Efficiency Estimation Methods for Electric Drives using Squirrel-Cage Induction Motors

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Abstract

This thesis presents a study on the online in-service estimation of the efficiency of an induction machine. The purpose is to be capable of measuring the efficiency in an industrial environment with non intrusive methods. A recap on the main efficiency estimations methods is done and tested. The methods accuracy and intrusion level are dependent on the readings and tests required. The methods studied are based on: the equivalent circuit, calculating all of its parameters; the segregation of losses, which is associated with the induction machine working principle and construction; the torque, that calculates the output power with speed and torque; the input current, which considers the relation of the load current with the percentage of load; the slip, which relates the ratio of the measured slip to the full-load slip with the percentage of load, and finally the nameplate, the less intrusive methods where the only readings required are the data from the nameplate. The several efficiency estimation methods are applied to two induction machines, one with 2.2 kW and the other with 5.5 kW. The results are compared to real efficiency, in which the methods with higher intrusiveness present a higher accuracy as expected. The methods have a bigger accuracy for bigger machines, so the results obtained for the 5.5 kW are the most satisfactory. An unexpected result was the nameplate method, with errors as low as other more intrusive methods and for a wider range of load percentage. No paragraph breaks.

Keywords: Efficiency estimation, In-service efficiency monitoring, Induction machine, Non-intrusive efficiency estimation

1. Introduction

Most of the consumption of electricity in the industrial sector is from induction machines. Therefore, the monitoring of the efficiency of these machines is important not only because of production costs but also considering the current energetic problem in the world. It is of major importance to try to minimize the world resource consumption and to have efficient machines working in the industry. For this reason, there is the need for sophisticated and precise methods of measuring the motors efficiency that can be used in an industrial environment.

In order to measure the real efficiency of a machine, very intrusive tests are required and most of the times, the machines cannot be taken out of service, its load cannot be uncoupled and sometimes the machines are not easy to reach. Thus it is necessary that these methods are as less intrusive as possible so there is no need for stopping or compromising the machine performance in order to measure its efficiency.

With less intrusive estimation methods, an estimation of the motor efficiency can be obtained during its working routine (in-service), although with reduced accuracy. This estimations methods are the main purpose of this study and are based on mathematical models of the motor and tend to use just line currents and voltages that can be taken online.

2. Background

The main estimation methods are presented in this section and are introduced in a decreasing level of intrusiveness.

2.1. Equivalent Circuit Method

It is possible to estimate the efficiency of the induction motor based on its equivalent circuit. This way the efficiency can be estimated for operating points and conditions rather than those at which measurements are made. The standard equivalent circuit method is presented by IEEE [1] and is the basis for further modified and less intrusive methods. There are several equivalent circuit methods and above are summarized the two most accurate and non intrusive, since the others are too impractical to be applied in an industrial motor.

The *Nameplate Equivalent-Circuit (ORMEL96) Method* is obtained from the nameplate data and the stator resistance. The stray load losses are represented by a parasitic resistance inserted in the rotor and the stator resistance can be estimated from nameplate data. The parameters of the equivalent circuit are solved from an assumed rated load condition and locked rotor condition, which completely rely on motor nameplate information and may have up to 20% inaccuracies according to NEMA [3] [2].

Another equivalent circuit method is the *Rockwell Motor-Efficiency Wizard (RMEW) Method*, which relies on measuring the input current, the input electrical power, the stator resistance and the output speed of the motor [4]. The stator resistance can be measured at a certain temperature and then be estimated for different temperatures. The other parameters of the equivalent circuit can be measured using two operating points.

2.2. Segregated Losses Methods

As the name suggests, these methods separate and estimate each one of the losses presented in section **??** and subtract them to the input value.

The IEEE Standard Test Procedure for Polyphase Induction Motors and Generators [1] states that horizontal machines rated at 0.7457 kW to 300 kW should be tested using Efficiency Test Method B, the input-output method with loss segregation. This method is less intrusive than the Equivalent circuit method because the locked rotor test is not required, but still has a high level of intrusion, although very accurate.

Between several methods of this type, the most suitable for the in-service efficiency estimation is the Ontario Hydro Modified Method E (OHME). This is an improved version of the IEEE Std-112 method E1 [1], which assumes a value for the stray load losses at a rated load depending on the motors size. In the OHME method the windage, friction, and core losses are combined and assumed to vary between 3.5%–4.2% of rated input power [7], making the no-load test not required. Once more, this assumptions degrade the accuracy of the results but decrease its intrusiveness.

2.3. Torque Methods

The basis for all the torque methods is that the output power of a motor is the product of the shaft angular speed and shaft output torque.

