Frequency Converter Driven Induction Motor Losses

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***Abstract*—Accurate measurement of power losses of high efficiency motors and converters is difficult and extra challenge is caused by pulse-width-modulated (PWM) signals. Soon, the converter-fed motors, converters, and power drive systems will get their own efficiency classifications. Also, the methods how the device losses shall be determined are given in corresponding standards. This paper presents 37 kW induction motor loss measurement results with sinusoidal and PWM supply. Five different commercial frequency converters are used to obtain single motor losses.**

Keywords—AC motors; induction motors; loss measurement; pulse-width-modulation converters; variable speed drives

I. Introduction

The introduction of energy efficiency regulations around the world has made the determination of losses and energy efficiency of the induction motor a more important topic. Currently, several IEC standards are under revision or under development. The standard IEC 60034-1: *Rotating electrical machines – Part 1: Rating and performance* [1] is under revision and publication is expected in 2014. In the next revision of the standard, also the converter-fed machines are expected to get their efficiency classes. The standard IEC 60034-2-1: *Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)* [2] is under revision, and the publication is expected in 2013. This standard has been a subject of many scientific articles, such as [3]–[5]. The revision of the standard IEC 60034-2-1 [6] will have significant advances over the first edition, such as a single preferred test method for induction motors, order of tests and measurement points in the test are fixed, and the minimum accuracy of the measurement instruments is increased. The standard IEC 60034-2-3: *Rotating electrical machines – Part 2-3: Specific methods for determining losses and efficiency from tests for converter-fed AC machines* [7] is under development and it is expected to be launched during 2013 as a technical specification. The Canadian Standards Association is developing the standard CSA 838: *Energy efficiency methods for three-phase variable frequency drive systems.* There is also development of Eco design standard that specifies the energy efficiency requirements for complete drive modules (CDM) and power drive systems (PDS). This standard defines the IE classes and provides limits as well as test procedures for their classification. The voltage source converters have been used almost four decades, but until now the converter efficiency is the object of interest due to standardization process and efficiency level classifications.

At present, there exists an application guide IEC 60034-17: *Cage induction motors when fed from converters* [8] and the standard IEC 60034-31: *Guide for the selection and application of energy-efficient motors including variable-speed applications* [9]. In [10], it is shown that the different laboratories testing the same motor came up with very different results. The Round Robin test series proved that the loss tolerance of 15% is reasonable. This shows that even the efficiency of grid connected machines is troublesome to determine. The determination of the stray load losses are the most often studied and criticized. The amount of the stray load losses has been studied using calorimeter [11] and eh-star method [12]. The converter-fed machines and pulse-width-modulated (PWM) signals create extra challenge to the motor efficiency determination. The efficiency measurement results of variable speed drives of three collaborating research institutes are presented in [13]–[15]. The authors suggest that the efficiency of VSD should be measured in operating point matrix and presented by contour curves. The additional harmonic losses caused by PWM methods have been studied widely in the literature, for example in [16]–[23]. Still, there exists no generally accepted way to determine the additional harmonic losses and whether the losses depend on load or not.

In this paper, a premium efficiency (IE3) 37 kW totally enclosed fan-cooled (TEFC) standard induction motor (Table I) heat run tests with sinusoidal and PWM supply are performed. Two heat run tests are performed with sinusoidal supply and with five different commercial frequency converters. Two of these converters are driven with two different switching frequencies. The specific details of the converters are omitted so that manufacturers of these converters cannot be identified.

This paper is organized as follows. Section II gives details of the laboratory equipment used in the tests. Section III concentrates on the motor efficiency measurements with

TABLE I
TEFC Motor Parameters for Delta Connection

Variable	Nominal value
Power, P_N (kW)	37
Current, I_N (A)	65.4
Voltage, U_N (V)	400
Torque, T_N (Nm)	239
Frequency, f_N (Hz)	50
Speed, n_N (rpm)	1482

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sinusoidal supply. In Section IV, the frequency converter driven motor losses are given and analyzed. Section V discusses the results and Section VI concludes the paper.

