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CONVERTER-FED INDUCTION MOTOR LOSSES: DETERMINATION WITH IEC METHODS

Examiners: Professor Juha Pyrhönen
D. Sc. Lassi Aarniovuori

ABSTRACT

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Master's thesis

2015

99 pages, 18 figures, 37 tables and 5 appendices

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Keywords: induction motor, frequency converter, losses, efficiency, summation of losses, IEC 2-3-A method, IEC 2-1-1B method

Energy efficiency is an important topic when considering electric motor drives market. Although more efficient electric motor types are available, the induction motor remains as the most common industrial motor type. IEC methods for determining losses and efficiency of converter-fed induction motors were introduced recently with the release of technical specification IEC/TS 60034-2-3. Determining the induction motor losses with IEC/TS 60034-2-3 method 2-3-A and assessing the practical applicability of the method are the main interests of this study. The method 2-3-A introduces a specific test converter waveform to be used in the measurements. Differences between the induction motor losses with a test converter supply, and with a DTC converter supply are investigated. In the IEC methods, the tests are run at motor rated fundamental voltage, which, in practice, requires the frequency converter to be fed with a risen input voltage. In this study, the tests are run on both frequency converters with artificially risen converter input voltage, resulting in rated motor fundamental input voltage as required by IEC. For comparison, the tests are run with both converters on normal grid input voltage supply, which results in lower motor fundamental voltage and reduced flux level, but should be more relevant from practical point of view. According to IEC method 2-3-A, tests are run at rated motor load, and to ensure comparability of the results, the rated load is used in the grid-fed converter measurements, although motor is overloaded while producing the rated torque at reduced flux level. The IEC 2-3-A method requires also sinusoidal supply test results with IEC method 2-1-1B. Therefore, the induction motor losses with the recently updated IEC 60034-2-1 method 2-1-1B are determined at the motor rated voltage, but also at two lower motor voltages, which are according to the output fundamental voltages of the two network-supplied converters.

The method 2-3-A was found to be complex to apply but the results were stable. According to the results, the method 2-3-A and the test converter supply are usable for comparing losses and efficiency of different induction motors at the operating point of rated voltage, rated frequency and rated load, but the measurements do not give any prediction of the motor losses at final application. One might therefore strongly criticize the method’s main principles. It seems, that the release of IEC 60034-2-3 as a technical specification instead of a final standard for now was justified, since the practical relevance of the main method is questionable.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT School of Energy Systems
Sähkötekniikan koulutusohjelma

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TAAJUUSMUUTTAJASYÖTETYN INDUKTIOMOOTTORIN HÄVIÖIDEN MÄÄRITTÄMINEN IEC:N MENETELMILLÄ

Diplomityö

2015

99 sivua, 18 kuvaa, 37 taulukkoa ja 5 liitettä

Tarkastajat: Professori Juha Pyrhönen
TkT Lassi Aarniovuori

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TkT Markku Niemelä

Hakusanat: induktiomoottori, epätahtimoottori, taajuusmuuttaja, häviöt, hyötysuhde, erillishäviöiden summausmenetelmä, IEC-menetelmä 2-3-A, IEC-menetelmä 2-1-1B

Energiatehokkuus on tärkeä sähkömoottorikäyttömarkkinoita koskeva aihe. Vaikka oikosulkumoottoria energiatehokkaampia moottorityyppejä on saatavilla, se on edelleen yleisin käytännön moottorityyppi. IEC:n menetelmät taajuusmuuttajasyöttöisten induktiomoottoreiden häviöiden ja hyötysuhteen määritykseen esiteltiin vastikään julkaistussa teknisessä spesifikaatiossa IEC/TS 60034-2-3. Induktiomoottorin häviöiden määrittäminen IEC/TS 60034-2-3:n menetelmällä 2-3-A on työn pääkohteena. Menetelmässä 2-3-A käytetään erityistä testikonvertterikäyrämuotoa ja erot induktiomoottorin häviöissä testikonvertterisyötöllä ja DTC-konvertterisyötöllä ovat työssä toisena kohteena. IEC:n menetelmissä kokeet suoritetaan moottorin nimellisellä pääaallon jännitteellä, mikä vaatii käytännössä taajuusmuuttajan syöttöjännitteen korottamista. Työssä kokeet suoritetaan molemmilla taajuusmuuttajilla käyttäen keinotekoisesti korotettua muuttajan syöttöjännitettä, jolla pääaallon jännite saadaan moottorin nimelliseksi IEC:n vaatimusten mukaisesti. Vertailun vuoksi kokeet molemmilla taajuusmuuttajilla suoritetaan lisäksi käyttäen normaalia verkkojännitesyöttöä, minkä pitäisi olla käytännön kannalta relevantimpaa. Menetelmässä 2-3-A kokeet suoritetaan moottorin nimelliskuormalla ja jotta tulokset olisivat vertailukelpoisia, myös kokeet verkkosyötetyillä taajuusmuuttajilla suoritetaan nimelliskuormalla, vaikka nimellisväännön tuottaminen alentuneella jännitteellä ja vuolla tarkoittaakin moottorin kannalta ylikuormaa. Menetelmässä 2-3-A tarvitaan tulokset myös sinisyöttökokeista IEC:n 2-1-1B-menetelmällä. Induktiomoottorin häviöt määritetään sinisyötöllä äskettäin päivittyneen standardin IEC 60034-2-1 menetelmällä 2-1-1B moottorin nimellisjännitteellä sekä kahdella alemmalla jännitteellä, jotka ovat verkkosyötettyjen taajuusmuuttajien lähtöjännitteiden pääaallon mukaiset.

Menetelmä 2-3-A todettiin monimutkaiseksi soveltaa, mutta sen antamat tulokset olivat vakaita. Työn tulosten perusteella menetelmä 2-3-A ja testikonvertterisyöttö soveltuvat induktiomoottoreiden väliseen häviöiden ja hyötysuhteen vertailuun nimellistaajuuden, nimellisjännitteen ja nimelliskuorman mukaisessa toimintapisteessä, mutta mittaukset eivät anna minkäänlaista ennustetta moottorin häviöistä loppukäyttökohteessa. Tämän perusteella vaikuttaa siltä, että IEC 60034-2-3:n julkaiseminen toistaiseksi teknisenä spesifikaationa lopullisen standardin sijaan oli vähintäänkin perusteltua, koska päämenetelmän käytännön merkitys on kyseenalainen.

ACKNOWLEDGEMENTS

This thesis was written at Laboratory of Electrical Drives Technology, at the LUT School of Energy Systems, in Lappeenranta University of Technology.

First, I would like to thank my supervisor Lassi Aarniovuori for providing an interesting subject for the thesis and for his constant inspiration and motivation. I would like to thank also my other supervisor Markku Niemelä for his guidance and feedback. To my examiner, Professor Juha Pyrhönen, I would like to express my deepest gratitude for invaluable advice for improvements, corrections and alternative perspective in finalizing this thesis. Special thanks go to Kyösti Tikkanen for arrangements in the laboratory and help with the measurements.

Lastly, I wish to thank my now almost 7-month-old daughter Tea for providing additional challenge, but at the same time the greatest joy and energy to go forward.

Lappeenranta, September 21, 2015

Hannu Kärkkäinen

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ABBREVIATIONS AND SYMBOLS

Acronyms

ABB	ASEA Brown Boveri
AC	Alternating Current
DC	Direct Current
DTC	Direct Torque Control
EMI	Electromagnetic Interference
HBM	Hottinger Baldwin Messtechnik
IEC	International Electrotechnical Commission
PWM	Pulse Width Modulation
SVM	Space Vector Modulation
TEFC	Totally Enclosed Fan Cooled
TS	Technical Specification

Roman variables

A	linear regression constant (slope)
B	linear regression constant (value at zero)
f	frequency
I	current RMS value
k	correction factor
n	rotational speed
p	number of pole pairs
P	power
r	ratio
R	resistance
s	slip
t	time
T	torque
U	voltage

Greek variables

θ	temperature
γ	correlation coefficient (linear regression)
τ	thermal time constant
φ	phase angle

Subsripts

0	no-load, no-load test
1	input
2	output
c	coolant, constant
C	frequency converter, on frequency converter supply
cool	(of) cool motor
end	end value
fe	iron, core
fit	fitted (calculated)
fw	friction and windage
fund	fundamental
HL	harmonic loss
i	inner
I/O	input-output, input-output method
L	load, load curve test
LL	stray-load / additional load
Lr	residual
meas	measured
N	nominal, rated, rated load test
r	rotor
rise	value of increase
s	stator
T	total
U1V1	between motor terminals U1 and V1
θ	temperature based, temperature corrected
η	efficiency

1 INTRODUCTION

Energy efficiency is an important topic when considering electric motor drives market. Efficiency regulations and standards steer the manufacturers and customers towards more efficient motors. Although more efficient electric motor types – such as permanent magnet synchronous or synchronous reluctance motors – are available, the induction motor remains as the most common type. Low cost, rugged structure and simple maintenance are some of the reasons behind steady success of the induction motor. Since the cost of the induction motor is relatively low, the energy consumed by the motor constitutes major part of the total lifetime cost of the motor, which raises the importance of the motor efficiency.

For efficiency figures to be comparable between different motors from different manufacturers, uniform testing methods for determining the motor losses and efficiency are important. Testing methods are defined in international standards. International Electrotechnical Commission (IEC) has recently released new standards considering efficiency of induction motors. Updated methods for determining motor losses were released in June 2014, and latest standard defining efficiency classifications was released in March 2014. Both new standards include improvements considering motors of higher efficiency.

In several applications, the electric drive system consists of an induction motor and a frequency converter. Frequency converter enables control of the motor speed and helps improving overall efficiency when rated motor speed is not needed. Although frequency converters have been available for a few decades, regulations and classifications have not included them as motor power supply until recently. IEC methods for determining losses and efficiency of converter-fed induction motors were released as a technical specification in 2013. In addition, IEC is working on efficiency classifications for converter-fed induction motors and the standard is expected to be launched in the near future.

IEC efficiency classifications play important role, since European Commission has already set regulations for minimum IEC efficiency classes of new electric motors. Current timetable of implementing new regulations reaches 2017, but further and tighter efficiency regulations are to be expected as motor efficiencies improve.

1.1 AC motor efficiency classes

Efficiency classifications for AC motors are defined in the standard IEC 60034-30-1. IEC 60034-30-1 was released in 2014 replacing the previous standard IEC 60034-30. IEC 60034-30-1 specifies efficiency classes for line operated AC motors. Upcoming standard IEC 60034-30-2 shall specify classifications for variable speed AC motors.

IEC 60034-30-1 defines four efficiency classes, IE1 – IE4, where IE1 has the lowest efficiency and IE4 the highest efficiency (IEC 2014b). The new premium efficiency class IE4 was introduced in this publication. The next classification, IE5, will be included in future editions of the standard when commercial products reaching the required efficiency levels become available. The IE-classes are defined by efficiency limits. For example, considering a 15 kW induction motor with a synchronous speed of 1500 rpm and a supply frequency of 50 Hz, the classification is defined by the limits shown in Table 1.1.

Table 1.1. Example of IEC efficiency classification for AC motors of 15 kW and 50 Hz with synchronous speed of 1500 rpm (4-pole). (IEC 2014b)

Efficiency [%]	**IE-class**
≥ 88.7	IE1
≥ 90.6	IE2
≥ 92.1	IE3
≥ 94.0	IE4

The efficiency classifications to be introduced with IEC 60034-30-2 for variable speed motors shall have similar classification with slightly lower efficiency limits for each IE-class. Currently, there exists only technical specification IEC/TS 60034-2-3 for determining the efficiency and losses of converter-fed induction motors. Before classifications are applicable, the methods for determining the efficiencies have to be established by international standards.

In 2009, European Commission introduced a timetable for implementing the minimum electric motor efficiency regulations. The limits specified by the regulation are to be implemented in three stages and the second stage came into force 1.1.2015. (European Commission 2009.) The three stages of the regulations are shown in Table 1.2. The current timetable reaches only to year 2017. However, as the efficiencies of new electric motors improve and variable speed motors get their own IE-classes, the progress of tightening efficiency limits for new motors can be expected to continue in the future. In addition to the European regulations, similar trend is going on around the world.

Table 1.2. Current timetable of European Commission regulations for electric motor energy efficiency. (European Commission 2009)

Applies from	**Requirements**
16.6.2011	Motors shall meet the limits of IE2 efficiency class
1.1.2015	Motors with rated output power of 7.5 kW – 375 kW shall meet the limits of IE3 efficiency class, or IE2 efficiency class, if equipped with variable speed drive.
1.1.2017	Motors with rated output power of 0.75 kW – 375 kW shall meet the limits of IE3 efficiency class, or IE2 efficiency class, if equipped with variable speed drive.

1.2 Scope and structure of the thesis

As the induction motor efficiencies improve, the determination of the efficiency and losses becomes harder. In addition, determining the losses of converter-fed induction motor accurately is especially difficult. Recent IEC publications target to give better tools for determining losses of induction motors and the methods for determination of converter-fed motor losses have also been introduced.

In this master's thesis, the main interest are the latest IEC methods for determining induction motor losses and efficiency on frequency converter supply. The losses and efficiency of a 15 kW induction motor are determined on both sinusoidal (mains) supply and on frequency converter supply. Two frequency converters, each utilizing different output waveform, are used in the converter measurements. The first converter is set to provide a waveform defined by IEC, and the second converter represents a more typical converter for final application. The possible differences in the motor losses when fed with the two different converter waveforms are another target of this study. The primary method used in the measurements is the IEC summation of losses method, in which total motor losses are determined from separate loss components. In addition, simple input-output losses are calculated for comparison. The efficiency and losses of the frequency converters are not taken into account in the analysis.