Knowing the shaft torque T_{shaft} and measuring or estimating the rotor speed ω_r and the input power P_{In}, it is possible to calculate the efficiency following (1).

$$\eta = \frac{T_{shaft}\omega_r}{P_{In}} \tag{1}$$

This output torque is the air-gap torque T_g subtracted by the torque losses,$P_{fw} + P_{SL}$, associated with friction, windage, and stray losses caused by rotor currents, respectively. (1) is then equivalent to

$$\eta = \frac{T_g\omega_r - P_{fw} - P_{SL}}{P_{In}}. \tag{2}$$

The Air-Gap Torque (AGT) Method calculates the air-gap torque with line currents and voltages. The torque derivation takes into account the unbalanced supply, which reflects the industrial plants reality, and can be measured online, which is financially appealing for industries that cannot afford stopping its machines. However, the losses have to be measured with the no load test, representing the main drawback of this method for its high intrusion level.

The Shaft Torque Method measures the output power ($T_{shaft}\omega_r$) directly from the shaft using torque transducers. However, this method is too expensive and highly intrusive.

2.4. Current Methods

The current methods provide a higher accuracy when compared to the slip methods. Both are based on nameplate parameters and in the *Standard Current Method*, it is assumed that load current varies linearly with the percentage of load.

$$\eta = \frac{I}{I_{\text{rated}}} \cdot \frac{P_{\text{output, ratod}}}{P_{\text{input}}} \tag{3}$$

This method results in errors due to the actual non linearity of the load curve and tends to overestimate the efficiency curve. As in the slip methods, the manufacturer parameters are not reliable when there's the need for high precision, since by NEMA [2] the current should not vary by more than 10% of the nameplate current.

The advantage of this current based method is its simplicity and non intrusiveness. In order to improve its accuracy it is possible to add the no load current to the formula given by (4), yet it would be more intrusive to measure it.

$$\eta = \frac{I - I_{no_{l}oad}}{I_{rated} - I_{noload}} \frac{P_{outputrated}}{P_{input}} \tag{4}$$

This method, on the other hand underestimates the efficiency, so an average of the two usually gives a better result.

2.5. Slip Methods

This type of methods are based on the assumption that the ratio of the measured slip to the full-load slip is proportional to the percentage of load. *Standard Slip Method* is a simple method, which uses the measurements of the speed to find the slip, which is usually a reading with low intrusiveness. The input power has also to be measured, being it a more intrusive procedure. The efficiency is then approximated by (5).

$$\eta = \frac{s}{s_{rated}} \frac{P_{outputrated}}{P_{input}} \tag{5}$$

The obvious error is that the slip ratio represents the percentage of load and the efficiency is not equal to the percentage of load [8].

The previous method can be improved by correcting the rated nameplate speed for voltage variations in the *Ontario Hydro Modified Slip Method* given by

$$\eta = \frac{s}{s_{rated}} \frac{P_{outputrated}}{P_{input}} \left(\frac{V}{V_{rated}} \right)^2 . \tag{6}$$

Although this methods are an improvement of a merely nameplate based efficiency estimation method, it still uses nameplate data with its associated inaccuracies. Also the voltage will not always be the rated one in which the values of the nameplate were measured.

These slip methods can still be improved by measuring the current and the stator resistance ,

$$\eta = (1 - s) \left(\frac{3 I_{Load}^2 R_s}{P_{Load}} \right) . \tag{7}$$

2.6. Nameplate Methods

The methods that use motor information from the nameplate data are naturally the least intrusive methods, since there is only the need to access the motor's nameplate.

In the *Standard Nameplate Method* efficiency is assumed to be constant and equal to the value in the nameplate [7]. Therefore, this method has greater accuracy in cases where the efficiency-load curve is reasonably flat so that the value of efficiency in the nameplate, correspondent to full load, is suitable for a large range of load percentage. Hence, this method can have a large error in accuracy when applied to certain types of motors with non flat curves.

Also, the field environment may be different from the one used to acquire the nameplate data values, which influences the voltage unbalance and the harmonics content. Additionally, the nameplate data is no longer valid for rewound motors, although there is the opinion that if the rewound follows the *Electrical Apparatus Service Association (EASA)* standard procedures, the efficiency is not reduced [7].

Another disadvantage of these methods is that there are a couple of different standards for efficiency tests and measurement procedures, which leads to discrepancies in the adopted testing standards when nameplating the efficiency [6].

A variation of the previous method is the *Volgelsang and Benning (V & B) Method* with two different options, the first requires tests with no load, normal load and unpowered while the second uses Nameplate data.

3. Experimental Tests

The efficiency estimation methods are tested in two induction machines with 2.2 kW (IM1) and and 5.5 kW. Not all the estimation methods presented in chapter were tested, since several of them require software or models that are not public or available. Hereupon, within the segregated losses methods, the IEEE std-112 Method B was tested and some approximations are presented in order to reduce its intrusiveness. The standard equivalent circuit is also calculated with several approximations. For the slip and current methods, six methods were tested, with different levels of intrusion and accuracy.