II. LABORATORY MEASUREMENT

The laboratory measurement setup is given in Fig. 1. All the data is gathered continuously during the measurements with a 10 second interval through a LabVIEW interface to obtain the different quantities with exactly the same time stamp. Electric power is measured with a 12-channel Yokogawa WT1600 power analyzer equipped with a high accuracy Hitec Zero-Flux CURACC current measurement system (300 A peak). The rotational speed and torque is sensed with a 500 Nm HBM T12 torque transducer. The ambient temperature is measured with three A-class PT-100 sensors installed 210 mm away from non-drive end and sides of the machine. The temperature sensors with four-wire compensation circuits are read by a Keithley 2701 data acquisition system with a Keithley 7702 40-channel differential multiplexer module. The system resolution is 0.01 K and the accuracy is ±0.06 K plus the sensor error ±(0.15 + 0.002 |T|) K. The measurement accuracies of the instruments are collected in Table II. The same measurement setup is used in [24] to obtain the motor losses with sinusoidal and PWM supply simultaneously by a calorimetric and input-output method. The input-output method with this instrumentation in these measurements has proven to give comparable loss change results with the calorimetric method.

The frequency converters are driven with a frequency reference without a slip compensation. Thus, the converter output frequency is equal to the frequency reference. In modern commercial frequency converters, the user is not able to choose the switching frequency, but only the converter operation mode, and the converter software detects the best available switching frequency. The switching frequency is a function of ambient temperature, motor operating point, and the desired performance. The slip depends on the motor load and losses, and the slip can be used as one indicator of the motor losses. The temperature rise of the motor is the main dimensioning principle in the motor design process, and it can be used as an indicator of loss changes [25].

III. SINUSOIDAL SUPPLY TESTS

As a starting point, the efficiency measurements according to the draft standard IEC 60034-2-1 Edition 2 are performed two times to reduce the effect of measurement errors in the results using the method B – Summation of losses, additional load losses according to the method of residual loss. The no-load test is performed right after the heat run test when the motor is warm. This can be considered as the most significant improvement in Edition 2 compared to Edition 1. This leads to lower friction and windage losses with grease lubricated bearings. The friction and windage losses are a function of motor temperature. Two no-load tests (one with a cold motor and another with a hot one) and an additional no-load run are performed. In the first no-load test, the stator winding temperatures were 24 °C with the cold motor, and in the second test 92 °C with the hot machine, when the friction and windage losses were 272 W and 147 W, respectively. Before the no-load run, the motor was warmed up with the load to a winding temperature over 100 °C and the shaft coupling was removed.

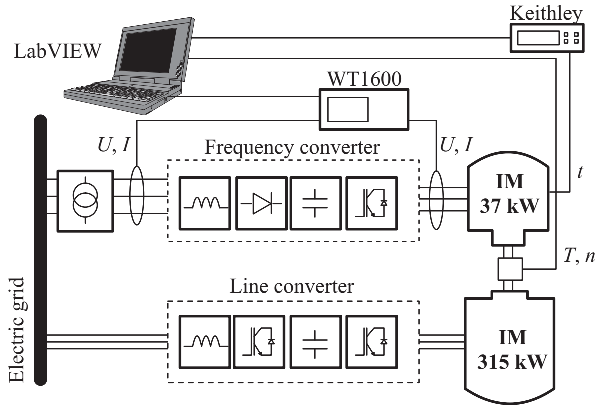

Fig. 1. Measurement setup.

TABLE II
MEASUREMENT INSTRUMENT ACCURACIES

Quantity	Instrument	Accuracy
Power	Yokowawa WT1600	Basic power accuracy 0.1%
Current	Hitec Zero-Flux	AC accuracy 0.01% rdg + 0.002% rng
Mechanical power	HBM T12	Accuracy class 0.03
Temperatures	Keithley 2701	±(0.21 + 0.002 |T|) K

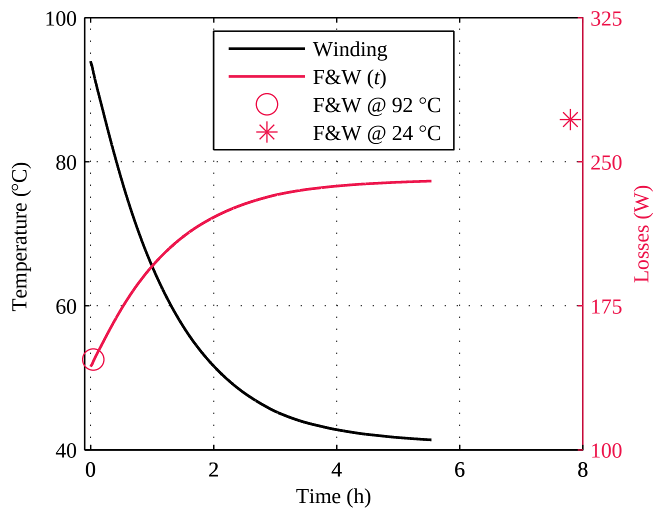

Fig. 2. Friction and windage losses and winding temperature as a function of time.

