Energy Efficiency Assessment For Inverter-Fed Induction Motors

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Abstract

This paper addresses the technical issues in the energy efficiency assessment for inverter-fed motor drives according to the international technical standard (TS) IEC 60034-2-3:2013. The critical points on the TS procedure are investigated by means of experimental results, with special emphasis on the influence of the DC bus voltage, the thermal aspects, the dead-times influence and compensation on the measurements suggested by the TS. For an easier fulfilment of the thermal constraints on the maximum winding temperature variation during the test, imposed by the Norm, a very simple thermal network is proposed. The model is also useful to evaluate the time duration of the experiment. The results of the experimental activity performed on two different induction motors are included in the paper.

1 Introduction

The 46% of the total electricity consumption in the world is used by electric motors. Restricting the field to the industrial environment only, the share gets even bigger. As regards the European market, the European Commission has recently established a regulation, amended by a very recent act [1], regarding the eco-design requirements of electrical motors, including those integrated in other products. As pointed out in [2], a substantial improvement of energy utilisation is achieved by resorting to Variable Speed Drives (VSD).
The increasing use of electric motors fed by inverters has guided the international and national committees towards the definition of standardised procedures for the assessment of the efficiency of such tightly connected system. In particular, energy efficiency classes have been or shall be defined for motors, inverters and drive systems, i.e. motors connected to inverters [3].
A rule-of-thumb method is proposed in [4], to quantify the motor efficiency fed by converter supply. The paper reports a detailed list of the losses that can be ascribed to the adoption of converter power supply.
The documentation produced so far regarding the motor energy efficiency classification is summarised in IEC 60034-2-3:2013, issued under the light form of a technical specification (TS) because of the many issues arisen during the draft works. The tests to be carried out are the same as in the well-established standard IEC 60034-2-1 which has been renewed in 2014. Since it is not easy to consider a series of tests of general applicability, most of the details in IEC 60034-2-3 are still under definition [5].
In this sense, some parameters have already been arranged, such as the inverter switching frequency, which usually ranges from few kHz up to tens of kHz in order to cover a wide variety of applications. As regards the inverter topology, some preferences can be inferred, as the choice of a two-level inverter, even though very likely multi-level or matrix converters are going to increase their presence in the market. A fundamental point is that the IEC 60034-2-3:2013 applies to the squirrel cage induction motors only, although the extension to synchronous permanent magnet machines is under study.
Research activities regarding the electrical losses measurement techniques in synchronous machines have been reported in [5],[6]. At present, European Commission is working towards new directives, which are going to affect the motors and drives market even more [3].
This paper aims at contributing with comments, suggestions and modifications to the procedure indicated by the TS, to increase its practical applicability. The execution of several measurements, on different motors and under different test conditions, was also the key for a better understanding of the influence of the inverter supply on the efficiency assessment. The only way to highlight the critical points in a measurement procedure is to try a practical implementation. At the light of this (maybe trivial) consideration, the work was mainly based on laboratory tests.
The voltage bus and the dead times influence and compensation (both completely neglected by the TS) on the measurements have been considered and analysed.
In particular, the paper comments on the definition of the voltage DC bus level for the tests execution and it proposes a suitable operative method. As part of the process, several hints for carrying out the tests are reported, as an aid for both legislative authorities and industrial manufacturers.
In view of an industrial application of the testing method, the authors adopted a simplified thermal model [7] of the winding to estimate the time duration of the test that allows fulfilling the constraint on the maximum winding temperature variation during the experiment. Since successive thermal transient points mark the scheduling of the tests, the availability of a winding thermal model could be appreciated if the high costs for hiring the measurement equipment are considered.
Experimental results on winding thermal time constant of different motors size ranging from 1 kW to 55 kW have been collected and reported in the following.
The discussion will keep a close eye on the additional losses introduced by the inverter and the experiment settings influence. Their impact on residual and stray load losses will be analysed and discussed.