Additionally, the possibility to run motor efficiency tests on frequency converter supply without risen converter input voltage is investigated. The motor rated voltage is typically the same as the grid voltage. In the IEC methods for frequency converter supply, rated fundamental motor voltage is required and in order to achieve this, the frequency converter input voltage has to be risen above the grid voltage. When a converter is fed directly from the grid, the fundamental motor voltage is considerably lower than rated. Therefore, in addition to the risen voltage tests, the efficiency tests are made on both frequency converters running at the grid voltage.

A brief introduction to induction motor losses is given in chapters 1.3 and 1.4. Classification of the separate induction motor loss types and sources of the losses are explained in chapter 1.3. Chapter 1.4 gives insight to the effect of the frequency converter supply on the induction motor losses. The current IEC methods for determining induction motor losses are introduced in chapter 2. Although only a few of the IEC methods are valid for efficiency classifications, all methods are shortly covered in the text to give a wider look into possible methods for determining motor losses. The third chapter includes all performed measurements and their results with detailed descriptions of the methods and procedures used in the measurements. In chapter 4, the encountered problems and uncertainties of the measurements and methods are discussed. In the last chapter, most important conclusions of the thesis are presented along with some suggestions for future work.

1.3 Induction motor losses

The purpose of an electric motor is to convert electrical energy into mechanical energy. The electrical energy used by the motor is never completely utilized in the mechanical load because part of the energy is lost in different stages of the process. The losses of an induction motor depend on several different factors such as load, frequency of the supply voltage and size of the motor. In addition, the waveform of the supply voltage has a significant effect on motor losses. The losses are at minimum when an induction motor is fed with pure sinusoidal voltage. However, using a frequency converter can largely reduce energy consumption in variable load applications although the modulated waveform of the converter supply is far from ideal when considering the motor losses.

Induction motor losses can be categorized either by the location where they occur in the motor, or by their electromagnetic origin. Based on their location, the induction motor losses are divided into winding losses, iron losses and friction & windage losses. Based on electromagnetic origin, the winding and iron losses can further be divided into fundamental losses, space harmonic losses and time harmonic losses. (Boldea & Nasar 2002b, p. 2.)

The most typical classification is based on both the location and the electromagnetic origin. In this classification, the winding and iron losses contain all fundamental electromagnetic losses, friction and windage losses include all mechanical motor losses, and all harmonic losses are combined and referred to as additional load losses (or stray-load losses). Summary of the classification of the induction motor losses is presented in Table 1.3.

Table 1.3. Classification of the induction motor losses by location in the motor and by electromagnetic origin. The third classification is the commonly used classification where all harmonic losses are referred to as additional load losses or stray-load losses.

Classification by location in motor	Losses in stator and rotor windings		Losses in magnetic circuit core materials		Mechanical losses of the motor
Classification by electromagnetic origin	Fundamental winding losses	Harmonic winding losses	Harmonic iron losses	Fundamental iron losses	-
Commonly used classification	Winding losses	Additional load losses (Stray-load losses)		Iron losses	Friction and windage losses

Winding and iron losses consist of separate components for stator and for rotor. The stray losses are typically considered only on load and therefore they are called additional load losses or stray-load losses. The stray losses occur also at no-load but in practice, the no-load stray losses end up included in the iron losses because of the test procedures.

The proportions of induction motor loss components depend on the size of the motor. Figure 1.1 shows typical loss distributions from induction motors with rated powers of 0.75 kW to 160 kW. The loss distributions of Figure 1.1 do not necessarily represent the latest high and premium efficiency motors well, but they give a good overall view on typical proportions of loss components and their dependence on motor size. The relative proportions of rotor winding losses and iron losses vary only slightly with motor size, representing approximately one fifth of total losses each. The stator winding losses, in turn, comprise major part of the losses in small induction machines, but as the motor size increases, the share of stator winding losses is reduced significantly. The portions of mechanical losses and stray-load losses, on the contrary, are very little in small induction motors, while in larger motors of 160 kW, both constitute approximately 10 % of total losses.

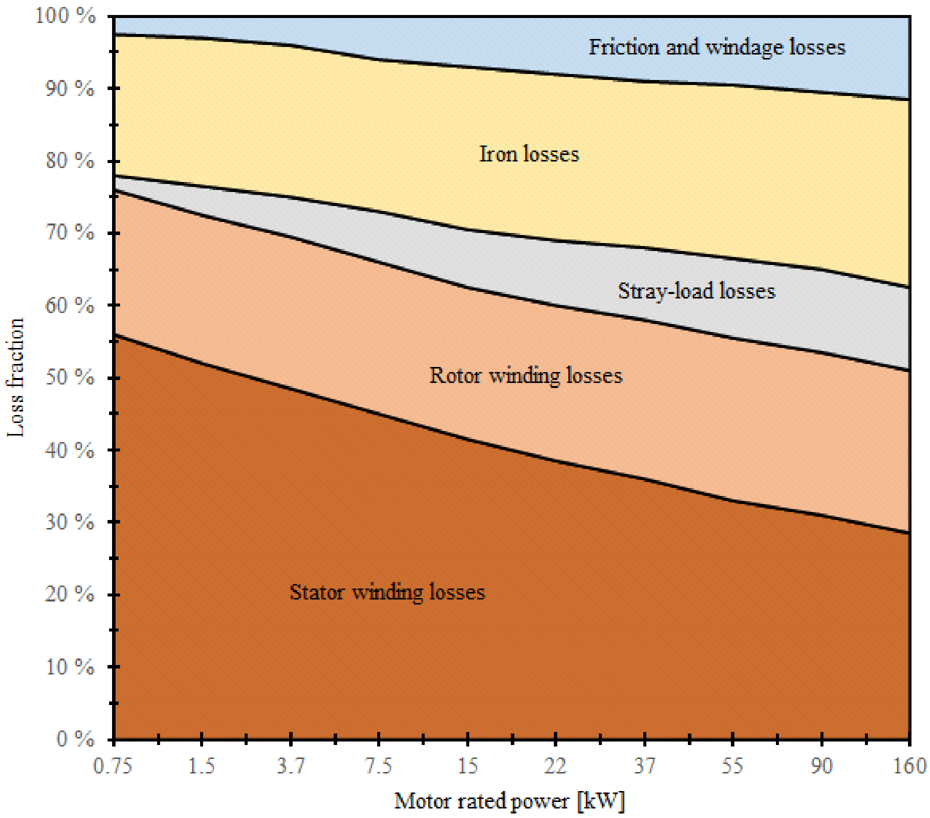

Figure 1.1. Typical loss distribution of four-pole induction motors. The figure shows relative proportions of each loss component and their dependence on the motor size (motor rated power from 0.75 kW to 160 kW). Data adopted from de Almeida et. al. (2008).

On a sinusoidal supply, the sources of losses are fundamental and space harmonic iron and winding losses and mechanical losses. Time harmonic losses are by definition absent when the supply is purely sinusoidal. However, time harmonics may occur with a mains supply, if there are other power electronic devices nearby in the same distribution network (Boldea & Nasar 2002b, p. 30). The output voltage and current of a frequency converter, on the contrary, contain large amount of high frequency time harmonics. These cause considerable additional harmonic losses in the motor. However, in several applications, the ability to control the motor speed can easily compensate and exceed these losses in the reduction of total power consumption of the motor.

1.3.1 Winding losses

Resistive losses in stator copper windings and rotor cage cause significant part of total motor losses especially under load. These losses are proportional to the square of the current and the resistance of the winding (Pyrhönen et. al. 2008, p. 458). Stator winding losses are caused by the magnetizing current and the torque-depending component of the stator current. In the rotor, the resistive losses are due to slip-speed induced current, which also depends heavily on the load. Only a very small slip resulting in small rotor current is needed to maintain nearly synchronous speed in no-load situation.

Winding losses are also affected by the temperature characteristics of the conductor resistance. When the temperature rises, the conductor resistance rises depending on the material specific temperature coefficient. If the motor load remains constant, also stator and rotor currents need to remain constant, thus the losses increase in the winding resistances when temperature rises.

1.3.2 Iron losses

Iron or core losses occur in the magnetic core materials of the stator and the rotor and they are caused by two separate phenomena: eddy currents and hysteresis. Iron losses are proportional to frequency and the peak flux density (Mohan 2003. p. 15-3). Iron losses in the stator are more significant than in the rotor, since frequency of the rotor current is proportional to slip, which is typically only a few percent. Iron losses of the stator are nearly independent of the load. Rotor iron losses on the contrary depend on slip, which depends on load.

Eddy currents are induced by moving or changing magnetic flux in any conductive material. Alternating current (AC) in the stator windings produces a rotating flux wave, which induces eddy currents in stator core. The stator core is constructed from thin steel laminations to reduce eddy currents. The thinner laminates are used, the smaller eddy currents are induced. In addition, the materials used have an impact on the eddy current and hysteresis losses. In the rotor, eddy currents are induced similarly in the rotor core as in the stator core. However, in the rotor the fundamental flux wave moves at only the slip-speed and the induced eddy currents are significantly smaller – in practice negligible. Eddy currents produce heat in the resistances of the laminate sheets.

Hysteresis losses are caused by the magnetic properties of the core material. When ferromagnetic material, such as steel, is brought to a magnetic field, magnetic dipoles of the material are aligned with the field. After the magnetic field is removed, part of the alignment is retained. When opposite magnetic field is then applied, the magnetic dipoles turn correspondingly. During this process, energy is needed to align the dipoles and remove the retained alignment. The energy needed to remove the retained alignment is lost as heat. In the stator, the magnetic field changes at supply frequency and in the rotor at a lesser frequency determined by the slip-speed, hence the hysteresis losses are much smaller in the rotor. Hysteresis losses can be minimized by selection of the core material.

1.3.3 Friction and windage losses

Friction and windage losses include all mechanical losses of the motor. Friction occurs in the bearings and seals of the motor. Windage losses are caused by the cooling fan and the rotor air resistance. Friction and windage losses are principally independent of the load, but they are proportional to the speed of the motor. In the case of induction motor, slip increases with load. Hence, the motor speed decreases with load, which slightly lowers friction and windage losses. Friction losses can be reduced by using higher quality bearings. Windage losses in turn, can be reduced indirectly by better motor efficiency, which reduces the ventilation requirements and allows downsizing the fan. Additionally, optimizing the design of fan blades, fan housing and motor frame fins can improve the efficiency of the cooling itself.

1.3.4 Stray-load losses

Stray-load losses are also called additional load losses and they consist of all the losses not accounted by mechanical losses and fundamental winding and iron losses. These losses include space harmonic losses caused by non-ideal behavior of the air-gap flux. Also time harmonic components of the supply voltage cause additional load losses. Stray-load losses are load-dependent and usually assumed proportional to torque squared (Mohan 2003, p. 15-4; IEC 2014a).

Space harmonic losses

Air-gap flux density waveform is rather step-like than pure sinusoidal wave. Stator windings are not ideally distributed along the stator bore. They are placed in slots and the distribution of the slots causes the stepped waveform. Stepped waveform always contains harmonics, and the flux harmonics induce corresponding currents in the rotor. These space harmonics cause additional iron and copper losses in the rotor and in the stator. Space harmonics also cause torque ripple, vibrations and noise, which add up losses.

Space harmonics can be reduced by induction motor design choices. Higher stator winding slot number per pole and phase results in more sinusoidal air-gap flux-wave. Rotor cage is often skewed to reduce the effects of space harmonics. In addition, avoiding certain stator and rotor slot number combinations is preferable. (Boldea & Nasar 2002a, pp. 34–35.)

Time harmonic losses

The non-fundamental high frequencies carried with the supply voltage are called time harmonics. Time harmonic losses are usually considered only when the motor is fed with a frequency converter. However, time harmonics can occur in lesser degree with mains supply. Time harmonics have similar effects as space harmonics causing additional iron and copper losses and vibrations. Time harmonics are dampened by the stator inductance but they may still cause substantial losses also in the rotor. Effects of time harmonics are further discussed in the following chapters.

1.3.5 Summary of the loss dependencies on different factors

Several factors affect differently on each of induction motor loss components. Brief explanations were given with the descriptions of the loss sources. A summary of the dependences of each loss component is shown in Table 1.4.

Table 1.4. Dependencies of the induction motor loss components.

Loss component	**Dependences**	**Load dependence**	**Speed / frequency dependence**
Stator winding losses	- Square of stator current and stator winding resistance (I^2R). - Stator winding temperature.	Torque squared	Approximately not dependent on speed and frequency
Rotor winding losses	- Slip - Temperature	Torque squared	Approximately not dependent on speed and frequency
Iron losses	- Supply frequency - Peak flux density	Slightly decreases on load	Increases with supply frequency
Friction and windage losses	- Rotational speed	Slightly decreases on load	Increases with rotational speed
Stray-load losses	- Relative to torque squared - Supply voltage quality	Torque squared	Increases with supply frequency

1.4 Additional losses on frequency converter supply

In many applications, flexible control of motor is required. Efficient control of induction motor speed can be achieved via altering the frequency and voltage of the motor supply current. A frequency converter can be used to achieve this. However, all electromagnetic motor losses are increased due to high frequency harmonics of the converter supply. Total increase in losses is typically 10–20 % resulting in energy efficiency decrease of 1–2 % at full load (Mohan 2003, p. 15-7; Aarniovuori et al. 2013).

There are two types of frequency converters: voltage source converters and current source converters. A voltage source frequency converter rectifies the input voltage into direct current (DC) intermediate circuit and constructs the fundamental output waveform from the intermediate circuit voltage by switching according to the reference waveform. Several modulation methods exist to produce AC-voltage from DC-voltage and pulse width modulation (PWM) is the most common method used in frequency converters. Two most relevant PWM-types considering modern frequency converters are the different variants of the space vector modulation (SVM) and the direct torque control (DTC). DTC is actually a control method, but due to its nature, it counts also as PWM-type of its own.