After this, the motor was cooled down during the no-load run. The no-load losses keep the motor winding temperature slightly over 40 °C. The iron losses are assumed to be constant during the no-load run, and the temperature correction of the stator winding losses was carried out in the calculation of friction and windage losses as a function of time in Fig. 2.

The loss indicators and efficiencies of the measurements are tabulated in Table III and the loss components in Table IV. The efficiency determined with the input-output and summation of losses methods has only minor differences. All the loss indicators show slight increase in the losses in the second measurement. The slip, the temperature rise, and the stator current have all slightly higher values. Before these measurement series, the winding temperature-resistance curve

TABLE III

LOSS INDICATORS AND EFFICIENCIES

Indicator of losses	**1**	**2**
IEC efficiency	94.62	94.55
In-out efficiency	94.55	94.48
Temperature rise (°C)	63.9	66.4
Stator current (A_{RMS})	65.9	66.1
Slip (%)	1.31	1.33

TABLE IV

MOTOR LOSSES ACCORDING TO IEC 60034-2-1

Losses (W)	**1**	**2**
Stator-winding	717	729
Rotor winding	495	507
Iron	425	419
Friction and windage	153	152
Additional load	322	327
Total	**2112**	**2134**
Input – output	2138	2167
Difference	26	33

was measured. In the rated load heat run tests, the motor winding temperature was 91.1 °C and 91.6 °C both resulting 111 mΩ winding resistance. In the analysis of the sinusoidal supply, the resistance-temperature curve was used instead of the resistance measurements. This procedure ensures that there exist no errors in the resistance measurements due to weak contact between the measurement instrument and the motor terminal, and the stator winding resistance measurement results are comparable to each other. The efficiencies in Table III are calculated using the mechanical shaft power P_2 instead of the electric input power P_1. The efficiency can be calculated using both the input or output power with well-known equations as given in [2]

$$\eta = \frac{P_1 - P_T}{P_1} = \frac{P_2}{P_2 + P_T} \quad (1)$$

where P_T is the total losses. The relationship

$$P_1 = P_2 + P_T \quad \equiv \quad P_2 = P_1 - P_T \quad (2)$$

does not hold true because the total losses P_T is manipulated in any way. In this context, this means that when the total losses of the motor are corrected to the reference temperature, the efficiencies calculated from the input and output power are slightly different. It is reasonable to use the mechanical output power when the efficiencies are calculated because if the motor losses were larger, the motor would take more power from the grid to overcome these larger losses. The correlation coefficient γ is 99.9% in the determination of the additional load losses in the measurement series.

The results in Tables III and IV indicate that with this measurement setup, the IEC efficiency measurement procedure gives comparable results with the input-output efficiency. The direct input-output measurement can be considered as more sensitive to the measurement errors than the IEC method. The second input-output loss value is used when the sinusoidal supply is compared with PWM supply at 50 Hz point.

IV. CONVERTER SUPPLY

Two heat run tests with a load were performed with each frequency converter. In the 50 Hz and 45 Hz points, 100% and 81% of the motor nominal torque were used as a load reference, respectively. In addition, the 45 Hz heat run test was carried out with the generator supply. At the 50 Hz point, increased converter input voltage was used to avoid overmodulation or field-weakening operation, and to reduce the overload condition of the motor. In each measurement, the fundamental wave voltage was checked to be equal to the motor rated voltage. The maximum allowable torque with the nominal rotational speed when fed from the converter is 92% of the nominal torque according to the motor manufacturer. Therefore, the motor slip and the stator current are greater than the nominal slip (1.2%) and the rated current (65.4 A) in the frequency converter measurements with the nominal load. Because the fundamental wave voltage is equal to the motor rated voltage, and the mechanical power is set to the same value with all the converters, the stator current amplitude is directly related to the motor losses. At the 45 Hz point, the converter input voltage is equal to the motor rated voltage. Thus, the frequency converter operates at linear modulation range in both points, and hence, the results in these measurement points should be fully comparable. In the heat run tests, the motor was driven until to reach the thermal equilibrium.

In all these measurements, the cables from the power supply to the converter and from the converter to the motor are the same. The length of the converter input cable is 12 meters and from converter to the motor 8 meters.