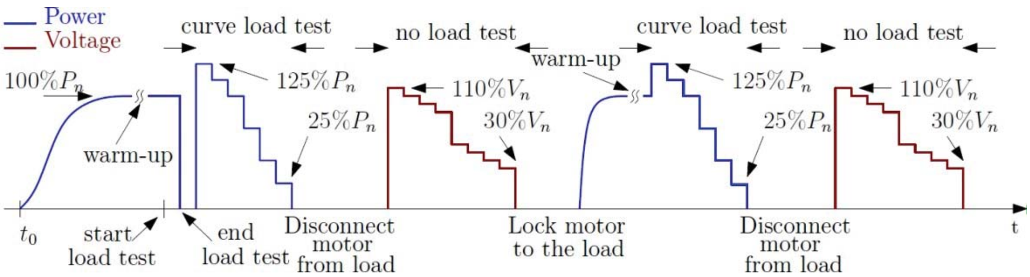

Figure 1: Timeline of the procedure for the energy efficiency assessment with sinusoidal and VSI fed I.

2 International Standard IEC 60034

The international standard IEC 60034-2-1, regarding the energy efficiency measurements with sinusoidal voltage supplied, has been recently renewed with the updated 2014 edition. The new standard introduces significant changes with respect to the previous version, hereafter summarized:

- *grouping of the test methods into preferred methods and methods for field or routine testing;*
- *addition of the details of the requirements regarding instrumentation;*
- *addition of the description of tests required for a specific method in the same sequence as requested for the performance of the test* [1].

The same method for the assessment of energy efficiency of induction motors is going to be regulated too, as in the TS IEC 60034-2-3:2013. While for the former standard the procedure is well known, the tests with voltage source inverter (VSI) is under way. However, some recent works report some practical issues for the actual implementation of the required procedures [5, 6].

2.1 IEC 60034-2-3:2013

In order to perform the energy efficiency assessment with VSI, the test procedure repeats the same steps of the IEC 60034-2-1. In particular, both the load and no-load tests were carried out in the same order, Figure 1. The TS states quite clearly that the no-load test must be carried out immediately after the sinusoidal voltage fed ones. The thermal equilibrium shall be re-established by running the machine under test at nominal load. Some uncertainty arises immediately when the motor is fed by a standard two-level commercial inverter. In particular, the problem is the generation of a three-phase voltage system that accomplishes the requirements fixed by the TS and reported hereafter. The TS states that the output voltage has to obtained by the sine/triangle technique, using as references three sinusoidal phase voltages U^*_{UD}, U^*_{VD}, U^*_{WD} (with respect to the neutral point D of the inverter), summed up to a linearity extended signal U^*_{ext}, defined as:

$$U^*_{ext} = \frac{1}{2}\min\left(abs(U^*_{UD}, U^*_{VD}, U^*_{WD})\right) \tag{1}$$

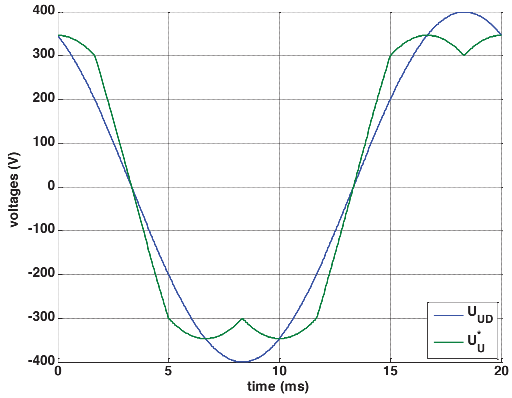

Figure 2: Required shape of the output phase voltage.

What the TS omits to say is that, in practice, the same voltage output can be obtained with the standard space vector modulation (SVM) as well. The voltage output waveform should look like Figure 2.