1.4.1 Pulse width modulation

Originally, in pulse width modulation, the switching duty cycle is varied according to reference frequency. An example of a PWM voltage waveform and the corresponding fundamental wave is shown in Figure 1.2. The frequency converter PWM-voltage consists of variable length pulses of constant voltage and the width of the pulses determines the amplitude of the resulting fundamental wave. The fundamental waveform is drawn in Figure 1.2 with sinusoidal curve, which can be derived from the PWM-voltage by low-pass filtering.

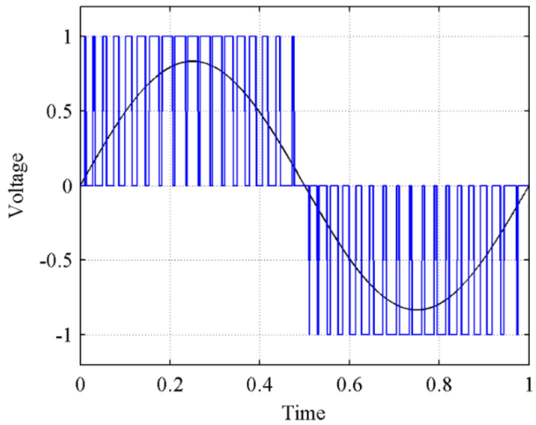

Figure 1.2. An example of a PWM-waveform. Stepped line is the actual voltage curve and sinusoidal line is the fundamental waveform.

The example in Figure 1.2 showed a clean PWM waveform to illustrate the principle. An example of an actual two level PWM waveform of a frequency converter is presented in Figure 1.3. Between zero and maximum altering square-wave voltage has high amount of distortion. This distortion contains harmonic frequencies. In the case of carrier-based PWM, these harmonics are near the converter carrier frequency and its multiples. An example of the harmonic content of a PWM modulated waveform with fundamental frequency of 50 Hz and carrier frequency of 4 kHz is presented in Figure 1.4 (on page 25). In addition to the carrier based PWM methods, there are also random PWM methods. In random PWM there is no constant carrier frequency, hence the harmonics are more evenly distributed along the spectrum.

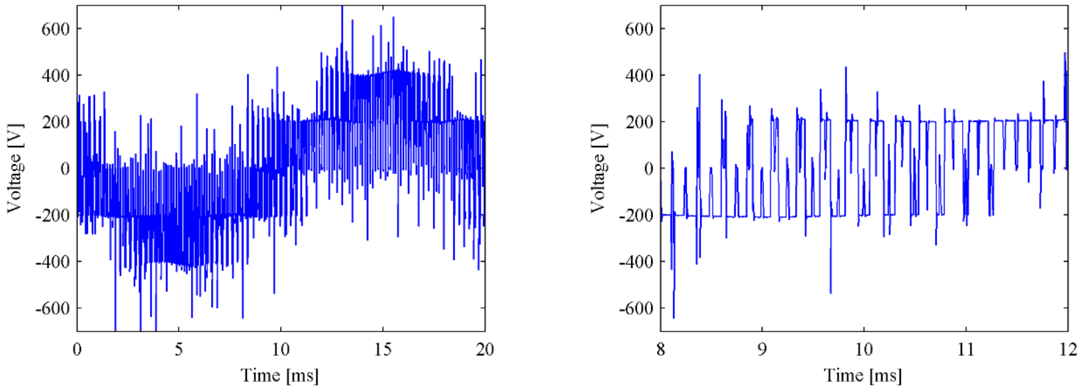

Figure 1.3. An example of an actual output voltage waveform of a commercial two level frequency converter. The fundamental frequency is 50 Hz and carrier frequency 4 kHz. Left plot shows the waveform during a complete fundamental frequency period of 20 ms. The right plot gives a closer view between 8 ms and 12 ms marks of the first plot, making the squared waveform more easily seen.

The PWM time harmonics cause additional iron and windage losses in the motor in comparison to the sinusoidal supply. Winding losses increase due to the skin effect, which is more prominent in the rotor bars than in the stator windings. Skin effect is stronger in large induction motors of MW-range (Boldea & Nasar 2002b, p. 33). Iron losses are increased with PWM-supply because harmonics cause ripple in flux density and slightly increase its peak value.

Time harmonic losses are nearly independent of load and to some degree dependent of the switching frequency of the converter. The slip speed on harmonic frequencies is high compared to fundamental slip, thus small changes of motor load have almost no effect on harmonic slip. According to studies, higher switching frequency decreases motor losses (Aarniovuori et al. 2010; Yamazaki & Kuramochi 2012). However, higher switching frequency increases frequency converter losses (Aarniovuori et al. 2010; Yamazaki & Kuramochi 2012) and has to be taken into account when considering the total efficiency of an induction motor drive. Leakage inductances tend to filter current harmonics and therefore motors with higher leakage inductance may have less harmonic losses (Mohan 2003, pp. 15-7 – 15-8). Time harmonic losses can also be reduced by using multilevel inverter. In multilevel PWM, there are more than two DC-voltage levels. Therefore, the resulting inverter output waveform is less distorted. For example, according to Hothongkham & Kinnares (2007), the harmonic losses of an induction motor with a 7-level inverter are considerably lower than with a 2-level or 3-level inverter. However, the cost and complexity are the main disadvantages of a multilevel inverter.

Space vector modulation

The reference voltage of an induction machine can be represented by a rotating space vector. The space vector consists of positive and negative phase voltage vectors of each three phases. In SVM, this space vector is used directly as the base of the modulation.

The output voltage of a frequency converter can also be described with vectors. Each of the three phases form positive and negative voltage vectors in 60° angle from each other. Additionally, two zero voltage vectors can be formed: one zero vector when all phases are positive and the other when all phases are negative.

In SVM, the reference voltage space vector is calculated and then constructed from the closest two phase voltage vectors and zero voltage vectors of the converter. The direction and amplitude of the resulting voltage vector is determined by durations of the phase voltage and zero vectors. The resulting voltage has a square waveform, as usually in the case of PWM.

Switching frequency is typically constant in SVM and hence time harmonics occur around carrier frequency and its multiples. This appears as peaks in the frequency spectrum and produces additional noise and electromagnetic interference (EMI). An example of SVM harmonics is shown in Figure 1.4 (page 25). Random modulation methods can be implemented to reduce the effects of the high harmonic frequency peaks (Kuisma 2004; Khan et al. 2010; Bolognani et al. 1996).

The phase voltage vectors can produce sinusoidal voltage only up to certain amplitude. This is result from the fact that highest amplitudes can be obtained in the directions of the phase voltages. Operating outside the sinusoidal region is called overmodulation. Overmodulation causes additional distortion in the voltage and it should generally be avoided.

Direct torque control

DTC is originally an induction motor control method, which is based on estimating motor state and directly applying appropriate stator voltage vector (Mohan 2003, p. 8-1). In the case of DTC, stator voltages are treated as six vectors, which correspond to the positive and negative phase voltages. Nowadays, there are different DTC versions for other rotating field machine types, too.

Estimates of the induction motor stator and rotor flux linkage space vectors, torque and rotor speed can be calculated from stator phase currents and voltages. When the direction and amplitude of stator flux linkage space vector are known, they can be directly controlled by applying any of the six stator voltage vectors when needed. Because also rotor flux linkage vector is calculated, torque can be increased by increasing the phase shift, which corresponds to slip, between the space vectors. In addition, the amplitude of the flux linkage space vector also affects torque. (Niiranen 1999, Boldea & Nasar 1998)

Typical principle of controlling the stator flux linkage amplitude in DTC is to use a hysteretic band around the reference value. Calculations for the estimates are made at a fixed interval but changes in stator voltage are only applied if the stator flux linkage is outside the hysteretic range. The error between reference and estimated flux linkage is then corrected with the best suiting stator voltage vector. (Boldea & Nasar 1998.)

DTC does not have a constant switching frequency, because changes in stator voltage are only applied when needed. The sampling interval is also short enough not to cause significant periodicity. The harmonic content of DTC-controlled voltage is thus essentially random and distributed more evenly along the spectrum compared to SVM. Therefore, the noise and EMI problems of SVM are less prominent. An example of a DTC modulated waveform is shown in Figure 1.5. The harmonics of DTC modulated voltage have significantly smaller amplitude than those of a SVM voltage with constant switching frequency (Figure 1.4), but they are spread more evenly along the spectrum.

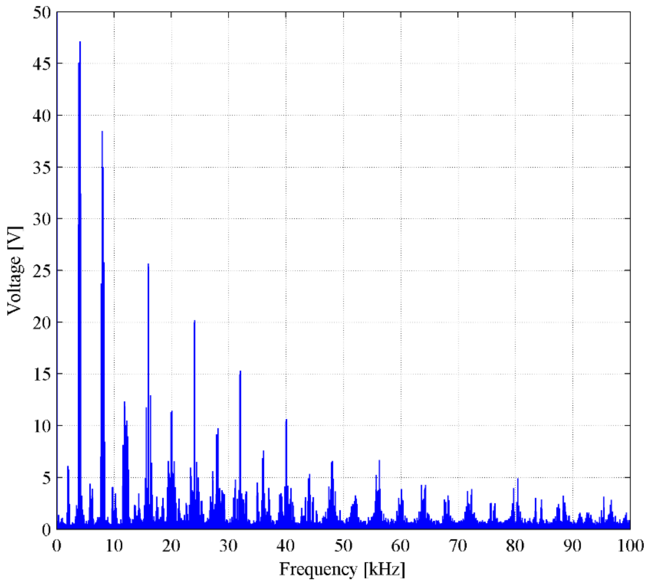

Figure 1.4. An example of harmonic content of a SVM voltage waveform with a carrier frequency of 4 kHz, fundamental voltage of 230 V and fundamental frequency of 50Hz. The fundamental frequency, which is also the first harmonic, is not visible in the plot. The most significant high frequency harmonics are located near the carrier frequency and its multiples.

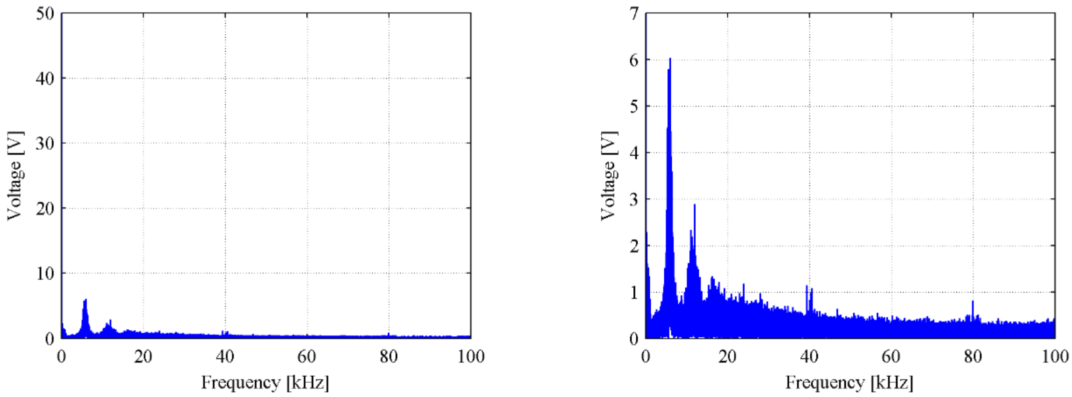

Figure 1.5. An example of harmonic content of a DTC modulated voltage waveform with fundamental frequency of 50Hz. The left plot shows the harmonics in similar scale as the SVM harmonics in Figure 1.4. The right plot has smaller voltage scale to bring the high frequency harmonics more visible.

2 INTERNATIONAL STANDARDS FOR DETERMINING INDUCTION MOTOR LOSSES

The most important publications considering determination of induction motor losses and efficiency are the standards IEC 60034-2-1, IEC 60034-2-2 and the technical specification IEC/TS 60034-2-3. IEC 60034-2-1 contains several different methods for determining losses of induction machines, DC machines and synchronous machines. The methods described in IEC 60034-2-1 for induction machines are divided to preferred methods and methods applicable to field and routine testing. IEC 60034-2-2 is supplement to IEC 60034-2-1 defining additional methods for testing large machines. IEC/TS 60034-2-3 designates specific methods for converter-fed induction motors. The methods and procedures for converter-fed motors are similar to those for motors on sinusoidal supply, although with some additional procedures for determining time harmonic losses. Summary of the standards and their current revisions is shown in Table 2.1.

Table 2.1. Current IEC-standards considering determination of induction motor losses and efficiency. (IEC 2014a; IEC 2013; IEC 2010b)

Publication	Current version	Release year	Scope
IEC 60034-2-1	Edition 2.0	2014	DC machines, AC synchronous and induction machines
IEC 60034-2-2	Edition 1.0	2010	Large machines
IEC/TS 60034-2-3	Edition 1.0	2013	Converter-fed induction motors

2.1 Preferred methods for induction machines according to IEC 60034-2-1

The standard IEC 60034-2-1 Edition 2.0 defines three preferred methods for determining losses of induction machines. All three methods are for different machine types or rating ranges and therefore only one preferred method applies to each induction machine. Summary of preferred methods and their ranges of application are presented in Table 2.2. (IEC 2014a.)

Table 2.2. Preferred methods for testing induction machine losses and efficiency according to IEC (2014a).

