situations. In the case of PVUR, which does not incorporate any phase angle information, can give 0% unbalance even though the phase angles may be greatly unbalanced as long as the magnitudes are the same.

3.1.2 Standards

Several IEEE and IEC standards concerning “Power Quality” in fact discuss “normal operating conditions” [Bollen 2000]. Concerning voltage unbalance, the European voltage characteristics standard states the following [EN50160]:

“Under normal operating conditions, during each period of one week, 95% of the 10 minute mean rms values of the negative phase sequence component of the supply shall be within the range 0 to 2 % of the positive phase sequence component. In some areas with partly single phase or two phase connected customers’ installations, unbalances up to about 3 % at three phase supply terminals occur.”

The ANSI standard limits it to 3 % at the electricity meter under no load conditions [Lee 1999]. Such standards do not imply compulsory compliance; the supply companies strive to deliver a product according to this standard, but they can not or do not always guarantee it. In practice, the voltage unbalance can exceed that 2 or 3 % level. Moreover, voltage unbalance at the motor terminals can also be caused within the infrastructure of companies themselves. Industrial and commercial facilities may have well balanced incoming supply voltages, but unbalance can develop within the premises due to non-uniformly distributed single-phase loads, unbalanced or overloaded equipment, high impedance connections (e.g , bad or loose contacts), badly repaired motors, etc. Sometimes, unbalance and/or over voltages are also caused by improper power factor correction. Note also that the standards do not include any reference to phase angle information.

Voltage unbalance can have a detrimental effect on three-phase induction motors. This is considered in 3.2. To protect induction machines, the NEMA Standard MG 1-1993: Motors and Generators and the IEC 60034-26 prescribe that the machines must be derated. For instance, NEMA directs that an unbalance of 3 % requires a 12 % larger motor. It should be noted that these two standards use different voltage unbalance definitions.

3.1.3 Effect of Voltage Unbalance on Induction Motors

The adverse effects of unbalanced voltages on induction motors have been studied at least since the 1950s [Lee 1999]. It is common to study the behavior of the positive and negative sequence components of the unbalanced supply voltage to understand the effect of unbalance on the motor. The positive sequence voltage produces a positive torque, whereas the negative sequence voltage gives rise to an air gap flux rotating against the forward rotating field, thus generating a detrimental reversing torque. So in fact, the motor behaves as consisting of two separate motors, one running at slip s with terminal voltage V_p per phase and the other running with a slip of (2-s) and a terminal voltage of V_n. The result is that the net torque and speed are reduced with possible torque pulsations and noise. At normal operating speeds, the unbalanced voltages cause the line currents to be unbalanced in the order of 6 to 10 times the voltage unbalance [IEC 60034-26]. With reduced overall torque the motor will take longer to speed up, changing its thermal behaviour detrimentally. Further, if full load is still demanded, the high slip, and hence the low negative sequence impedance ($R'_2/(2-s)$!!), give rise to large negative sequence currents, generating more heat. The reduction of peak torque compromises the ability of the motor to ride through dips and sags. Premature failure can be prevented to some extent by derating the machine according to the standards, allowing the machine to operate within its thermal limitations.

3.1.4 Measurements

Further tests were conducted to study the way that supply unbalance affects the efficiency of three-phase induction motors. The test setup was the same as in Section 2.4 and Figure 1. Also, the same induction motor was used as for the standard efficiency measurements of Section 2.4.

Setup

To create an unbalanced voltage supply a transformer (230V : 24V) was placed in each line. The transformers were fed with an adjustable voltage in phase with each corresponding phase voltage of the power supply. Three different unbalance situations were created: one with 2% VUF and the others with different supply voltage settings with a VUF of 3%. Table 1 gives an overview of these different conditions of voltage supply.