The output voltage magnitude should be measured with high precision transducers. However, different instruments could lead to different efficiency results [2]. The TS specifies that the output voltage must have some characteristics, such as no missing pulses. Furthermore, no control action should be considered, such as slip compensators. All this implementation aspects will be adressed and discussed in Section 3. The efficiency has to be calculated by considering the additional losses coming from the converter supply too. These additional losses are of two types, depending on whether they are load-dependent or not. The no-load dependant losses are calculated as the difference between the power losses between the no-load tests with converter supply and the oned with sinusoidal power supply. The load-dependent are the additional harmonic losses from the curve load test with converter supply and sinusoidal supply respectively. The additional motor losses are added to the motor losses obtained with the sinusoidal supply test, obtaining the total losses with converter supply, $P_{T,c}$. The motor efficiency fed by power converter is given by the following equation:

$$\eta = \frac{P_2}{P_2 + P_{T,c}} \tag{2}$$

where P_2 is the output power.

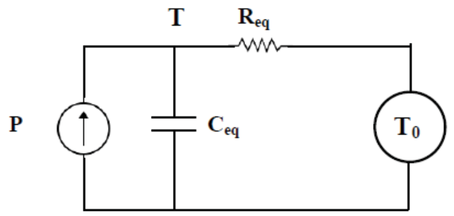

Figure 3: First order winding thermal network.

3 Experimental tests and procedure hints

The experimental procedure for the execution of the required tests following IEC 60034-2-3:2013 is almost the same as for the conventional procedure with sinusoidal supply. However, many aspects that have not been yet considered in the TS actually complicate the implementation. This section lists the authors' choices in the tests execution, providing hints for the design of the experiments.

3.1 Time duration

Tests for the assessment of the energy efficiency can last for several hours. However, most of this time is spent to bring the motor to the thermal equilibrium at nominal load. This condition is sorted out by monitoring the stator winding temperature estimated from stator resistance measurements [3]. The temperature measurement by means of temperature sensors is considered as well. According to the international standard guidelines [3], the thermal equilibrium is obtained when the motor temperature gradient is 2°K per hour when the motor is operating at nominal load.

The critical point is on the design of the variable load test duration, since the standard is vague about, stating that "tests shall be performed as quickly as possible to minimize temperature changes in the machine during testing". The maximum allowable temperature change is not given. On the other hand, an increment of 5°K is tolerable when passing from the nomimal to variable load test. In the experiments, we took the same interval as admissible temperature change for any step during the load curve test.

Interesting analyses of the electrical machine thermal behaviors in short-time transient are present in literature ([7], [8]). In particular the first order thermal model proposed in [7] allows predicting the winding temperature behavior during overload condition.

In Fig. 3 it is shown the used thermal model for predict the winding temperature T, where P is the equivalent losses generator in the winding, C_{eq} is the equivalent thermal capacitance of the winding and insulation system and R_{eq} is the equivalent thermal resistance between stator winding and insulation system. The short time thermal model can be used in this context since it allows a fair approximation of the time duration of the test in the specified temperature variation range. The windings temperature can be estimated as:

$$T = T_0 + R_{eq} P_{in} \left(1 - e^{-\frac{t}{\tau_{eq}}} \right) \tag{3}$$

where T_0 is the temperature at the starting instant t_0 and $\tau_{eq}=R_{eq}C_{eq}$ is the short time thermal model time constant.

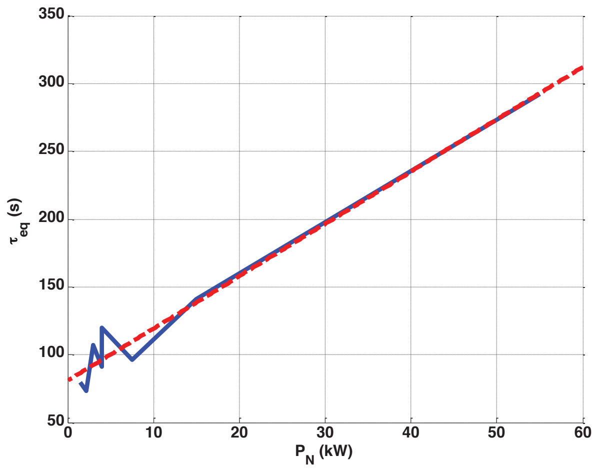

Figure 4: Experimental τ_{eq} measurements for IMs ranging from 1 to 55 kW and linear interpolation (dotted).