Method	Description	Required tests	Application
2-1-1A Input-output method	Torque measurement	- Dynamometer test	All single-phase machines
2-1-1B Summation of losses: Residual losses	Stray-load losses from residual loss	- Rated load test with torque - Load curve test with torque - No-load test	Three-phase machines with rated output up to 2 MW.
2-1-1C Summation of losses: Assigned value	Stray-load losses from assigned allowance	- Load test at reduced voltage - No-load test	Three-phase machines with rated output greater than 2 MW

2.1.1 Method 2-1-1A – Input-output measurement

The method 2-1-1A is the preferred method for all single-phase machines. The method is based on measuring electrical input power and mechanical output power in the case of a motor, or mechanical input power and electrical output power in the case of a generator. Before taking measurements, the machine is run to a sufficient thermal equilibrium. The difference between output power and input power is equal to motor losses. (IEC 2014a.)

The accuracy of the input-output method relies heavily on the accuracy of the electric input power, torque and rotational speed measurements. For example, when motor efficiency is 90 %, an error of 1 % in any of these measured quantities results in 10 % error in the losses. More particularly, the accuracy of the mechanical torque measurement has been typically considered uncertain, although with modern transducers the accuracy has improved considerably. Since single phased machines have typically lower efficiency than larger three-phased machines, the method is more suitable for them.

Any separate loss components cannot be determined with the input-output method. However, the measurements and calculations are simple. The only time consuming part of the input-output method is the heat run to achieve stable operating temperature before taking the measurements.

2.1.2 Method 2-1-1B – Summation of losses with stray-load losses determined from residual loss

The method 2-1-1B is the preferred method for all three-phased machines up to output power of 2 MW. The method consist of three separate tests: rated load test, load curve test and no-load test. Stator and rotor winding losses are calculated from the results of rated load test. Iron losses and mechanical losses are determined from no-load test. Load curve test with mechanical torque measurement is required for the determination of stray-load losses. (IEC 2014a.)

For the rated load test, the machine is run at rated load until sufficient thermal stability is achieved and measurements are made. Load curve test consists of six test points between and including 25 % and 125 % of rated load. The no-load test in turn, is run without load and at eight different test points between and including 30 % and 110 % of rated voltage. (IEC 2014a.)

The summation of losses results include the segregated motor loss components, since the total losses are determined as sum of the separate losses. The tests are based on mainly measuring electrical quantities and only the stray-load loss determination requires torque measurement. However, the method 2-1-1B is rather complex considering both measurements and calculations.

2.1.3 Method 2-1-1C – Summation of losses with stray-load losses from assigned value

The method 2-1-1C is the preferred method for large induction motors of output power greater than 2 MW. The method 2-1-1C is similar to method 2-1-1B, except the load losses are determined from test with reduced voltage and stray-load losses are defined as an assigned allowance. The assigned value for stray-load losses is specified in the standard and it depends on rated power of the motor. (IEC 2014a.)

Torque measurement, which is often unpractical for large motors, is not required in method 2-1-1C (IEC 2014a). The assigned value of stray-load losses is based on large amount of data (IEC 2014a), but it does not take account any design-specific properties of the tested machine.

2.2 Additional methods defined in IEC 60034-2-1

The standard IEC 60034-2-1 Edition 2.0 defines five additional methods for determining induction machine losses. These five methods have greater uncertainty than the three preferred methods and are only recommended for field-tests, routine-tests or customer-specific acceptance tests. (IEC 2014a.) Summary of these methods is presented in Table 2.3.

Table 2.3. Additional methods for testing induction machine losses and efficiency. (IEC 2014a)

Method	Description	Required tests	Requirements
2-1-1D Dual supply back-to-back	Dual supply back-to-back-test	- Dual supply back-to-back-test	Machine set for full load, two identical units, two different frequency power supplies
2-1-1E Single supply back-to-back	Single supply back-to-back-test	- Single supply back-to-back-test	Two identical units (wound rotor), slip frequency power supply
2-1-1F Reverse rotation	Stray-load losses from removed rotor and reverse rotation test	- Rated load test - No-load test - Test with rotor removed - Reverse rotation test	Auxiliary motor with rated power between 1–5 times the total losses of the tested machine
2-1-1G Eh-star	Stray-load losses from Eh-star test	- Rated load test - No-load test - Eh-star test	Windings connected in star connection
2-1-1H Equivalent circuit	Currents, powers and slip from the equivalent circuit method, stray-load losses from assigned value	- No-load test - Test at reduced frequency or test at rated frequency	Method only to be used if no possibility to use other methods; some designed values of the machine need to be available

2.2.1 Methods 2-1-1D and 2-1-1E – Dual supply and single supply back-to-back tests

The back-to-back test methods 2-1-1D and 2-1-1E both require two identical machines for the tests. The dual supply test is applicable to all induction motors while single supply test is only suitable for wound rotor machines. Both these tests are based on coupling the two machines mechanically together and running one machine as a motor and the other as a generator. In method 2-1-1D, the total losses of the setup are determined from the input electric power of the motor and the output electric power of the generator and the total losses of one machine are half of the total losses of the setup. In method 2-1-1E, the losses of one machine are half of the total power consumption of the setup. (IEC 2014a.)

Both dual and single supply back-to-back test are based on only measuring electric quantities and therefore torque measurement is not required. However, both methods require two identical machines. Both methods also require two power supplies with different frequencies, since one of the machines has to operate as a generator. In addition, the assumption that the losses of one induction machine are half of the total losses of both motor and generator is not accurate. The losses of an induction machine operating as a generator can be significantly lower than the losses of an identical machine operating as a motor (Hadžiselimović et. al. 2013).

2.2.2 Method 2-1-1F – Reverse rotation method

Method 2-1-1F is based on determining separate losses. The rated load and the no-load test are utilized similarly as in method 2-1-1B for calculating winding, iron and mechanical losses. The stray-load losses, in turn, are determined from method-specific tests.

In method 2-1-1F, stray-load losses are determined from a combination of reverse rotation test and test with rotor removed. With the rotor removed, the stator is supplied with six different current values of up to 150 % of the rated current. In reverse rotation test, the machine under test is rotated at synchronous speed in direction opposite to the normal rotation. Currents of same values as in the test with rotor removed are fed to the stator while the rotor is being rotated to reverse direction. Determining the stray load losses is based on the differences between the measurements from these two tests. (IEC 2014a.)

The method 2-1-1F requires disassembling the motor and therefore it is best suited for motor manufacturers. The method also requires a dynamometer, although no actual load test is performed. According to Aoulkadi & Binder (2008), the slip of 2 used in the reverse rotation test causes different main flux and space harmonic behavior compared to normal operation. According to them, the method generally gives too high values for stray-load losses (Aoulkadi & Binder 2008).

2.2.3 Method 2-1-1G – Eh-star method

Method 2-1-1G is based on determining separate losses. The rated load test and the no-load test are utilized similarly as in method 2-1-1B for calculating winding, iron and mechanical losses. The stray-load losses are determined from Eh-star test. The Eh-star test requires that the motor windings are connected to star and that the star point is connected to neutral or to earth. Two of the motor phases are connected normally to the power supply and the third phase is connected to the supply via a resistor, hence, the motor is intentionally supplied with unbalanced voltage. The test is run at six test points and the stray-load losses are calculated for each point. The stray-load loss data is smoothed for determining the rated load stray-load losses. (IEC 2014a.)

The Eh-star test does not require load or torque measurement and the test itself is rather simple. However, the calculations for determining the losses are very complex. Additionally, a power resistor of a value that depends on motor rated voltage and rated current is required. This means that for each tested motor a specific resistor is needed. According to Aoulkadi & Binder (2008), the Eh-star method gives comparable results with load curve test-based determination of stray-load losses.

2.2.4 Method 2-1-1H – Determining separate losses from equivalent circuit parameters

The equivalent circuit method 2-1-1H should only be applied if a load test is not possible. The method is based on determining T-model equivalent circuit parameters. No-load losses are determined from a no-load test at rated frequency. Motor impedances are determined from a reduced frequency locked rotor test, or from rated frequency tests at locked rotor and running rotor. Additionally, four designed values of the machine need to be available: stator leakage reactance to rotor leakage reactance ratio, temperature coefficient of rotor windings, stator leakage reactance and magnetizing reactance. Separate load losses except stray-load losses can be then calculated from the equivalent circuit parameters. Stray-load losses are determined from assigned value as in method 2-1-1C or from tests as in method

2-1-1F or method 2-1-1G. Friction and windage losses are determined from the no-load test. (IEC 2014a.)

The equivalent circuit method does not require a load test or torque measurement, but the equivalent circuit calculations are rather complex. The reduced frequency test requires frequency converter supply or generator supply, but using the other option of running two rated frequency tests, this can be avoided. According to Hsu et. al. (1998), an advantage of the method is that the performance of the motor can be calculated at any load when the parameters are known. However, the impedance values can change significantly between standstill and no-load speed (Hsu et. al. 1998). In addition, the method is based partly on design parameters and therefore it does not take into account all variations in final products.

2.3 Specific methods for large machines, IEC 60034-2-2

Three additional methods, which are mainly applicable to large electric machines, are introduced in IEC 60034-2-2 Edition 1.0. The methods are calibrated machine method, retardation method and calorimetric method. These methods are to be used when testing at full load is not practical and leads to higher uncertainty. (IEC 2010b.)

2.3.1 Calibrated machine method

To utilize the calibrated machine method, a machine with known relationship of mechanical and electrical power is needed. A calibrated machine and the machine to be tested are mechanically coupled together and one is used as a motor and the other as a generator. Mechanical output power of the machine under test is determined from the electrical power of the calibrated machine. (IEC 2010b.)

The accuracy of the method relies on the accuracy of the input-output relationship of the calibrated machine, particularly around the rated power of the tested machine. The test and calculations are as simple as with a basic input-output test. However, in case of large machines, the preparations can be demanding.

2.3.2 Retardation method

The retardation method is based on large machines having notable rotational inertia. The machine under test is accelerated to a speed higher than rated speed and then disconnected from supply source. After the source is disconnected and electromagnetic transients have decayed, the only force left rotating the machine is inertia and this knowledge can then be used to determine machine losses. However, in the case of induction machines, the method is only suitable for determining the sum of friction and windage losses. (IEC 2010b.) The method is simple and the only larger requirement is the ability to raise the machine speed above rated.

2.3.3 Calorimetric method

In the calorimetric method, the losses are determined directly by measuring the heat produced by the tested machine. For the machine to be tested a reference surface is determined in such a way, that all heat generated inside it is either measured calorimetrically or dissipated through the reference surface. The losses of the machine are equal to the produced heat and can be determined from the flow and temperature rise of the coolant and the heat dissipated through the reference surface. (IEC 2010b.)

Since the motor losses are determined directly from the heat production, there is no need for torque measurement. On the other hand, the test setup is rather complex and the measurements are very time consuming since thermal equilibrium has to be established every time before taking recordings. The accuracy of the methods depends on how accurately heat transfer through both cooling system and through reference surface is determined. In addition, the thermal stability of the whole system is pronouncedly important since variations in temperature affect directly to the results.

2.4 Specific methods for converter-fed induction motors according to IEC/TS 60034-2-3

The technical specification IEC/TS 60034-2-3 Edition 1.0 defines test methods for determining losses and efficiency of induction motors with frequency converter supply. The methods are summation of losses with test converter supply, summation of losses with specific converter supply, input-output method and calorimetric method. The summation of losses methods and calorimetric method utilize procedures described in chapters 2.1.2 (method 2-1-1B) and 2.3.3 (calorimetric method). The input-output method is similar to the corresponding method described in chapter 2.1.1 (method 2-1-1A). Summary of the methods is presented in Table 2.4. (IEC 2013; IEC 2014a.)

Additional time harmonic losses of a converter driven induction motor vary with load, with operating speed, and with any change in the drive assembly. In the IEC methods, the losses of converter-fed motor are determined at the motor rated voltage, the motor rated load and the motor rated fundamental frequency. Therefore, IEC (2013) emphasizes that the losses determined by the methods defined in the standard are not intended to represent losses in the final application, but to allow comparison of additional time harmonic losses of different induction motors when supplied with a frequency converter. (IEC 2013.) In final application, the load torque of the electric drive system and the operating frequency may alter significantly from the motor rated values, and therefore the losses are different, too.

Table 2.4. Test methods for determining frequency converter driven induction motor losses. (IEC 2013; IEC 2014a)

Method	Description	Required tests	Requirements
2-3-A Summation of losses: Test converter supply	Harmonic loss determination with test converter	On sinusoidal supply: - Tests according to method 2-1-1B On test converter supply: - Load curve test with torque - No-load test at rated voltage	Sinusoidal supply and test converter supply for 1.25 x full load operation
2-3-B Summation of losses: Specific converter supply for final application	Harmonic loss determination with converter for final application	On sinusoidal supply: - Tests according to method 2-1-1B On specific converter supply: - Load curve test with torque - No-load test at rated voltage	Sinusoidal supply and specific converter supply for 1.25 x full load operation
2-3-C Input-output	Torque measurement	- Dynamometer test	Dynamometer for full load, specific converter supply
2-3-D Calorimetric	Loss determination from coolant temperature rise	- Calorimetric measurements	Specific converter supply, measurement according to IEC60034-2-2

2.4.1 Method 2-3-A – Summation of losses with test converter supply

The method is based on the procedures defined in IEC 60034-2-1 method 2-1-1B. First, tests according method 2-1-1B are performed to determine loss components on sinusoidal supply. Second, the load curve test and a no-load test at rated voltage are performed on test converter supply. Load-dependent additional harmonic losses are determined from the difference between the stray-load losses on converter supply and on sinusoidal supply. Similarly, no-load additional harmonic losses are determined from the difference between the results of the no-load test on converter supply and the no-load test on sinusoidal supply. The total losses of a converter-fed motor are the sum of fundamental losses, load-dependent harmonic losses and no-load harmonic losses. (IEC 2013.)