Table 1: Comparison of the three unbalanced supply voltage cases in terms of phase voltages of the power supply, PVUR, LVUR, VUF, the alternative formula for the VUF and the positive and negative sequence components

case	Va [V]	Vb [V]	Vc [V]	LVUR [%]	PVUR [%]	VUF [%]	VUFa [%]	V_1 [V]	V_2 [V]
3%A	230	230	210	2.96	5.97	2.99	2.98	$223.3\angle 0$	$6.67\angle -60$
3%B	234	234	213	3.06	6.17	3.09	3.07	$227\angle 0$	$7\angle -60$
1%	234	230	218	2.04	4.11	2.11	2.12	$227.3\angle 0$	$4.81\angle 46.4$

The test results are presented in Figure 3. Efficiency is calculated according to the standard IEEE112 Method B. Due to equipment limitations the measurements with a VUF of 1% were made up to 95% of nominal load only. Although only three unbalanced situations were considered, some important conclusions can be drawn. Firstly, unbalanced supply conditions that are well within the margins of the standards can adversely influence the efficiency. In this experiment there is an efficiency decrease of about 1% for nominal load conditions. Note that the IEC definition of voltage unbalance (VUF) is used. Secondly, the change in efficiency is not solely proportional to the VUF. This is illustrated by the fact that the efficiency for the VUF of 2% is worse than the efficiency for the 3% VUF cases. Thirdly, different unbalanced supply cases with the same VUF can result in different efficiency values.

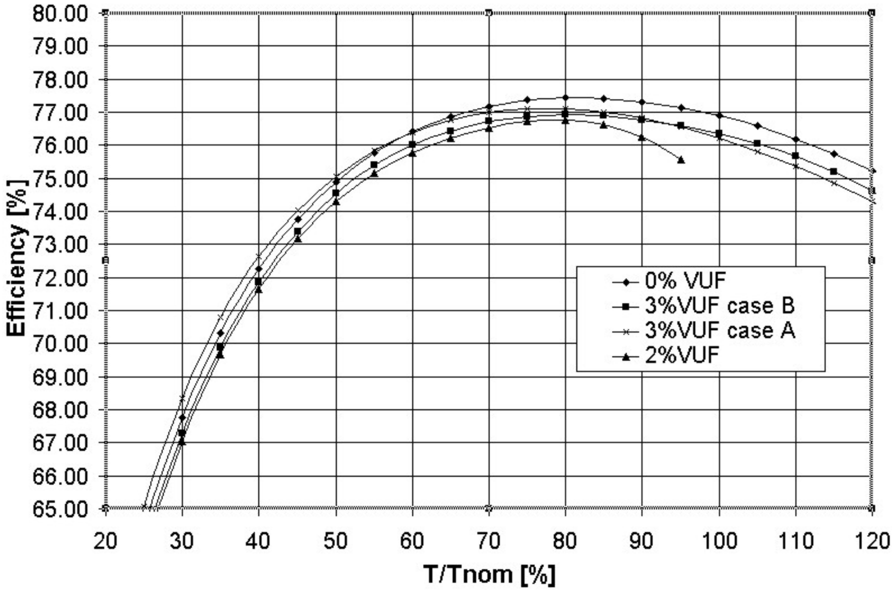

Figure 3: Efficiency curves of a three phase 1.1 kW induction motor, determined according to IEEE standard 112 Method B and for three unbalanced situations

Future Work

The crossing over of the two '3%VUF' efficiency curves in Figure 3 begs for an explanation which could be found in the difference of positive and negative sequence voltages. A possible explanation for the worse efficiency of the 2% unbalance case may be found in the deviation of the phase angles of the negative and homopolar sequence voltages. It is not inconceivable that different motor designs have different sensitivity to unbalance and thus it is possible that an EFF1 motor is less efficient than some EFF2 motors under the same unbalanced conditions. To provide a scientifically based explanation for these effects, further investigation is required using additional measurements on motors of different rating by different manufacturers (thus of different designs) supported by simulations based on discrete circuit modelling and/or Finite Element Analysis.

4 Conclusion

The observations presented in this paper expose vagaries of efficiency measurement methods prescribed by reputable standards. It seems that there is need for a more unified and rigorous approach to efficiency determination in motor driven systems. There is a further need for the cognizance of operating realities such as power quality (e.g. unbalanced supply conditions) in the determination of induction motor efficiency, which standards presently ignore.

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