3.1. Reference Efficiency

The focus of this study is to compare different efficiency estimation methods so there is the need to measure the true efficiency of the machine to use it as a reference.

The efficiency of both machines is calculated by performing a load test and acquiring the input power P_s, the rotor speed N and the torque T. The rotor angular velocity ω_r is obtained from the rotor speed N and the useful mechanical power P_{mec} is calculated by

$$P_{mec} = T\omega_r . \tag{8}$$

The efficiency of both machines is calculated as follows

$$\eta = \frac{P_{mec}}{P_s} \times 100 \tag{9}$$

and plotted in figure 1. The torque is calculated indirectly in both machines. In IM1 through the torque coefficient of the DC machine K, obtained in [5] and in IM2 through a DC machine with movable stator.

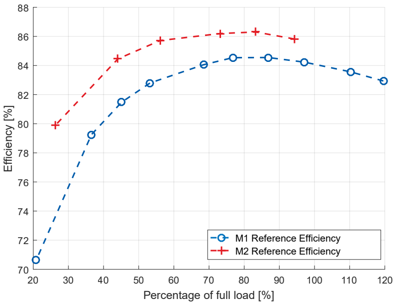


Figure 1: Efficiency curve of both machines

3.2. Equivalent circuit

This method is highly intrusive since the tests needed require the machine to be taken out of service and uncoupled from its load. Note that the no load readings are taken after the motor has been running long enough for the bearings to be properly lubricated, at rated voltage and frequency. In this case, the machine was kept running until its temperature stabilized. With the parameters obtained, it is possible to calculate the estimated efficiency of the machine.

The efficiency is calculated and plotted in figures 2 and 3 for two different values of stator resistance. The hot resistance is the value measured when the machine has been working for some time and is shut down, while the cold resistance is the value measured with the machine at ambient temperature. The error is a bit smaller for the hot resistance value, since the machine warms up with the increase of load.

Overall, this method is extremely accurate in both machines, having an error smaller than 3% in the worst case, and approximately 0.3% to 0.5% in the normal operating region of the induction machine (80% to 120% of full load), marked by the shaded area in both graphs.

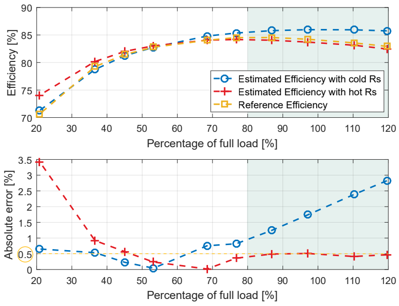


Figure 2: IM1 Efficiency curve obtained with the equivalent circuit estimation method

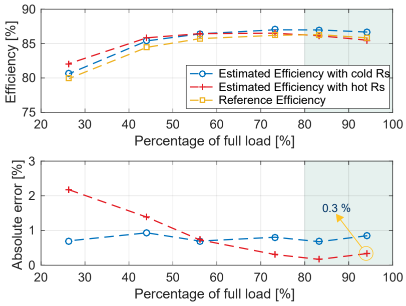


Figure 3: IM2 Efficiency curve obtained with the equivalent circuit estimation method

3.3. Method B IEEE Std.112

With a lower level of intrusion than the equivalent circuit method, is the IEEE Std-112 Method B, since it does not require a blocked rotor test. The purpose of this method is to calculate each type of loss individually to obtain the efficiency. It requires the acquisition of measurements at four different conditions: with the machine turned off, during the no load test, at rated load and in a range of several load points.

The calculations in this section refer to a star connected induction machine.

The stator copper joule loss P_{sCu} is calculated for each point taken during the no load test by

$$P_{sCu} = 3I_{nl}^2 R_{s\ nl}. \tag{10}$$

As seen in section **??**, the rest of the power loss is due to losses in the core and windage and friction,

$$P_C + P_{Fe} = P_{nl} - P_{sCu}. \tag{11}$$

This power is plotted against the line-to-line squared voltage ($V_{ll} = \sqrt{3}\ V_{ph}$). To obtain the windage and friction value, the curve is extended to zero with a linear regression from the points of lower voltage. The windage and friction power loss P_{fw} is the interception with the zero voltage axis, for it is a constant loss. The voltage is squared in order to linearize the power curve. In figure 4 this procedure is represented for IM2.