The test converter is a frequency converter, which fulfills the conditions and requirements defined in IEC (2013) to ensure comparability of test conditions. Detailed specifications for test converter operation and for checking its conformity are given in IEC (2013).

The test converter voltage waveform is not load-dependent, which may not be the case when using manufacturer specific control schemes. If the waveform alters with load, the load curve test and no-load test can give inaccurate results. On the other hand, the motor losses on test converter may be quite different from motor losses with a specific frequency converter (and a manufacturer specific control scheme).

The losses are determined at the rated motor voltage and at the rated motor frequency. In final application, at the motor rated speed, the fundamental voltage of converter-fed motor is typically lower than rated. In addition, the usage of a frequency converter usually means that the motor rated frequency is not used constantly. Since the motor losses depend on the motor fundamental voltage, the fundamental frequency and the operating speed, the losses at real use situations may deviate considerably from the test results at the rated motor values.

The method 2-3-A gives the separate motor loss components, although the additional time harmonic losses of converter supply are only divided to a load-dependent part and a no-load part. For the method to be accurate, the motor fundamental voltage and the test conditions should be as similar as possible during both tests on sinusoidal supply and on converter supply.

The method 2-3-A is quite complex consisting of full sinusoidal efficiency tests with the method 2-1-1B, and two additional tests on converter supply. Separate tests on sinusoidal and on converter supply are required, since the 2-1-1B-method is not directly applicable to converter-fed motors. The reason is that the rotor iron losses are assumed insignificantly small in the 2-1-1B-method, which is not accurate for a converter-fed motor.

2.4.2 Method 2-3-B – Summation of losses with specific converter supply

The method 2-3-B is similar to method 2-3-A, the only difference being the use of a specific frequency converter for final application instead of the test converter (IEC 2013). The main disadvantage of this method when compared to the method 2-3-A is the lack of comparable voltage waveform. In addition, when using a specific frequency converter with a specific control method, variations in converter waveform at different loads are possible, which may make the results inaccurate.

2.4.3 Method 2-3-C – Input-output method

In method 2-3-C, the efficiency and losses are determined by measuring electric input power and mechanical output power of the motor (IEC 2013). The procedures are similar to the method 2-1-1A on sinusoidal supply; hence, the description given in chapter 2.1.1 applies to method 2-3-C. However, on frequency converter supply, the electric power measurement needs to have sufficient bandwidth because of the converter supply harmonics.

2.4.4 Method 2-3-D – Calorimetric method

This method refers directly to the calorimetric method of IEC 60034-2-2 described in chapter 2.3.3. The IEC calorimetric method applies only to machines with water cooling. (IEC 2013.)

2.5 Summary of the IEC methods

The IEC methods for determining induction motor losses contain large variety of possible choices for different applications. The method 2-1-1B can be considered as the most accurate of the methods, given that all the requirements are met and procedures followed in detail. However, the method 2-1-1B is rather complex both for the measurements and calculations, which applies naturally to the other loss segregation methods 2-1-1C, 2-1-1F and 2-1-1G, too.

The simplest of the IEC methods is the input-output method. As torque measurement with modern torque transducer can be quite accurate, the input-output method could be considered as a quick and easy alternative.

Some of the methods, like the dual supply tests and reverse rotation method, are practically only suitable for motor manufacturers. The accuracy of these methods is also a bit questionable. The Eh-star method and equivalent circuit method can be alternatives when the facilities are limited.

For determining the losses of a converter-fed induction motor, four different methods are given. The loss segregation methods 2-3-A and 2-3-B are meant for comparing losses of converter-fed motors. For the method 2-3-A, the converter waveform is defined by IEC (2013) to ensure the comparability of the results. However, the "test converter supply" is not intended to give any realistic measure or prediction of the losses in final application with a specific frequency converter. The method 2-3-B, in turn, can be used with any specific converter supply. The method 2-3-B is supposed to give comparable results for different motors supplied with that specific converter, but the accuracy of the determined losses cannot be ensured since the voltage waveform is not necessarily load-independent. The methods 2-3-C and 2-3-D can be used for determining the actual losses with a specific frequency converter, but the accuracy and comparability of the results may not be as good as with the 2-3-A and 2-3-B methods.

3 MEASUREMENTS

The losses and efficiency of a 15 kW totally enclosed fan cooled (TEFC) induction motor were determined with standard measurements and the procedures and the test results are presented in this chapter. The measurements were made on a sinusoidal supply and with two different frequency converter supplies. The first frequency converter was set to provide the test converter waveform specified for method 2-3-A in IEC (2013). The second frequency converter, in turn, utilized classical direct torque control (DTC).

The IEC summation of losses methods were used for the measurements. For measurements on sinusoidal supply, the method 2-1-1B was used. The measurements with the test converter supply are according to method 2-3-A and the measurements with the DTC converter supply are according to method 2-3-B. In the methods 2-3-A and 2-3-B, the sinusoidal supply tests according to the method 2-1-1B are required and those are presented first.

The input-output method was applied to all measurements for comparison. Acquiring the data for the input-output method did not require any additional procedures during the tests. The input-output calculations are according to the IEC method 2-1-1A for the tests on sinusoidal supply and according to IEC method 2-3-C for the tests on frequency converter supply.

According to IEC (2014a; 2013), the rated motor voltage shall be used for the tests. However, the frequency converter rated input voltage is usually equal to the motor rated voltage (i.e. 400 V) and as a result, the output will be often – depending on the hardware and modulation – lower than 400 V. In order to produce fundamental rated voltage for the motor without risk of overmodulation, the frequency converter needs to be fed with risen input voltage considerably higher than the rated voltage. This does not represent a typical final application, where the supply voltage is usually equal to the rated voltage and therefore the fundamental motor voltage ends up being lower than rated. The differences between these two situations were investigated by running the tests in both scenarios. For the first test run, the sinusoidal supply tests and the tests with both frequency converters were run at the rated motor fundamental voltage of 400 V. The supply voltages of both test converter and the DTC converter were risen high enough for the fundamental output voltages to reach 400 V without overmodulation. For the second test run, the test converter was fed with rated input voltage of 400 V and the tests were run at the fundamental output voltage that the test converter was able to produce with the input voltage of 400 V without overmodulation. The motor voltage on sinusoidal measurements of the second test run was reduced to match the fundamental test converter output voltage. The third test run was performed similarly to the second run, but the DTC frequency converter was used. Summary of the test runs and voltages is shown in Table 3.1.

Table 3.1. Summary of the test runs and input voltages.

Test run	Motor input voltage (fundamental)	Input voltage of the test converter	Input voltage of the DTC converter
Rated voltage (first run)	**Rated voltage, 400 V**	Risen voltage, 460 V	Risen voltage, 433 V
Reduced voltage run 1 (second run)	Reduced voltage, 350 V	**Rated voltage, 400 V**	-
Reduced voltage run 2 (third run)	Reduced voltage, 377 V	-	**Rated voltage, 400 V**

As IEC (2014a; 2013) requires, all measurements were made at the rated motor supply frequency of 50 Hz. The procedures and calculations presented in chapters 3.3, 3.4 and 3.5 follow the rated voltage test run (first run). The procedures and calculations for converter-fed motor in chapters 3.4 and 3.5 are from test converter measurements with rated motor fundamental voltage. All figures, determined losses and other example data are also from the rated voltage sinusoidal supply measurements and the rated motor fundamental voltage measurements on the test converter supply. The results from the rated motor fundamental voltage measurements on DTC converter supply are presented in chapter 3.6. The results from all tests at reduced motor fundamental voltage are presented in chapter 3.7. Complete results from all tests and calculations are tabulated in Appendix 5.

3.1 Measurement setup

The measurement setup consists of the motor under test, a larger machine for load, power supply, and instruments for measuring and recording data. The setup for sinusoidal measurements is given in Figure 3.1. Electric quantities were measured with Yokogawa WT1600 power analyzer. Yokogawa PZ4000 analyzer was utilized for measuring power supply harmonics. Power analyzers were equipped with Hitec Zero-Flux CURACC current measuring system. Winding resistance and temperatures were measured with Keithley Integra Series 2701 Ethernet multimeter systems. Resistance was measured with four-wire method directly from the motor terminals. Ambient temperature was measured with four-wire A-class Pt100 sensor, which was positioned 20 cm behind the motor air inlet. The motor did not have any preinstalled temperature sensors and for measuring stator winding temperature, a two-wire B-class Pt100 sensor was installed on the winding end surface with thermally conductive adhesive. The mechanical torque and operating speed were measured with HBM T12 digital torque measurement system with rated torque of 200 Nm. All measurement data was gathered with a LabVIEW™ interface on a PC. The electric power was supplied from the mains via a variable transformer, which is capable of nearly continuous voltage adjustment on 0–720 V scale. The load was created with a line converter driven 37 kW induction machine acting as a generator. The generated power was fed back to the mains.

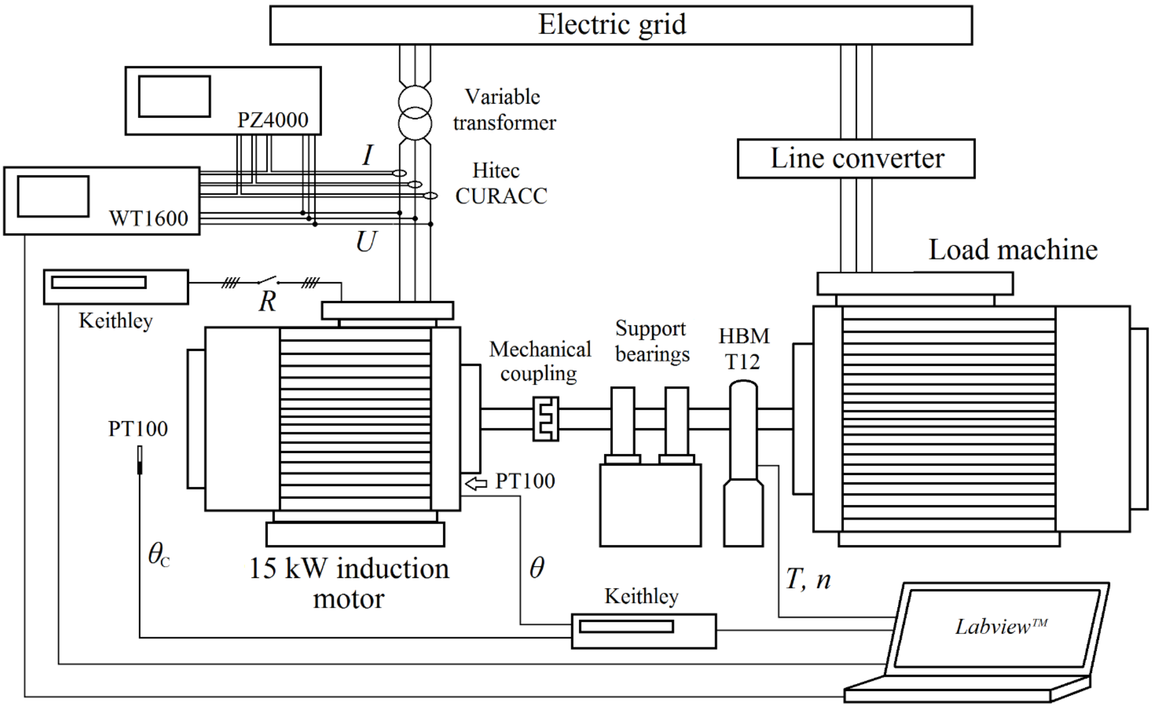

Figure 3.1. Measurement setup for tests on sinusoidal supply. The 15 kW induction motor was loaded with a larger machine. All measurement data was gathered with a LabVIEW-interface simultaneously from several instruments.

Additional mechanical parts of the setup include two ball bearings for supporting the axle and a coupling. These are required for fast disconnecting of the load between the load curve test and no-load test. Both bearings are located between the tested motor and torque transducer, therefore causing a slight offset in measured torque. The torque loss of the bearings was measured by rotating the decoupled axle with the load machine at the rated speed of the 15 kW induction machine. The torque of the bearings was taken into account when analyzing the acquired data.

The measurement setup for the frequency converter supply is shown in Figure 3.2. The only changes compared to the sinusoidal supply setup are the frequency converter and a second measuring point for the electric quantities. Both input and output of the frequency converter were measured with Yokogawa WT1600 power analyzer and for observing the fundamental voltage of the converter output, another Yokogawa PZ4000 analyzer was added.