Equation (1) can be rewritten as follows:

$$t_1 = -\tau_{eq} \ln\left(1 - \frac{5}{R_{eq} P_{in}} \right) \tag{4}$$

where t_1 is the time for the stator windigns temperature to reach an increment of 5°K respect to the nominal condition one.

Experimental activity concerning the evaluation of the winding thermal time constant of different industrial TEFC induction motors size ranging from 1 kW to 55 kW have been collected and showed in Fig. 4. It is has been noticed that, for the investigated machines, the thermal time constant is proportional to the motor size. This suggests an useful instrument to estimate the duration of the curve load test, meanwhile guaranteeing a small winding temperature variation as required by the standard. It is worth to highlight that the same time can be used for the sinusoidal supply tests as well.

3.2 DC bus voltage

A recent work [2] have shown that the variation of motor losses by using five different converters could still return acceptable results thanks to the reasonable tollerance of 15% provided by european regulamentation. Thus, motor constructors are not forced to equipe their laboratories with special equipments other than the precise measurement ones. The TS states that the DC bus shall be adjusted for each working condition of the machine during the curve load and no load test.

Standard inverters can satisfy this condition by means of either autotransformers or controlled rectifiers, which bypass the typically uncontrolled, equipped one. However, the determination of the right DC level to fullfil the standard requirements during tests remain quite challenging. Motor temperature is an important issue, since it is the mirror of the stator resistance value, which is responsible of a large portion of the motor losses.

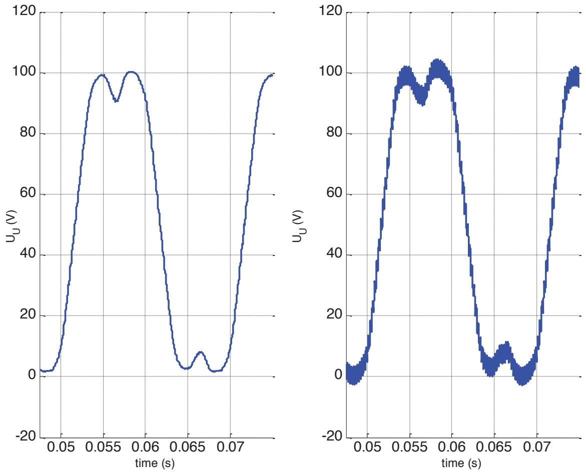

Figure 5: Motor voltages with different modulation indexes.

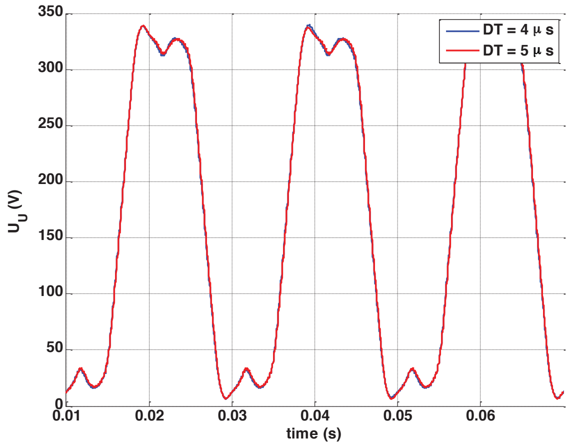

Figure 6: Measured voltage output of phase U respect to the negative DC rail at 0.5% of P_N

Therefore, the shorter the tests, the more accurate the measurement. There should be no time spent on evaluating the optimal value of the DC bus amplitude that, by standard, should be just high enough to avoid overmodulation. Standard autotransformers changes the voltage output magnitude with a manual knob. The manual search of the optimal value is time consuming and out of the standard principles.