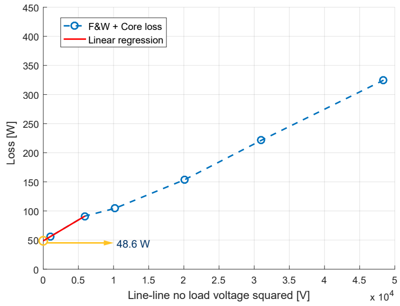


Figure 4: Extraction of friction and windage losses for IM2

The loss increases linearly with the squared voltage, since core losses are related to the square of the magnetic flux B, which is proportional to the square of the voltage. In figure 5, the exact same procedure is represented for IM1. Here, the friction and windage power loss reveals a non-linear evolution and reaches negative values. This is not the expected behavior of this type of loss and is not considered accurate. Since the iron core of IM1 is smaller than IM2, the fluxes induced in the core are smaller, so joule losses become increasingly prevalent as the machine size decreases, not having enough precision to segregate the friction and windage losses. Therefore, the power plotted does not only represent the core and mechanical losses, but can also include eddy currents.

The next step is now to calculate the core losses, eddy currents and hysteresis losses. Since it is not possible to calculate the core loss precisely in IM1, it is considered null. This is going to influence the accuracy of the further efficiency estimations.

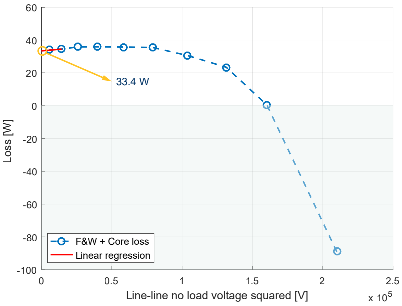


Figure 5: Extraction of friction and windage losses for IM1

The core loss P_C can be calculated from the points taken in the no load test as follows

$$P_C = P_{nl} - P_{sCu} - P_{fw} \tag{12}$$

This power curve can be interpolated for the values of core voltage in the load condition to obtain the core loss, also in the load condition. The voltage drop in the iron core V_{core} is represented schematically in the equivalent circuit in figure 6. According to [1], the voltage drop across the stator leakage reactance is considered to be negligible. Focusing on the left loop of the equivalent circuit and neglecting the stator leakage reactance X_s, the circuit is simplified in figure 7. The core voltage $\overline{V_{core}}$ is obtained by subtracting the resistive voltage drop in the stator winding from the terminal voltage $\overline{V_t}$ as follows,

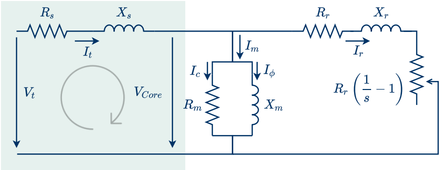


Figure 6: voltage drop in the core represented in the equivalent circuit of the induction machine

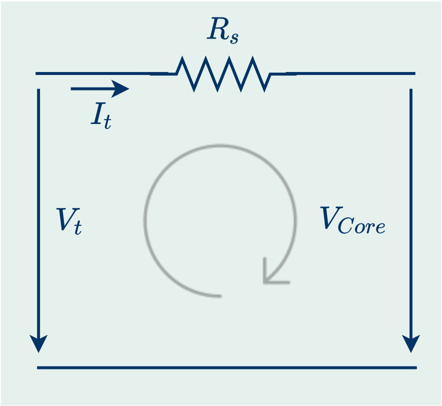


Figure 7: Simplified circuit for the core voltage calculation

$$\overline{V_{core}} = \overline{V_t} - \sqrt{3} I_t R_s. \tag{13}$$

where R_s is the stator winding resistance. Considering that the stator line-to-line voltage is of the form

$$\overline{V_t} = V_t e^{j0}, \tag{14}$$

the line current $\overline{I_t}$ is equal to

$$\overline{I_t} = I_t \cos\theta + jI_t \sin\theta. \tag{15}$$

Combining both equations, the following relation is obtained

$$V_t - \overline{V_{core}} = \sqrt{3} R_s I_t \cos\theta + j\sqrt{3} R_s I_t \sin\theta \tag{16}$$

and solving it for V_{core} one gets

$$V_{core} = \sqrt{(V_t - \sqrt{3} R_s I_t \cos\theta)^2 + (\sqrt{3} R_s I_t \sin\theta)^2} \tag{17}$$

since $PF = \cos\theta$, the equation to calculate V_{core} is deduced

$$V_{core} = \sqrt{(V_t - \sqrt{3} R_s I_t PF)^2 + (\sqrt{3} R_s I_t \sqrt{1 - PF^2})^2}. \tag{18}$$

The values of P_C in the the load condition are an interpolation of the values of the no load P_C obtained in (3.3) for the new values of V_{Core}. The core loss in the no load condition is plotted in blue in figure 8 and the interpolated values in red.