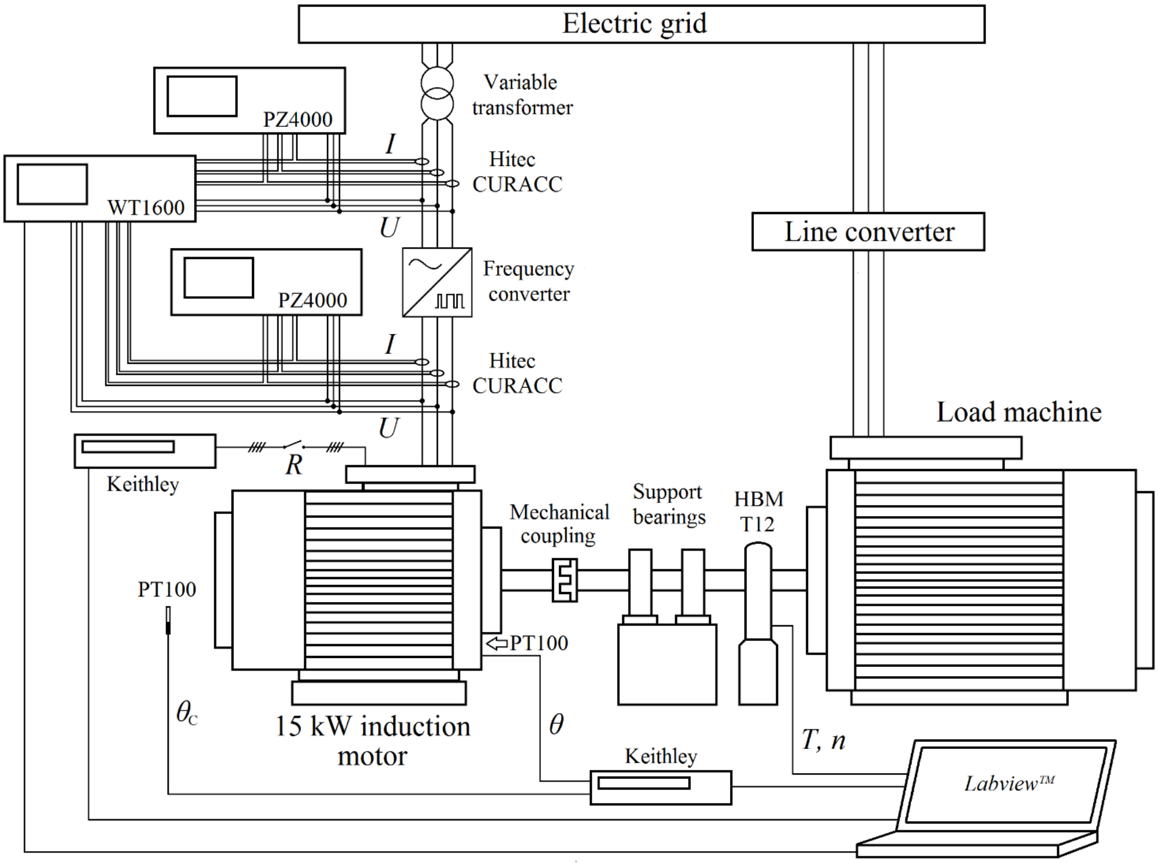

Figure 3.2. Measurement setup for tests with frequency converter supply. In addition to measurements with sinusoidal supply, the setup includes a frequency converter and output measurements of the converter supply.

The instruments used for measuring each of the quantities are listed in Table 3.2. In Table 3.2 are also shown the instrument accuracies and the IEC accuracy requirements for each quantity. The presented instrument accuracies are one-year accuracy values, where available. If the devices were more recently calibrated, the tolerances would be better.

Table 3.2. The instruments used for measuring each quantity and the accuracy of the instruments. The IEC accuracy requirements for each of the quantities are also included. (HBM 2015; IEC 2013; IEC 2014a; Keithley 2002; Thermibel 2015; Yokogawa 1999; Yokogawa 2008; Yokogawa 2009)

Quantity	**Instrument**	**Accuracy (Instrument specifications)**	**IEC required accuracy**
Power	Yokogawa WT1600	±(0.15 % of reading + 0.05 % of range) at 50 Hz. ±(0.45 % of reading + 0.2 % of range) at 1 kHz – 50 kHz.	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0. At converter supply, also accuracy of 0.5 % up to 10 x switching frequency
Voltage	Yokogawa WT1600	±(0.15 % of reading + 0.05 % of range)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
Current	Yokogawa WT1600	±(0.15 % of reading + 0.05 % of range)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
	Hitec CURACC	±(0.01 % of reading + 0.005 % of range)	
Fundamental motor voltage (on converter supply)	Yokogawa PZ4000	±(0.15 % of reading + 0.075 % of range)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
Motor torque	HBM T12	Class 0.03	Class 0.2
Rotational speed	HBM T12	±150 ppm Speed resolution 0.1 rpm	± 0.1 rpm
Ambient (coolant) temperature	Keithley 2701	± 0.06 °C	± 1 K
	Pt100 Class A	± (0.15 + 0.002 | t |) °C	
Stator winding temperature	Keithley 2701	± 0.06 °C	± 1 K
	Pt100 Class B	± (0.30 + 0.005 | t |) °C	
Stator winding resistance	Keithley 2701	± (0.01 % of reading + 0.002 % of range)	Class 0.2 & overall uncertainty of 0.2 % of reading

The instrument accuracies and the IEC requirements are reported differently; hence, the comparison is not straightforward. However, most of the measurement instruments seem to fulfill the required accuracy classes. Additionally, IEC (2014a) requires that measuring equipment must reach an overall accuracy of 0.2 % of reading of all electrical quantities. The overall accuracy requirements are further investigated in chapter 4.

In addition to the accuracy requirements of the measurement instruments, IEC (2014a) defines requirements for the stability and quality of the power supply. The average supply frequency during the tests should not vary more than ± 0.1 % of the required frequency. Additionally, IEC (2014a) refers to IEC (2010a), defining limits for harmonic voltage factor and asymmetry of the supply.

3.2 Test values

Several consecutive readings of test quantities were taken for each test point as required by IEC (2014a). Test values for each of the quantities were calculated as arithmetic average of approximately stable consecutive readings during each test point. Values recorded during transitions at beginning and end of tests and between load points were left out of calculations.

Recorded electric input power, terminal voltage, line current and supply frequency are all three-phase quantities. For input power, the test value is the sum of the line values. For voltage, current and frequency, the test values are arithmetic averages of the line values. The stator winding resistance value is the average of the three line-to-line resistance values.

3.3 Summation of losses – Sinusoidal supply

The method of summation of losses consists of three tests by which the separate losses are determined: rated load test, load curve test and no-load test. The tests were carried out in the order presented in this chapter and without unnecessary interruptions to minimize changes in the motor temperature during the tests.

The procedures followed the method 2-1-1B of IEC (2014a) for the most parts. The length of the load points of the load curve test and the length of the voltage points of the no-load test were longer than what is suggested by IEC (2014a). The latest edition 2.0 of IEC 60034-2-1 defines a new requirement that each load point should be applied for no longer than 15 s at most (IEC 2014a). The 45-second duration for each of the load points has been in regular use in the laboratory. As a shorter duration might cause additional changes in laboratory procedures, it was not applied at this point.

3.3.1 Rated load test and winding losses

The resistive winding losses were determined from the rated load test. Before beginning the test, stator winding temperature of the cool motor θ_{cool} and stator winding resistance R_{cool} were determined with the motor at ambient temperature. R_{cool} was determined by measuring all three line-to-line resistances. The winding temperature θ_{cool} was approximately 22.2 °C during the measurements. Determining the winding resistance for cool motor is presented in Appendix 2. When R_{cool} is determined, only one line-to-line resistance needs to be measured during the tests for determining the (average) stator winding line-to-line resistance.

Rated load was applied to the motor at the rated voltage of 400 V and mains frequency of 50 Hz. The motor was left running and the winding temperature was observed at 10-second intervals. According to IEC (2014a), the rate of change of the motor temperature must be less than 1 K per half hour and this requirement was fulfilled before taking recordings of the rated load test. Temperature curves for the heatrun of the rated voltage measurements run are presented in Figure 3.3. For the test run in this example, the motor was left running overnight and the winding temperature settled to approximately 89 °C. In the first picture, curves for the full 22-hour heat run are shown and the second picture gives a closer look at the last 60 minutes. The first picture shows that 22 h is more than enough for achieving thermal equilibrium. The temperature rise rate curve shows that approximately 4 h heat run is enough for this motor to meet the required less than 1 K per 0.5 h temperature rise rate. The second picture shows that although the temperature slightly fluctuates during the last half hour, the maximum rate of temperature change is approximately 0.3 K per half hour.

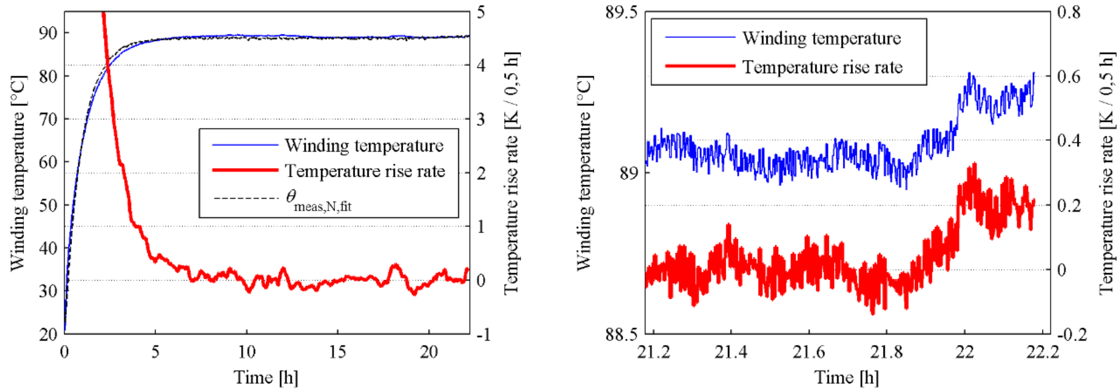

Figure 3.3. Temperature measurements and rise rates during the heat run of the rated voltage test run. Left plot shows the whole 22-hour heat run and the right plot is a more detailed view of the last 60 minutes. The dashed line in left plot depicts the stator winding temperature $\theta_{\mathrm{meas,N,fit}}$ calculated from the thermal time constant τ determined for the motor. Calculations and determination of τ are presented in Appendix 2.

The thermal response of an electric motor is often described with a thermal time constant τ. The thermal time constant was determined for the 15 kW motor from the measurement data in Appendix 2. The stator winding temperature curve was calculated from the determined time constant τ = 54 min and the fitted curve $\theta_{\mathrm{meas,N,fit}}$ is shown in Figure 3.3. The fitted temperature curve seems to settle more quickly than the measured temperature curve. However, the temperature rise rate falls to 1 K / 30 min only 7 minutes earlier according to the fitted curve data. In addition, the minimum time needed for the rate of change of the stator winding temperature rise to fall to 1 K / 30 min was estimated from the time constant (Appendix 2). The calculated time was 206 min, which is less than the 242 min needed according to the measurement data and the 235 min needed according to the fitted curve. The deviance is caused by the ambient temperature θ_{c}, which increased slowly during the first few hours of the heatrun. It seems that the time needed for the temperature rise rate to settle to the required 1 K / 30 min can be only roughly predicted from the thermal time constant if the ambient temperature is not stabilized. It may also be that the motor thermal behavior should be described with a more complicated manner than just with one time constant.

Measurements were taken at the end of the heatrun. Input power $P_{1,N}$, mechanical torque T_N, line current I_N, terminal voltage U_N, operating speed n_N, supply frequency f_N, stator winding temperature $\theta_{meas,N}$ and coolant temperature $\theta_{c,N}$ were recorded at one-second intervals. The motor was stopped and line-to-line resistance R_{U1V1} between terminals U1 and V1 was measured for 45 seconds at one-second intervals. The delay from stopping the load to the beginning of resistance recording was 18 s and additional 12 s had to be discarded as erroneous, which resulted in total 30 s delay. The problems and accuracy of the resistance measurement are further discussed in chapter 4.

The resistance $R_{U1V1,N}$ at rated load was determined by extrapolating to the stopping moment from the recorded R_{U1V1}-curve. The extrapolation procedure is presented in chapter A2.2.1 of Appendix 2 and the measured and extrapolated resistance curves are shown in Figure 3.4. The stator winding line-to-line resistance R_N was calculated from $R_{U1V1,N}$ with equation (A3.1) of Appendix 3. The stator winding temperature θ_N in turn, was calculated from R_N with equation (A2.15) of Appendix 2.

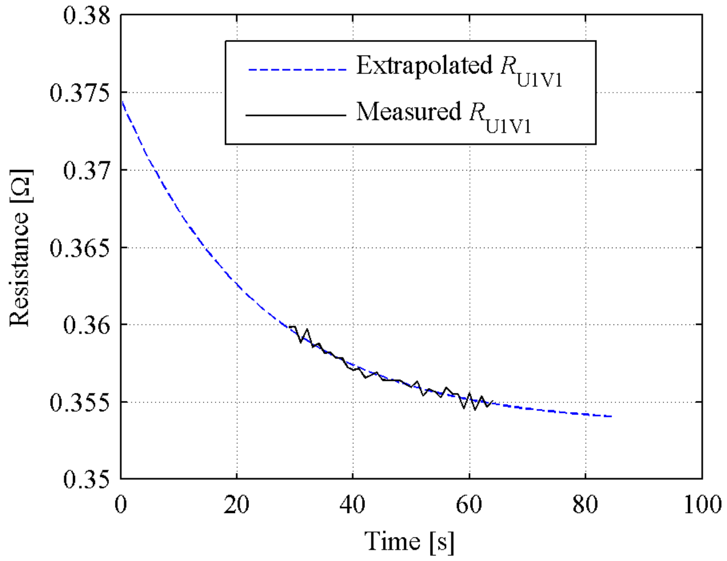

Figure 3.4. The measured and extrapolated curves for R_{U1V1} as function of time at the end of rated load test. At t = 0 s, the motor was stopped from rated load. The value of extrapolated R_{U1V1}-curve at t = 0 s is the rated load value $R_{U1V1,N}$.

Determining winding losses

Stator winding losses are the line current I_N caused ohmic losses of stator winding line-to-line resistance R_N according to equation (IEC 2014a)

$$P_{s,N} = 1.5 \cdot I_N^2 R_N . \tag{3.1}$$

Rotor winding resistance is not determined in the method 2-1-1B. Instead, the rotor winding losses are calculated from the air gap power, which is equal to the difference between input power and stator losses, and the slip according to equation

$$P_{r,N} = \left(P_{1,N} - P_{s,N} - P_{fe,N}\right) \cdot s_N , \tag{3.2}$$

where s_N is the per-unit slip at the rated load, $P_{1,N}$ is stator input power, $P_{s,N}$ is stator winding loss and $P_{fe,N}$ are rated load iron losses determined from the no-load test in chapter 3.3.3. The per-unit slip is calculated from the rotation speed n_N and power supply frequency f_N with equation

$$s = 1 - \frac{n_N \cdot p}{f_N} , \tag{3.3}$$

where p is the number of pole pairs of the motor. (IEC 2014a.)