A possible solution is to mantain the same DC bus level during the tests execution. However, the bus level varies with the load conditions. The experiments shows that the variation remains within 3% from the 125% load test to the 25% load one. Furthermore, the differences in efficiency calculation for the motor under test are really small and they can be considered almost equal to measurment errors. The no-load test does not alter the level of DC bus, since no load is connected. However, different voltage magnitude, from 110% down to 30% of the nominal one, are required for collecting the necessary measurements. A constant DC voltage would mean a large variation of the modulation index of the inverter, which in turn affects the harmonic content of the generated voltage. Therefore, it is necessary to adjust the DC bus level at each voltage test.

As an example, Figure 5 reports a comparison between voltage waveforms with the same fundamental amplitude, but very different DC buses.

The reference voltage was $U^*=0.3U_n$ = 230V (phase voltage)-to-phase, RMS value, last step of the no-load test); the left-hand curve is relative to a DC bus voltage U_{dc}=350V, while the right-hand was obtained at U_{dc} =120V. Defining the modulation index M as

$$M = \frac{\sqrt{2}U^*}{U_{dc}} \qquad (5)$$

the two curves have $M=0.92$ and 0.49, respectively.

Both curves have a low-frequency shape that matches that of Figure 2, but the harmonic content is clearly different, and this affects the iron losses due to the higher harmonic content. The variation of the DC bus with the voltage reference, indicated in the TS, aims at setting a constant modulation index for the whole test.

The DC bus voltage amplitude could be pre-calculated by considering the fundamental amplitude U^*_f at each step and the lower DC voltage (around $\sqrt{3}\ U^*_f$) that prevents the inverter from saturation. For the sake of safety, a slightly higher value will be selected, to bear possible inverter and motor non-idealities.

3.3 Dead time effects

The inverter non-idealities force the introduction of dead time to avoid leg shot through. Since neither speed nor current control is implemented, the output voltage is obtained in open loop. Therefore, the output voltage waveform must be compared with correct voltage shape, given by the TS and reported in Figure 2.

TS 60034-2-3 specifies that a second order filter, with 500 Hz cut-off frequency and a damping of 0.7 can be used for the purpose. A high sampling voltage transducer, such as a differential probe connected to an oscilloscope with high sampling frequency, was used to check out the voltage shape. The inverter nonideality strongly affects the actual output voltage. Figure 6 reports the measured output of one phase with two different dead time values. For both value there is a voltage deviation from the desired one. The voltage output shape can be improved by means of a dead time compensation strategy, even the simplest one based on the step compensation synchronised with the phase current sign, or a more refined one [8]. Another important item is the actual voltage fundamental amplitude during the load test. Even if the DC bus is kept at a fixed value or adjusted at each step, the voltage amplitude changes along with the working load conditions when no dead time compensation is implemented. Conversely, the fundamental amplitude remains quite constant when a simple dead time step compensation is implemented. Also the no-load tests are strongly affected by the dead times. It is known that induction motors with no load and in open loop control may present instability problems [12]. In some cases, it was not possible to carry out the tests as the voltage magnitude was increased to reach the nominal value.

TABLE I: MOTORS PARAMETERS

Data	Motor A	Motor B
Rated Power P_n	1.5 kW	1.5 kW
Rated frequency f	50 Hz	50 Hz
Poles	4	4
Efficiency class	IE2	IE3
Rated Voltage V_n	230 V	230 V
Rated current I_n	6.6 A	6.2 A

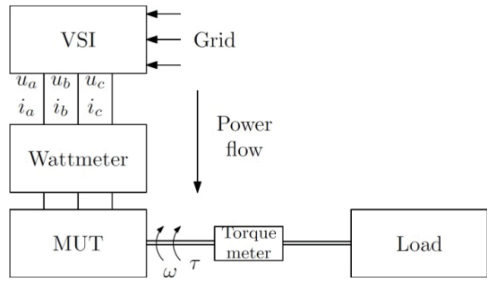

Figure 7: Experimental rig for the energy efficiency assessment with the separation losses method.