A. Motor Losses

The frequency converters in Figs. 3–8 are labeled with numbers. The first converter is using space-vector modulation with 4 kHz carrier frequency and the second one is the same converter with 2 kHz carrier frequency. The fifth and sixth are the same converter when switching frequency is high and low, respectively. Both the motor temperature and loss rise compared to the sinusoidal supply tests are presented in Fig. 3. In both the measurement points, the temperature rise correlates

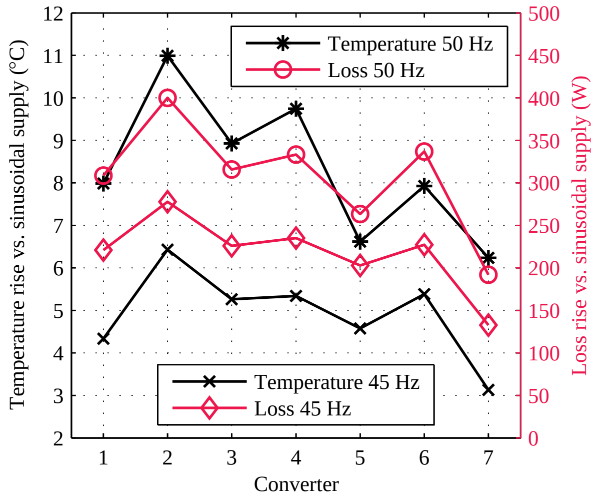

Fig. 3. Loss and temperature rises versus sinusoidal supply results in the 45 Hz and 50 Hz points.

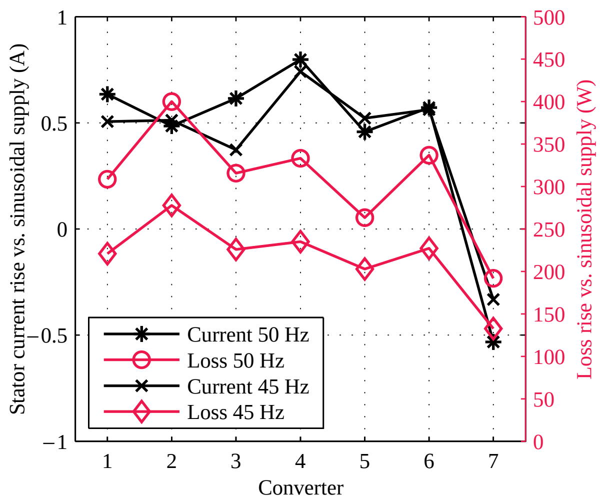

Fig. 4. Loss rises and stator RMS current value versus sinusoidal supply results in the 45 Hz and 50 Hz points.

with the loss rise. Basically, the loss and temperature rise results support each other. However, some results are also a bit non-logical, if we compare the motor losses measured with the converters 4 and 5 in the 50 Hz point. The difference in the temperature rise is more than 3 °C, but only 70 W in the losses. The average motor temperature rise is 8.3 °C and the losses 340 W greater in the nominal point with the PWM supply than with the sinusoidal supply. The average loss rise against 1 °C temperature rise is 41 W. Naturally, the temperature and loss rises are lower in the 45 Hz point than in the nominal point. The results in Fig. 3 show that the motor losses are 200 W less with the best converter than with the worst one. It should be kept in mind that this 200 W difference in the motor losses due to converter is 0.5% of the converter output power. The temperature rise is affected by ambient temperature changes and motor cooling efficiency variation due to air pressure, humidity, and temperature, but it can be considered as very stable indicator on the motor losses when thermal equilibrium is reached.

The stator current rise versus the sinusoidal supply is presented in Fig. 4. The rises of the stator current in both measurement points are almost equal. However, some non-logical behavior is presented again. The stator current rise with the converter 2 should be greater than with the converters 1 and 3 when comparing the temperature or loss rises. The stator current with the converter 7 is 0.5 A less than with the sinusoidal supply. The temperature and loss rises are also remarkably lower with this converter than with the other ones. Because the all loss indicators are in the same direction, we can reliably state that the motor losses are lower in these measurements with converter 7 than with the other converters in this measurement series. The motor losses may have decreased during these 16 heat runs and the results are not really comparable with the sinusoidal supply tests performed before the frequency converter heat run tests. The overall trend in the loss rise curve is that the losses are decreasing from the converter 1 to 7. If the converters were driven in a different sequence, the results might have been different. Similar conclusion can be drawn by using the slip shown in Fig. 5. The slip is not correlating with the losses in the same manner than