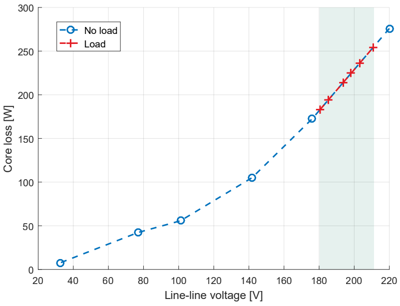


Figure 8: Core power loss interpolation for IM2

In the load condition, the joule losses are different from those calculated in the no load condition, since this losses are not fixed. The stator joule losses are calculated by

$$P_{sCu} = 3I_{load}^2 R_{s\ load}. \tag{19}$$

The power across the air gap P_{ag} is the sum of the losses in the iron and the copper losses in the stator subtracted from the input power

$$P_{ag} = P_{load} - P_C - P_{sCu}. \tag{20}$$

Since the rotor resistance R_r depends on slip, as it is explained in section **??**, the rotor joule loss is calculated by

$$P_{rCu} = P_{ag} s_{load}. \tag{21}$$

where s_{load} is the value of slip during the load test.

This way, the total conventional loss is the sum of all the fixed and variable losses calculated,

$$P_{conv} = P_C + P_{sCu} + P_{rCu} + P_{fw}. \tag{22}$$

With the torque obtained from the DC machines, it is possible to calculate the mechanical power with (8). Subtracting this power from the input power, one obtains the apparent total loss P_{ap}.

The stray load losses are calculated as follows

$$P_{sl} = P_{ap} - P_{conv} \tag{23}$$

since they correspond to the rest of the power that is not due to the losses already calculated.

Because the core losses were considered null for IM1, due to the lack of precision in the estimations, the stray load losses value used in the calculations is the standardized one in [1], for a 0.7457 kW to 90 kW machine.

Finally, the calculations are corrected to a reference ambient temperature of 25^{o}c [1].

The total loss is the sum of all the variable and constant losses:

$$P_{total\ loss} = P_C + P_{fw} + P_{sCu} + P_{rCu} + P_{sl}. \tag{24}$$

Since it was possible to segregate all the losses for IM2, their contribution to the total power loss is represented in figure 9 for the different load points. The highlighted zone is the normal operation region in which stator joule losses contribute the most. It can also be noted that for higher loads, the core loss becomes less relevant while the joule losses prevail. The stray load losses also increase and the friction and windage loss, which is constant for all load points, has a decreasing contribution to the total loss. This way, the efficiency is calculated by

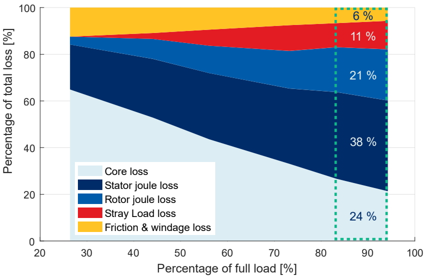


Figure 9: Induction Machine segregated losses percentage of total loss

$$\eta = \frac{P_{load} - P_{total\ loss}}{P_{load}} \times 100 \tag{25}$$

The efficiency curve and the difference between the estimated and reference efficiency curves of IM1 are obtained and depicted in figure 10.

The results are very satisfactory since with a less intrusive method, the absolute error is kept under 3% in the normal operating region, shaded in blue. It is also emphasized how small the difference is, around 0.2%, between the values corrected to a 25^{o}C temperature and the values without the correction. Depending on the conditions of the testing, if the extra readings needed to correct the values mean more intrusiveness, then not performing this correction should be considered, for it does not increase the accuracy of the estimation considerably.

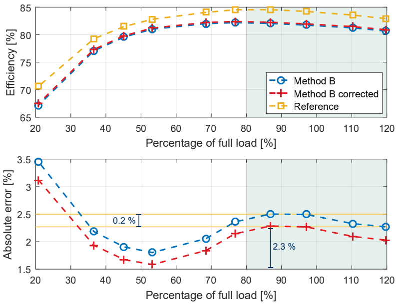


Figure 10: IM1 Efficiency curve obtained with Method B

As expected, the results in figure 11 obtained with the same method for IM2 are even better. Since all the losses were successfully segregated and there was no need to assume standardized values for some losses, the estimation is extremely precise, with an error very close to zero. On the point of lowest load, the stray load losses calculation become imprecise and have a negative value. This loss is assumed to be zero, which causes the error to rise as seen in figure 11.

3.4. Current Methods

Three current methods were tested in this experiment. The standard current method (Curr. method 1) is the simplest one, requiring only the current and power readings. The second method (Curr. method 2) is a corrected version of the first one that takes into account the offset of the current load curve by subtracting the no load current. The second method is expected to underestimate the efficiency so the third method (Curr. method 3) is the average of the first and second method and is supposed to increase the accuracy.