Figure 8: Induction Motors for the experimental tests.

With a dead time step compensation and the same motor, all no-load tests were carried out without instability problems. However, even the step compensation needs some manual tuning, since it is more effective if the compensation is switched off below a certain current magnitude. The best current threshold limit, though, must be found out manually, usually by means of trial and error tests.

4 Experimental activity

4.1 Setup description

The rig used for the energy efficiency assessment is sketched in Figure 7. The inverter used in the experiments is a conventional two-level voltage source inverter, with a rated RMS current of 12A. In Figure 8 are shown the two 1.5 kW total enclosed fan cooled, TEFC, induction motors, used for the experiments. The nameplate data of the two motors are reported in Table I.

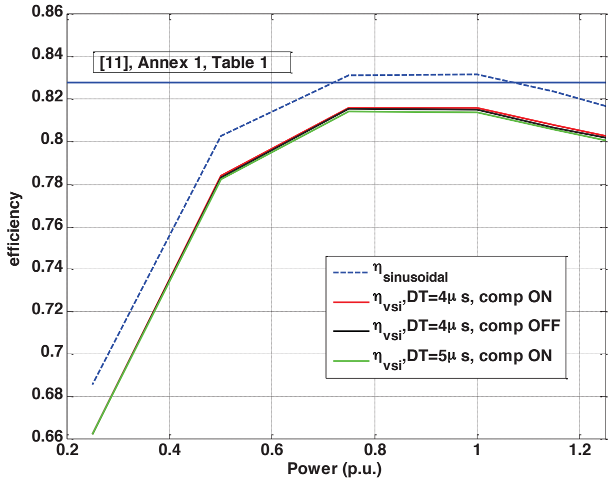

Figure 9: Efficiency results for Motor A.

The measurement instruments are delicate elements of the experiments. They must fulfil the requirements specified in both IEC 60034-2-1:2014 and TS IEC 60034-2-3:2013. In particular, the TS specifies additional requirements respect to [1], due to the presence of higher frequency harmonics caused by the VSI supply. Thus, the additional requirements regard the power analyser unit of Figure 7.

In this work, the N4L PPA2530 power analyser was used for both energy efficiency assessment and short time thermal model parameter estimation. The mechanical power was measured by means of a torque-meter Magtrol TMB 308/411 and a speed transducer connected to the load. It is worth to report that some power analysers are able to acquire even speed and torque values: the advantage of these instruments is that mechanical measurements are synchronised with the electrical ones.

4.2 Efficiency results

The efficiency results for the motors under test are reported in Figure 9, together with that obtained by the sinusoidal supply. It is worth to note that sinusoidal supply efficiency levels are higher by approximately 1.5%, as expected [2, 6]. The differences on the efficiency results coming from different DTs are reported in Figure 9. The small decrement with DT = 5μs compared with the case of DT = 4μs can be ascribed to the increased iron losses, as reported in Figure 10. Figure 11 reports the losses as function of the square of the motor voltage, with either constant or variable DC bus voltages (VSI power supply) and with pure sinusoidal supply. The Y-intercept represents the mechanical losses, while the slope of the interpolating curves is linked to the iron losses. According to Figure 5 and the related discussion, the constant DC bus introduces extra harmonic losses, which seem to slightly increase with voltage, as observed also by other authors [6]. It is worth to recall that such a test is not expected by the TS, while the variable DC bus and the pure sinusoidal measurement, prescribed by the TS, give basically similar result (Figure 11, the two lower curves). For them, the small difference in the mechanical losses may be ascribed to the different temperatures of the motor during the two tests.