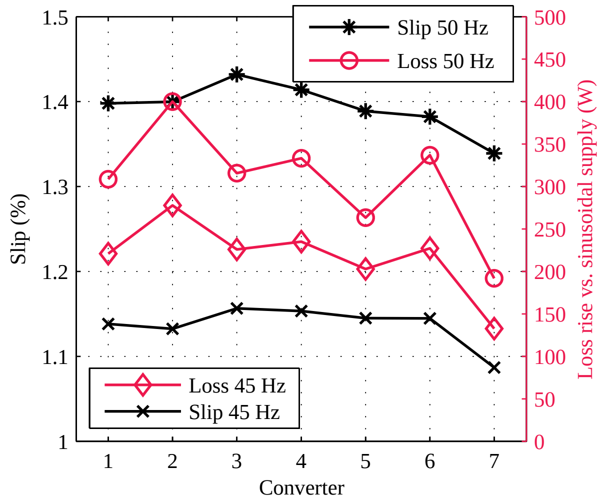

Fig. 5. Loss rises versus sinusoidal supply and motor slip value in the 45 Hz and 50 Hz measurement points. The sinusoidal supply slip in the 50 Hz point is 1.33% and in the 45 Hz point 1.12%.

temperature rise. The rotational speed value shown by the torque transducer was checked with a stroboscope to remove the possible error in the speed measurements, but we could not measure the PWM-voltage frequency reliable for all converters. Therefore, the slips in Fig. 5 are all calculated using 50 Hz as a converter output frequency.

The harmonic loss ratios in the 45 Hz and 50 Hz points are presented in Fig. 6. The harmonic loss ratio according to [7] is defined as

$$r_{HL} = \frac{P_{\mathrm{Harmonic}}}{P_{\mathrm{Loss\ (Sinusoidal)}}} \tag{3}$$

where P_{Harmonic} is the extra harmonic loss produced by the frequency converter and $P_{\mathrm{Loss\ (Sinusoidal)}}$ the sinusoidal supply losses. The result in Fig. 6 shows that the harmonic loss ratios are different but comparable in both measurement points. The increase of the harmonic losses is from 9 to 19% depending on the converter in the nominal point and 1%-unit less in the

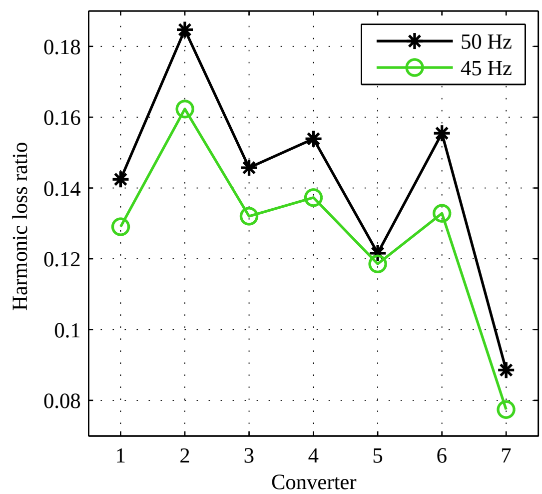

Fig. 6. Harmonic loss ratios in the 45 Hz and 50 Hz measurement points with different converters.

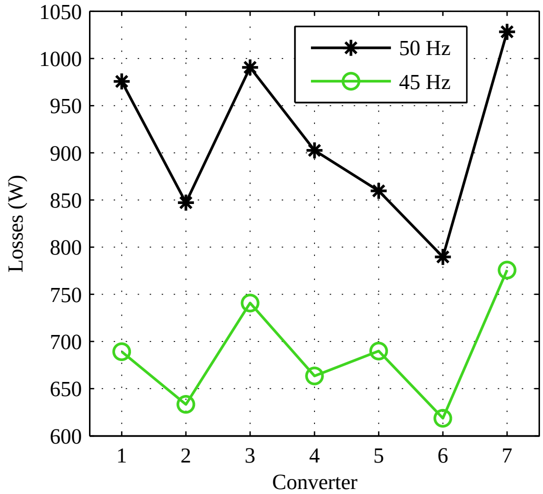

Fig. 7. Converter losses at the end of heat run tests.