These characteristics are indeed observed when performing the estimation test on the bigger machine IM2 in figure 12. Current method 3 gives an efficiency estimation very close to the reference one, with an error of less than 2% on the normal operation region shaded in blue. On the other hand,

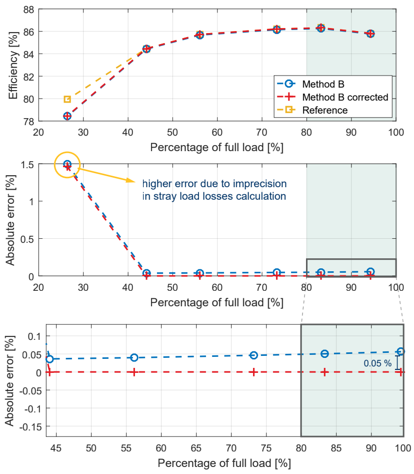


Figure 11: IM2 Efficiency curve obtained with Method B

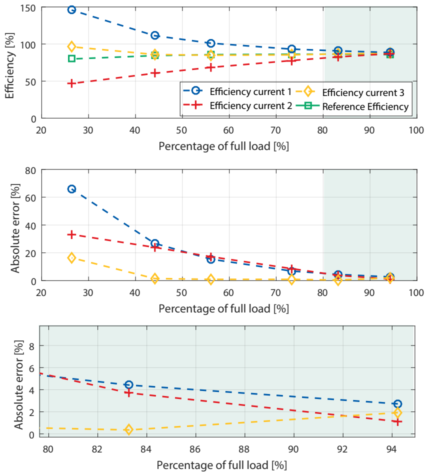


Figure 12: Current estimation method efficiency curve and absolute error for IM2

current method 1 turns out to be the most accurate in estimating the efficiency for the smaller machine IM1, showing a decrease in the absolute error of 7% to 2% between 95% to 120% of full load. This curves can be seen in figure 13. In this machine the estimations do not have the expected behavior. since the machine is smaller and precision errors start to become more relevant.

3.5. Slip Methods

The standard slip method (Slip method 1) is very simple and the readings required are the input power and rotor speed. The Ontario Hydro method (Slip method 2) is a variation of method 1 that corrects the rated nameplate speed for voltage variations, improving the accuracy in the shaded region near the full load point by 1% to 2% in both machines. Both curves are depicted in figures 14 and 15.

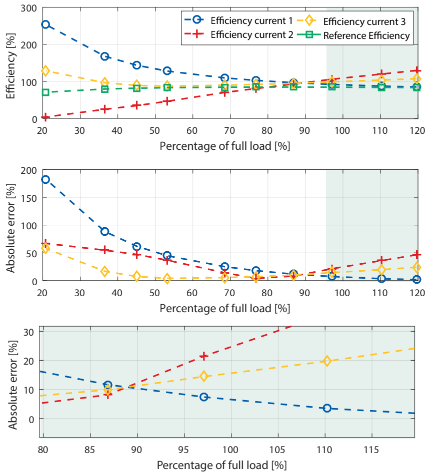


Figure 13: Current estimation method efficiency curve and absolute error for IM1

With the third method (Slip method 3), a considerably increase in accuracy is observed near the full load point, with an absolute error of approximately 1% in IM1 and 3% in IM2. With this increase in accuracy comes a higher intrusiveness, since this method requires additional measurements of stator resistance and current.

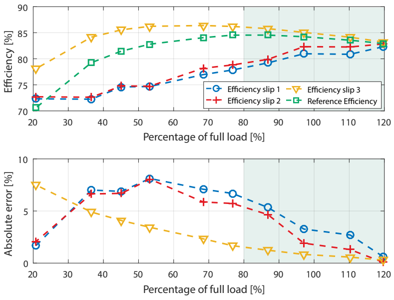


Figure 14: Slip estimation method efficiency curve and absolute error for IM1

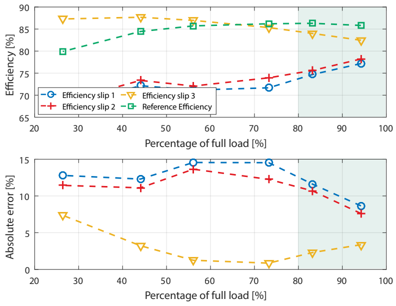


Figure 15: Slip estimation method efficiency curve and absolute error for IM2

3.6. Nameplate Method

The nameplate method is the less intrusive of all the methods studied since it only requires the nameplate data. The nameplate data is relative to one load point only, the rated or full load point. This way, the accuracy of this method is very dependent on the type of motor and on how much flat its efficiency curve is. As seen in figure 16, both efficiency curves are considerably flat, and IM2 has variation of efficiency of only 0.5% between 60% and 95% of full load.

These type of curves lead to a very small difference between the reference and estimated efficiency curves, even getting more accurate than other more intrusive methods. The efficiency curves and its absolute error for both machines can be observed in figure 17 and 18.