Separate efficiency tests can rarely be run at exactly same ambient temperatures. In order to get comparable results, the winding losses were corrected to reference coolant temperature of 25 °C as defined by IEC (2014a). The temperature correction calculations are presented in Appendix 2 and the uncorrected and corrected winding losses are shown in Table 3.3. The corrected winding loss values are very close to the uncorrected values. The corrections to 25 °C were small since the coolant air temperature during rated load test was 24.9 °C.

Table 3.3. The uncorrected and corrected winding losses at the 400 V, 50 Hz voltage and the rated 15 kW load. The temperature correction calculations are presented in Appendix 2.

Stator winding losses, $P_{s,N}$ [W]	485.7
Corrected stator winding losses, $P_{s,N,\theta}$ [W]	485.9
Rotor winding losses, $P_{r,N}$ [W]	300.0
Corrected rotor winding losses, $P_{r,N,\theta}$ [W]	300.1

3.3.2 Load curve test

The load curve test was performed immediately after the rated load test. Total delay between stopping from rated load for resistance measurement and reapplying the load was 128 s. The motor was run at the 400 V, 50 Hz supply voltage using six load torque points, which were 125 %, 115 %, 100 %, 75 %, 50 %, and 25 % of rated load as defined by IEC (2014a). Load points were applied in descending order. An example of typical torque curve during the load curve test is presented in Figure 3.5.

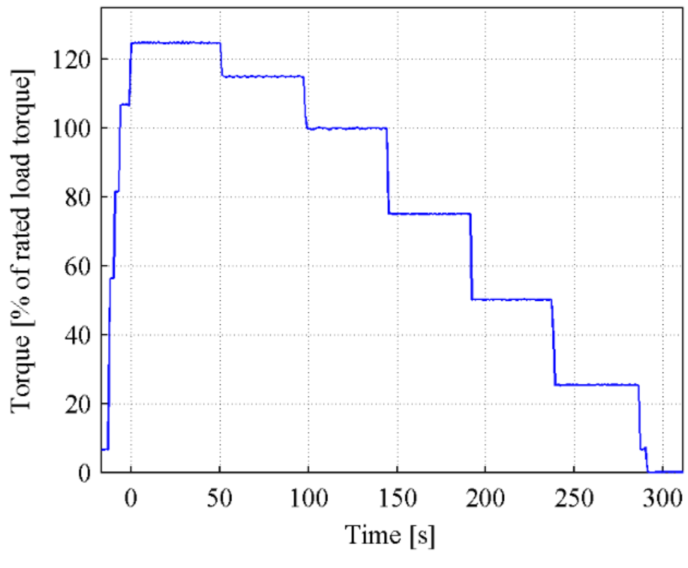

Figure 3.5. The measured torque during load curve test of the 400 V, 50 Hz test run in percents of rated load torque. The load points of 125 % to 25 % of rated load were applied in descending order and each point was run for approximately 45 seconds.

Each load point was run for approximately 45 seconds and input power $P_{1,L}$, mechanical torque T_L, line current I_L, terminal voltage U_L, operating speed n_L, stator winding temperature $\theta_{meas,L}$ and supply frequency f_L were recorded during the test at one-second intervals.

The line-to-line resistance R_{U1V1} was measured between terminals U1 and V1 immediately before the test and after the lowest load point for 15 s. Determining the stator winding resistance R_L for each load point is presented in Appendix 2. The measurement results from the load curve test are required for determining the stray-load losses in chapter 3.3.4.

3.3.3 No-load test: Friction and windage losses and iron losses

After the load curve test, the load machine was quickly decoupled from the motor and the no-load test was started immediately. The total delay between stopping the motor from last load point and starting the measurement of the first voltage point was 307 s. The motor was run at eight voltage points, which were 110 %, 100 %, 95 %, 90 %, 60 %, 50 %, 40 % and 30 % of rated voltage as defined by IEC (2014a). An example of voltage curve during the no-load test is shown in Figure 3.6.

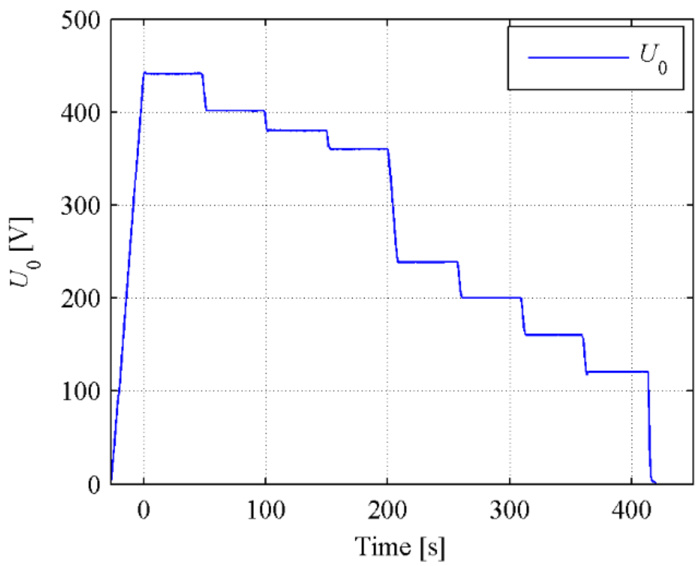

Figure 3.6. The measured voltage curve during no-load test. Voltage points between 110 % and 30 % of rated voltage were applied in descending order and each point was run for approximately 45 seconds. The delay of adjusting the voltage between the measurement points causes the total duration of all eight points to exceed 400 seconds.

The voltage points were applied in descending order. The voltage was manually adjusted from the variable transformer, which caused a delay of approximately 5 to 10 seconds between the voltage points. Each voltage point was run for approximately 45 seconds and terminal voltage U_0, line current I_0, input power $P_{1,0}$, stator winding temperature $\theta_{\mathrm{meas},0}$ and supply frequency f_0 were recorded at one-second intervals. The line-to-line resistance R_{U1V1} between terminals U1 and V1 was measured immediately before and after the test for 15 s. Determining the stator winding resistance R_0 for each voltage point is presented in Appendix 2.

Constant losses

The sum of friction and windage losses P_{fw} and iron losses P_{fe} is called constant losses (IEC 2014a). The constant losses represent all losses of the induction motor at no-load. This is based on the simplification that the rotor winding losses are insignificantly small.

For the no-load test, the constant losses P_{c} are according to equation

$$P_{\mathrm{c}} = P_{\mathrm{fw},0} + P_{\mathrm{fe},0}, \tag{3.4}$$

where $P_{\mathrm{fw},0}$ are the no-load friction and windage losses and $P_{\mathrm{fe},0}$ are the no-load iron losses. The constant losses can also be calculated from

$$P_{\mathrm{c}} = P_{1,0} - P_{\mathrm{s},0}. \tag{3.5}$$

where $P_{1,0}$ is the no-load input power, and

$$P_{\mathrm{s},0} = 1.5 \cdot I_0^2 R_0, \tag{3.6}$$

are the no-load stator winding losses of each voltage point. (IEC 2014a.) The constant losses for all voltage points are calculated from equation (3.5) in order to determine the friction and windage losses and the iron losses.

Friction and windage losses

The constant losses of four lowest voltage points are used for determining friction and windage losses. From the constant losses of 30 % – 60 % voltage points, a linear relationship of P_{c} as function of U_0^2 is developed as shown in Figure 3.7. (IEC 2014a.)

Iron losses do not exist without flux linkage and flux linkage is the integral of voltage, hence according to equation (3.4), the no-load friction and windage losses $P_{fw,0} = P_c$, when $U_0 = 0$ V. Therefore, $P_{fw,0}$ can be extrapolated from $P_c(U_0^2)$-line at zero voltage. The extrapolating procedure is presented in Appendix 2.

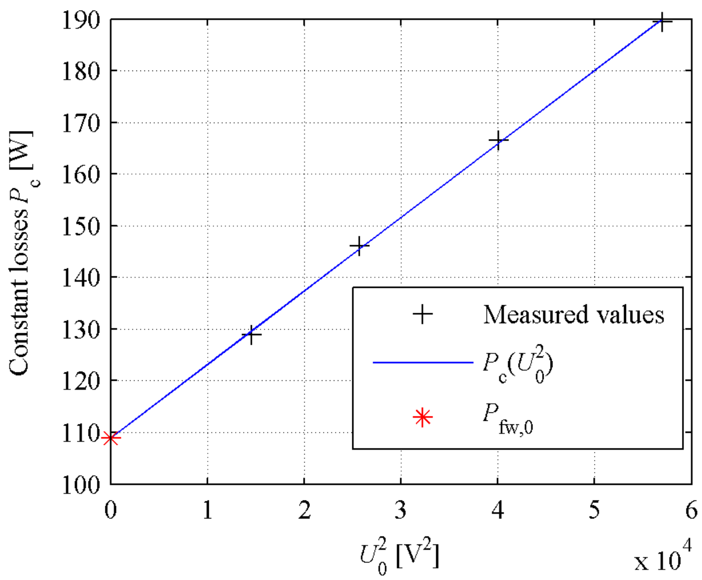

Figure 3.7. The principle of determining friction and windage losses. Four points marked with "+" are the values of constant losses at 30 % – 60 % voltage points drawn as function of U_0^2. The no-load friction and windage losses $P_{fw,0}$ are determined by linearly extrapolating constant losses to zero voltage. (IEC 2014a.) The measured values are from the no-load test of the rated voltage test run.

The friction and windage losses depend on the operating speed of the motor and therefore the rated load friction and windage losses of an induction motor are lower. The friction and windage losses at the rated load are calculated according to equation (IEC 2014a)

$$P_{fw,N} = P_{fw,0}(1 - s_{N,\theta})^{2.5}, \tag{3.7}$$

where $s_{N,\theta}$ is the temperature corrected slip according to equation (A2.19) of Appendix 2. The determined no-load and rated load friction and windage losses are presented in Table

3.4. For this motor, the friction and windage losses at rated load are only 5 W smaller than at no-load.

Table 3.4. 15 kW motor measured friction and windage losses at no load and at rated load.

No-load friction and windage losses, $P_{fw,0}$ [W]	108.9
Rated load friction and windage losses, $P_{fw,N}$ [W]	103.7

Iron losses

The constant losses of four highest voltage points are used for determining the iron losses. The no-load iron losses $P_{fe,0}$ can be solved from equation (3.4), giving

$$P_{fe,0} = P_c - P_{fw,0}\,. \tag{3.8}$$

From the results of equation (3.8) for the 90 % – 110 % voltage points, a relationship of iron losses as function of voltage $P_{fe,0}(U_0)$ is developed as shown in Figure 3.8. (IEC 2014a.)

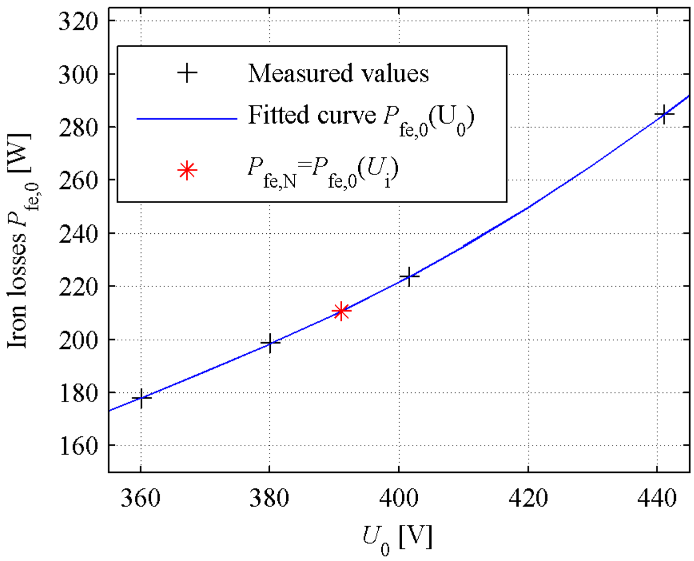

Figure 3.8. Determining the rated load iron losses. The four points marked with "+" are the values of no-load iron losses at 90 % – 110 % voltage points drawn as function of U_0. The rated load iron losses $P_{fe,N}$ are determined by interpolating from $P_{fe,0}(U_0)$-curve at voltage U_i.

To determine the rated load iron losses, the resistive voltage drop in the stator winding needs to be taken into account. Inner voltage U_i is the terminal voltage subtracted with the stator winding voltage drop. The iron losses at rated load $P_{fe,N}$ are interpolated from the $P_{fe,0}(U_0)$-curve at the inner voltage U_i. (IEC 2014a.) Determining the curve $P_{fe,0}(U_0)$ and the inner voltage U_i is presented in Appendix 2. The no-load iron losses at the rated voltage and the rated load iron losses are shown in Table 3.5. The voltage drop in the stator winding impedance is only 9 V, yet resulting in 13 W decrease in the iron losses.

Table 3.5. 15 kW motor iron losses. $P_{fe,0}$ is the iron loss when the stator winding impedance voltage drop is negligible and $P_{fe,N}$ is the iron loss at rated load, when the stator winding impedance voltage drop is approximately 9 V.