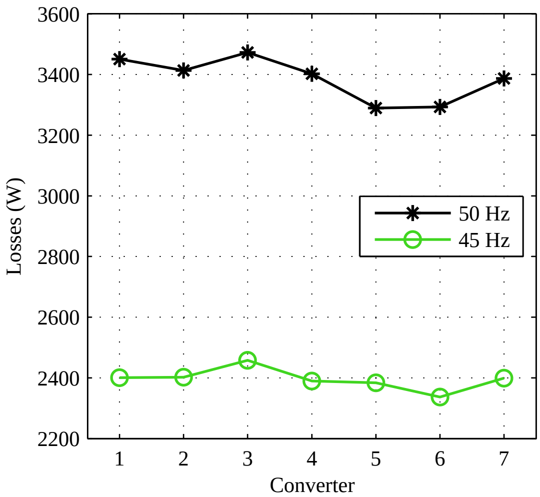

Fig. 8. Drive losses in the 45 Hz and 50 Hz measurement points.

45 Hz point.

B. Converter Losses

The commercial converters efficiency varies between 97–98%. The losses in the converter can be divided into five groups, input inductor losses, diode rectifier losses, intermediate circuit losses, IGBT module losses, and extra losses, which are comprised of the inverter self-usage, for instance the blower and control system power consumption [26]. The converter losses are mainly produced by the IGBT module and they are directly related to the switching frequency. All converter loss results include also the motor cable losses. The measured converter losses are presented in Fig. 7. The impact of the switching frequency can be clearly seen when comparing the results of the converter 1 against the converter 2, and the converter 5 against the converter 6.

C. Drive Losses

If we look at the drive total losses instead of the converter or motor losses, the accuracy of the loss results are theoretically and practically improved, because the drive efficiency is lower than the drive component efficiency. The loss measurement with the input-output method is not as sensitive to the input and output power errors. In addition, we do not have to measure the active power of PWM signal, which is the most problematic quantity in the converter-fed machine efficiency determination. The total drive losses in the nominal point and in the 45 Hz measurement points are presented in Fig. 8 for all converters.

The drive losses are from 3300 W to 3500 W in the nominal point and from 2350 W to 2450 W in the 45 Hz point. The drive efficiencies in the nominal point are from 91.4% to 91.9% depending on the converter used. The drive efficiencies are slightly higher in the 45 Hz operating point because of the improved efficiency of the motor with lower load. The impact of the switching frequency on the drive losses is marginal in both cases.

V. Discussion

The reliable comparison of different frequency converters in the drive efficiency point of view is troublesome and time consuming. Here, only one motor and two measurement points was used to test the efficiency of the drive. For full comparison, several load points have to be used. Because the motor losses depend on the temperature, the partial load losses cannot be determined with quick load points. The temperature relation of all motor loss components, such as friction and windage losses, should be measured in thermal equilibrium condition to obtain the best accuracy. In these tests, the first converter with 4 kHz carrier frequency and SPWM modulation gives a reliable estimate of the motor average loss increase in the frequency converter supply. Here, the same people have used the same measurement environment and procedure to obtain the motor losses fed with different converters. In addition, the same data analysis is applied, and even though, the measurement results include some non-logical behavior. The results could be very different if the power analyzer, the current measurement system or the torque transducer was replaced with another device. Another good question is that how accurately we need to measure the motor losses, because the mechanical and electrical characteristics of the motors tend to alter during time. Extreme care should be taken when inspecting the measurement results and asses the uncertainty of the converter-fed machines. In the comparative studies, no indicator of the losses should be used solely to draw conclusions. The slip of the motor and the temperature rise of the machine can strengthen the value of the input-output measurements that are sensitive to the errors. The calorimetric method is one alternative approach that could be used as a reference for the input-output measurement, but it is time consuming, quite challenging to arrange, and the results are troublesome to verify.

VI. Conclusion

According to these measurements, the standard induction motor losses increase from 9% to 19% in the frequency converter use compared to the sinusoidal supply at the nominal load point. This motor efficiency under sinusoidal supply is 94.6% and the efficiency is reduced down to 93.5%–94.0% when used with different converters. The loss increase as well as efficiency decrease are greater in the nominal point if increased converter input voltage is not used and normal overmodulation or field weakening procedure is allowed. As expected, the results obtained in the 45 Hz point are clearly comparable to those obtained in the 50 Hz point with the increased converter input voltage.

The drive losses results show that even if the construction of the converters, the modulating methods or the switching frequencies are slightly different from each other, the total drive efficiencies end up very close to each other when the same motor is used. The increase of the switching frequency decreases the motor losses but at the same time increases the converter losses. The actual energy saving potentials lies in the optimizing of the systems efficiency rather than in the choice of a single device such as a frequency converter.

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