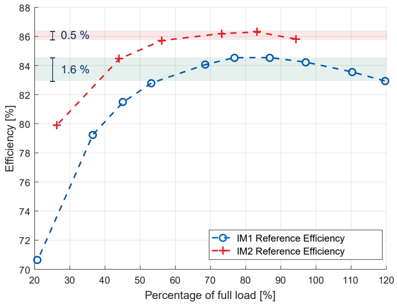


Figure 16: Induction Machines efficiency load curves

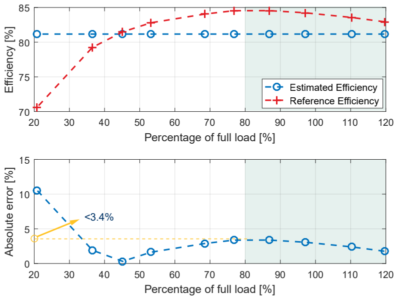


Figure 17: Nameplate estimation method efficiency curve and absolute error for IM1

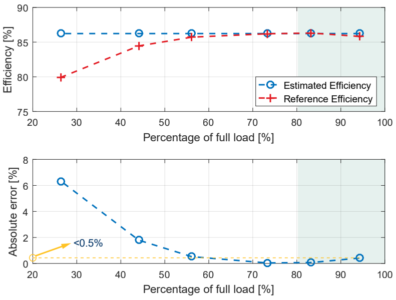


Figure 18: Nameplate estimation method efficiency curve and absolute error for IM2

3.7. Tests with connected inverter

The methods presented above are also applied to the same IM1 machine but with a connected inverter. As expected, the efficiency curve changes and can be seen in figure 19, next to the efficiency curve for IM1 without an inverter. Fed by an inverter, the machine is subjected to an input voltage with harmonic content. Since the core loss varies with frequency, this type of loss increases and the efficiency drops slightly. This behavior, naturally affects the accuracy of the estimation methods. In figure 20 and 21, the absolute error of each curve obtained with the efficiency estimation methods is

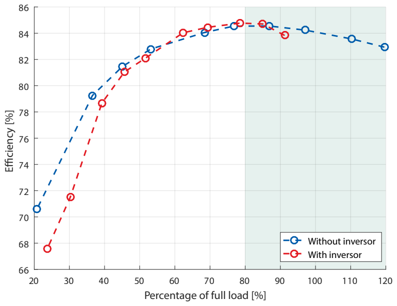


Figure 19: Efficiency curves for IM1 with and without a connected inverter

compared.

Overall, the methods accuracy drops by a small percentage but the shape of the curves is similar to the ones obtained without an inverter. The nameplate method, the equivalent circuit method and the Method B estimated curves, all keep their absolute error below 4% in between 80% and 90% of full load.

On the other hand, the estimation methods in figure 21 have a significantly decrease in their accuracy. The current method that had an error below 5% in the usual range of operation, with the inverter has an error from 5% to 10% in the best case. The slip method 3 has a satisfactory accuracy below 5% but is most intrusive slip method.

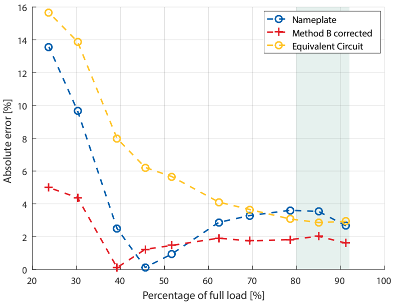


Figure 20: Efficiency estimation methods results for an inverter fed induction machine

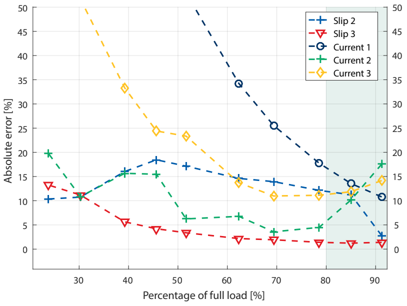


Figure 21: Efficiency estimation methods results for an inverter fed induction machine

4. Conclusions

The results of the efficiency estimation methods presented in section **??** are summarized in figure 22. On the left column, all the readings required for the several methods are presented: rotor speed (N), input voltage (V), input current (I), power factor (PF), stator resistance (Rs), mechanical torque (Torque), ambient temperature (Temp.) and nameplate data (NP). Following the parameters required, on the same column, are the tests required. On the first row of the table, all the methods tested are placed. The values in the table of the methods that require the stator resistance R_s, are done for a value of resistance measured are measured with the machine in a working temperature.

The last nine rows of the table, contain the maximum absolute error of each estimation in two intervals of percentage of full load. The first one, is the interval considered to be the usual range of percentage of load of a regular induction machine, the same used in chapter **??**, that goes from 80% to 120% of full load, or in the case of IM2, up to 95% of full load, since it was not possible to reach higher values. The second range presented, is the interval where the accuracy is considered to be acceptable and can vary from the usual range. The errors are considered acceptable under 10%. This interval is considered for some methods have an high accuracy in regions outside the normal working zone, so could still be used in special applications where the machine is working on a specific range of full load.