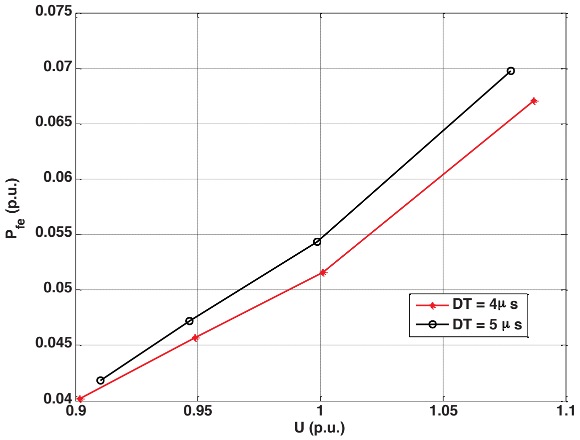

Figure 10: Iron losses with Motor A at different dead times.

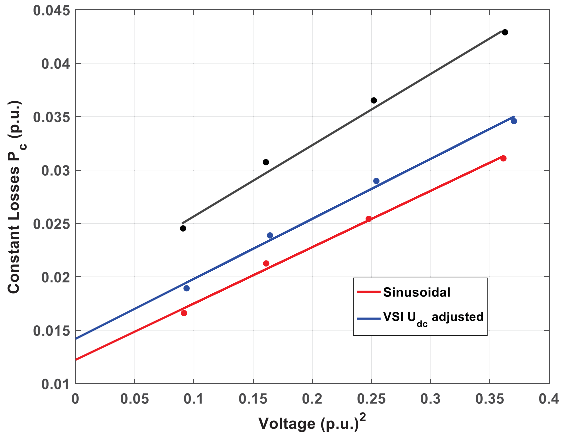

Figure 11: Mechanical losses with different supply conditions

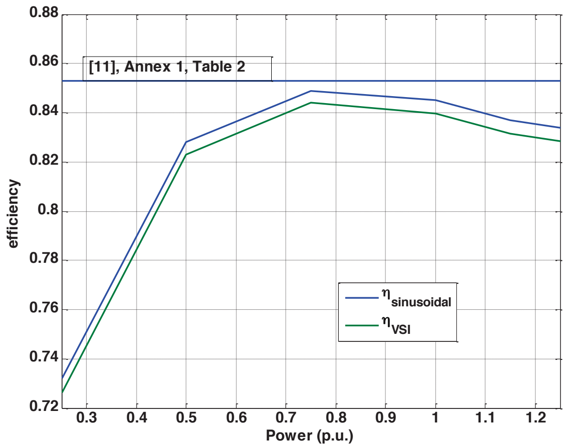

Figure 12: Efficiency results for Motor B.

Efficiency results for Motor B are reported in Figure 12. Figure 9 and 12 contain (as a straight line) the limits for the assessment of the IE2 and IE3 efficiency class respectively, according to the information given in European Directive 2005/32/EC [11].

While Motor A efficiency is under the limit and thus the claimed IE2 efficiency is confirmed (Figure 9), Motor B slightly exceeds the limit. It can anyway be considered an IE3 class due to tolerance of 5% on power losses which is allowed by [11].

5 Conclusions

The assessment of energy efficiency for inverter fed induction motor by the Technical Specification IEC 60034-2-3:2013 has been addressed and commented. Solutions for the practical implementation of the measurement procedure have been reported. Paying specific attention to the thermal condition monitoring and the DC bus voltage adjustment, the method proposed in the TS is feasible and give repeatable results. The compensation of the dead times helps in getting clean results, while the use of a simple thermal network model eases the design of experiment. Anyway, only more accurate thermal models could give the necessary confidence for the automation of the whole efficiency test, which represents the next research step.

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