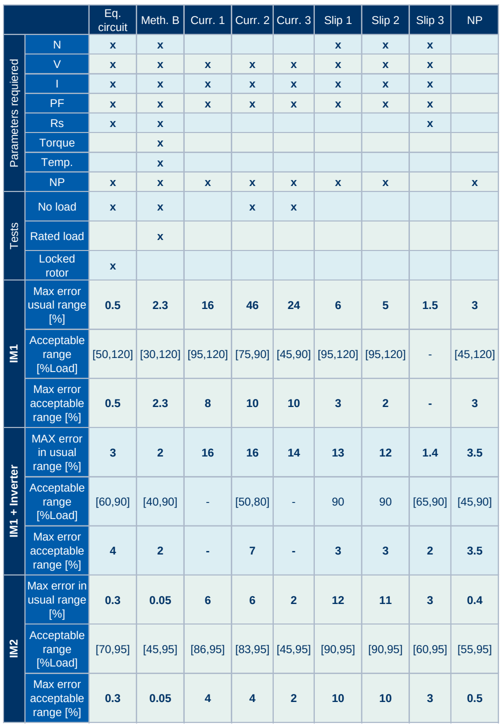
Starting with the most intrusive methods, the Equivalent Circuit (Eq. circuit) and Method B (Meth.B). Both have low values of absolute error for both machines. The equivalent circuit has an error under 0.5% in both machines for ranges of load wider than the usual operating region. The estimation using Method B has outstanding results for IM2 but an absolute error of 2.3% for IM1. This is due to the incapability of measuring the core losses in a the smaller machine, so applying this method for machines smaller than IM2 might not be most adequate. This imprecision in measuring the losses can also be improved by using more precise measuring instruments.

The current methods, on the other hand, represent the worst values of accuracy. In the smaller machine IM1, the values of absolute error are considerably higher comparing to the ones of IM2. This result suggests that the current methods are more suited for bigger machines. The current method 3 is supposed to be the most accurate, since it represents the average between the overestimation of method 1 and the underestimation of method 2. However, for its low level of intrusion, the current method 1 presents a good accuracy, under 6% of absolute error, for the bigger machine and should be considered. In the other two methods the intrusion level rises with the need of performing the no load test.

In the case of slip methods, the absolute error appears to be higher for IM2 comparing with IM1. Slip method 3 is the most accurate and the rise in intrusiveness is low, since the stator terminals are usually exposed making it possible to measure the stator resistance R_s.

Finally, the nameplate method has incredible results with an absolute error of 0.4% in IM2 for the normal working region and even being able to guarantee an absolute error under 0.5% from half to full load. This is mainly due to the flat shape of both efficiency curves. To be noted that the motors tested are not new and are subjected to several undesirable conditions, since they are used by students in classes. The machine IM2 has more than 50 years old for instance, so even in this conditions the nameplate data is still accurate to estimate the efficiency with an error lower than 3%.

The efficiency estimations with a connected inverter are in general less accurate because of the harmonic content added. However, the current methods are considerably improved, since the efficiency is now lower for low loads, the methods improve in this region. Although the error is higher, the methods are still suited for an inverter-fed induction machine. This is an important result since in the industry, most induction machines are connected to electrical drives.



		Eq. circuit	Meth. B	Curr. 1	Curr. 2	Curr. 3	Slip 1	Slip 2	Slip 3	NP
Parameters requiered	N	x	x				x	x	x	
	V	x	x	x	x	x	x	x	x	
	I	x	x	x	x	x	x	x	x	
	PF	x	x	x	x	x	x	x	x	
	Rs	x	x						x	
	Torque		x							
	Temp.		x							
	NP	x	x	x	x	x	x	x		x
Tests	No load	x	x		x	x				
	Rated load		x							
	Locked rotor	x								
IM1	Max error usual range [%]	0.5	2.3	16	46	24	6	5	1.5	3
	Acceptable range [%Load]	[50,120]	[30,120]	[95,120]	[75,90]	[45,90]	[95,120]	[95,120]	-	[45,120]
	Max error acceptable range [%]	0.5	2.3	8	10	10	3	2	-	3
IM1 + Inverter	MAX error in usual range [%]	3	2	16	16	14	13	12	1.4	3.5
	Acceptable range [%Load]	[60,90]	[40,90]	-	[50,80]	-	90	90	[65,90]	[45,90]
	Max error acceptable range [%]	4	2	-	7	-	3	3	2	3.5
IM2	Max error in usual range [%]	0.3	0.05	6	6	2	12	11	3	0.4
	Acceptable range [%Load]	[70,95]	[45,95]	[86,95]	[83,95]	[45,95]	[90,95]	[90,95]	[60,95]	[55,95]
	Max error acceptable range [%]	0.3	0.05	4	4	2	10	10	3	0.5

Figure 22: Efficiency estimation methods comparison

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