No-load iron losses, $P_{fe,0}$ [W]	223.5
Rated load iron losses, $P_{fe,N}$ [W]	210.5

3.3.4 Stray-load losses

Stray-load losses are determined from residual losses as defined by IEC (2014a). The residual losses P_{Lr} are – as the term refers – the residual value when the output power and all other determined losses are subtracted from the input power. Residual losses P_{Lr} are calculated for each load point of the load curve test from equation (IEC 2014a)

$$P_{Lr} = P_{1,L} - P_{2,L} - P_{s,L} - P_{r,L} - P_{fw,L} - P_{fe,L} , \tag{3.9}$$

where:

$P_{1,L}$ is the input power,
$P_{2,L}$ the output power,
$P_{s,L}$ are the stator winding losses,
$P_{r,L}$ are the rotor winding losses,
$P_{fw,L}$ are the friction and windage losses and
$P_{fe,L}$ are the iron losses

for each load point of the load curve test. $P_{1,L}$ is the measured input power from the load curve test. $P_{2,L}$, $P_{s,L}$, $P_{r,L}$, $P_{fw,L}$, and $P_{fe,L}$ are calculated from equations (A2.32) – (A2.37) of Appendix 2.

The principle of determining the stray-load losses from the residual loss data is shown in Figure 3.9. From the six residual loss values, a linear relationship for the residual losses as the function torque squared is formed (IEC 2014a)

$$P_{Lr} = A \cdot T_L^{\ 2} + B, \tag{3.10}$$

where T_L is the motor torque and constants A and B are determined with linear regression analysis. The linear regression analysis method is shown in Appendix 4. For applying the method of Appendix 4, y = P_{Lr} and x = T_L^2.

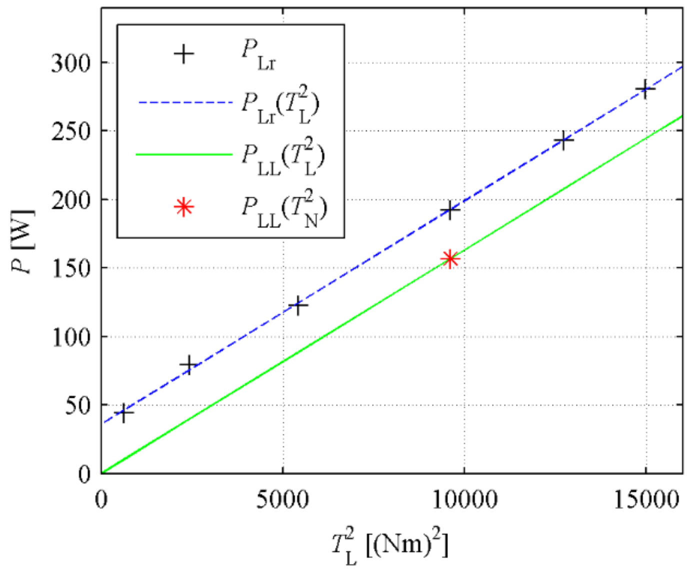

Figure 3.9. The principle of determining the stray-load losses P_{LL} from the residual losses P_{Lr}. From P_{Lr} values of each load point, a linear relationship of residual losses as function of torque squared $P_{Lr}(T_L^2)$ is formed. The stray-load losses as function of torque squared $P_{LL}(T_L^2)$ are determined by moving the $P_{Lr}(T_L^2)$-line to pass origin. The stray-load losses $P_{LL,N}$ at the rated load are determined from the $P_{LL}(T_L^2)$-line at the rated load torque T_N^2.

The stray-load losses are assumed zero at no-load, hence the equation for the stray-load losses is derived from equation (3.10) by removing constant *B*: (IEC 2014a)

$$P_{\mathrm{LL}} = A \cdot T_{\mathrm{L}}^{2}\,. \tag{3.11}$$

The stray-load losses $P_{\mathrm{LL,N}}$ at the rated load are calculated at the rated load torque T_{N} (IEC 2014a)

$$P_{\mathrm{LL,N}} = A \cdot T_{\mathrm{N}}^{2}\,. \tag{3.12}$$

According to IEC (2014a), the constant *B* in equation (3.10) should be less than 50 % of $P_{\mathrm{LL,N}}$ or there may have been errors in the measurements. Another constant needed for checking the validity of the results is the correlation coefficient γ of the residual loss data, which is determined from the linear regression analysis. According to IEC (2014a) it is required that $\gamma \geq 0.95$ for results to be satisfactory. The stray-load losses at rated load and the constants *B* and γ are shown in Table 3.6. The value of *B* is 22.8 % of $P_{\mathrm{LL,N}}$, which is well below the limit of 50 %. In addition, the value of γ is only fractions from 1 indicating an almost perfectly linear correlation of the residual loss points.

Table 3.6. The stray-load losses at rated load and the constants *B* and γ from the linear regression analysis.

Stray-load losses, $P_{\mathrm{LL,N}}$ [W]	156.9
B	35.82
γ	0.9998

3.3.5 Total losses and efficiency on sinusoidal supply

Total losses at reference coolant temperature of 25 °C are calculated from the determined loss components according to equation (IEC 2014a)

$$P_{\mathrm{T}} = P_{\mathrm{s},\theta} + P_{\mathrm{r},\theta} + P_{\mathrm{fw,N}} + P_{\mathrm{fe,N}} + P_{\mathrm{LL,N}}\,, \tag{3.13}$$

where:

$P_{s,N,\theta}$ are the temperature corrected stator winding losses determined from rated load test,
$P_{r,N,\theta}$ are the temperature corrected rotor winding losses determined from rated load test,
$P_{fw,N}$ are the rated load friction and windage losses determined from no-load test,
$P_{fe,N}$ are the rated load iron losses determined from no-load test, and
$P_{LL,N}$ are the rated load stray-load losses determined according to chapter 3.3.4.

The efficiency at reference coolant temperature (IEC 2014a)

$$\eta_{\theta} = \frac{P_{1,N,\theta} - P_{T}}{P_{1,N,\theta}}, \tag{3.14}$$

where $P_{1,N,\theta}$ is the temperature corrected input power from the rated load test. The segregated losses, the total losses and the efficiency at 400 V, 50 Hz sinusoidal voltage are presented in Table 3.7.

Table 3.7. The segregated loss components, total losses and efficiency of the 15 kW induction motor at rated voltage sinusoidal supply (400 V, 50 Hz).

Stator winding losses, $P_{s,N,\theta}$ [W]	485.9
Rotor winding losses, $P_{r,N,\theta}$ [W]	300.1
Friction and windage losses, $P_{fw,N}$ [W]	103.7
Iron losses, $P_{fe,N}$ [W]	210.5
Stray-load losses, $P_{LL,N}$ [W]	156.9
Total losses, P_T [W]	1257
Efficiency, η [%]	92.33

3.4 Summation of losses – Additional procedures for converter-fed motor

The summation of losses method for frequency converter driven motors includes the procedures with sinusoidal supply from chapter 3.3. All fundamental motor losses are determined from tests on sinusoidal supply. Determination of the additional time harmonic losses of a converter-fed motor is based on the difference between the losses on sinusoidal supply and on converter supply. The only loss components determined on the frequency converter supply are the stray-load losses and the constant losses. Hence, the tests required for the converter-fed motor are the load curve test and no-load test at the rated voltage (IEC 2013). In addition, rated load recordings for the input-output method were taken at the end of the heat run. The rated motor voltage measurements at the rated motor frequency (50 Hz) presented in this chapter were performed with the test converter supply. Results from measurements on the DTC converter supply are presented in chapter 3.6.

The rated voltage measurements on the test converter were performed according to the IEC (2013) method 2-3-A, with the exception that the durations of the load points were slightly longer than recommended. According to IEC (2013), samples for each load point should be taken for approximately 30 s. In these measurements, each of the load points was applied for the same 45 s period as with the load curve test on sinusoidal supply.

The frequency converter used in these measurements was set to provide the test converter waveform defined by IEC (2013) as closely as possible. Slip compensation was deactivated and the switching frequency of the test converter was set to the specified 4 kHz. In case of test converter operation, the switching frequency is equal to the carrier frequency. An example of harmonic spectrum of the test converter output voltage was shown in Figure 1.4 of chapter 1. The converter output voltage was checked for both the pulse pattern and the filtered waveform as instructed by IEC (2013).

The test converter was supplied with 15 % risen input voltage of 460 V. The risen input voltage was required for the test converter to be able to produce fundamental output voltage equal to the rated motor voltage of 400 V at the motor rated frequency of 50 Hz without overmodulation. The required input voltage for the rated load was 454 V. To keep the motor voltage at 400 V also during the 125 % and 115 % points of the load curve test, the input voltage had to be risen to 460 V.

3.4.1 Load curve test

Before beginning the load curve test, the motor was run at its rated load until the winding temperature rise rate was less than 1 K per half hour. When the required thermal stability was achieved, the recordings for the input-output method were taken and the motor was stopped for measuring resistance between terminals U1 and V1 for 45 seconds.

The load curve test was started immediately after the resistance measurement. Total delay between stopping the motor from rated load run and applying the first load point was 122 s. The motor was run at its rated voltage of 400 V and its rated frequency of 50 Hz at six torque points of 125 %, 115 %, 100 %, 75 %, 50 %, and 25 % of rated load torque. The load points were applied in descending order and run for 45 seconds each. During the test, input power $P_{1,\mathrm{L,C}}$, mechanical torque $T_{\mathrm{L,C}}$, line current $I_{\mathrm{L,C}}$, terminal voltage $U_{\mathrm{L,C}}$, operating speed $n_{\mathrm{L,C}}$ and supply frequency $f_{\mathrm{L,C}}$ were recorded at one-second intervals. Additionally, the fundamental wave voltage $U_{\mathrm{L,C,fund}}$ was measured during each load point. Resistance was measured between terminals U1 and V1 immediately after the test.

3.4.2 No-load test

After the load curve test, the load machine was quickly decoupled from the motor and the no-load test was started immediately. Total delay between stopping the motor and beginning the measurement was 159 s. The motor was run at rated voltage and frequency as defined by IEC (2013). The no-load test was run for approximately 45 seconds and terminal voltage $U_{0,\mathrm{C}}$, line current $I_{0,\mathrm{C}}$, input power $P_{1,0,\mathrm{C}}$ and supply frequency $f_{0,\mathrm{C}}$ were recorded at one-second intervals and also the fundamental voltage $U_{0,\mathrm{C,fund}}$ was measured during the test. The line-to-line resistance R_{U1V1} was measured between terminals U1 and V1 immediately before the test for 15 s and the stator winding resistance $R_{0,\mathrm{C}}$ was calculated with equation (A3.1) of Appendix 3.

3.4.3 Additional harmonic losses on converter supply

Stray-load losses $P_{\mathrm{LL,C}}$ of converter-fed motor include the harmonic load-dependent losses caused by the converter supply. According to IEC (2013), $P_{\mathrm{LL,C}}$ is determined from residual losses with similar method as P_{LL} on sinusoidal supply. The residual losses $P_{\mathrm{Lr,C}}$ of the converter-fed motor are the residual difference between input-output losses on converter supply and the fundamental loss components according to equation

$$P_{\text{Lr,C}} = P_{\text{1,L,C}} - P_{\text{2,L,C}} - P_{\text{s,L}} - P_{\text{r,L}} - P_{\text{fw,L}} - P_{\text{fe,L}} \,, \tag{3.15}$$

where:

$P_{1,\text{L,C}}$ is the input power on converter supply using 50 Hz supply frequency,
$P_{2,\text{L,C}}$ is the output power on converter supply using 50 Hz supply frequency,
$P_{\text{s,L}}$ are the stator winding losses on 50 Hz sinusoidal supply,
$P_{\text{r,L}}$ are the rotor winding losses on 50 Hz sinusoidal supply,
$P_{\text{fw,L}}$ are the friction and windage losses on 50 Hz sinusoidal supply and
$P_{\text{fe,L}}$ are the iron losses on 50 Hz sinusoidal supply

for each load point of the load curve test. $P_{1,\text{L,C}}$ is the measured input power from the load curve test on the frequency converter supply. (IEC 2013.)

The fundamental loss components $P_{\text{s,L}}$, $P_{\text{r,L}}$, $P_{\text{fw,L}}$, and $P_{\text{fe,L}}$ of each load point were calculated for determining the residual losses on the sinusoidal supply in chapter 3.3.4 (from equations (A2.33) – (A2.37) of Appendix 2). $P_{2,\text{L,C}}$ is calculated from (IEC 2013)

$$P_{\text{2,L,C}} = 2\pi T_{\text{L,C}} n_{\text{L,C}} \,, \tag{3.16}$$

where $T_{\text{L,C}}$ is the motor torque and $n_{\text{L,C}}$ is the operating speed in rounds per second of each load point on the converter supply.

Determining the stray-load losses from the residual losses is similar to the procedure in chapter 3.3.4. From the six residual loss values, a linear relationship (IEC 2013)

$$P_{\text{Lr,C}} = A \cdot T_{\text{L,C}}{}^{2} + B \,, \tag{3.17}$$

is formed and the constants A and B are determined with linear regression analysis presented in Appendix 4. For applying the method of Appendix 4, y = $P_{\text{Lr,C}}$ and x = $T_{\text{L,C}}^2$. The stray-load losses $P_{\text{LL,N,C}}$ at rated load are calculated from equation (IEC 2013)

$$P_{\mathrm{LL,N,C}} = A \cdot T_{\mathrm{N}}^{2}, \tag{3.18}$$

where T_N is the motor torque at rated load (from the rated load test on sinusoidal supply).

The calculated $P_{LL,N,C}$ and the constants B and γ from the linear regression analysis are shown in Table 3.8. The value of B is 42,9 % of $P_{LL,N,C}$ and the value of γ is almost 1. Both B and γ are well within the limits specified in chapter 3.3.4, hence the results can be considered reliable based on these indicators.

Table 3.8. The stray-load losses on test converter supply, and the constants B and γ from the linear regression analysis. The test was run with fundamental motor voltage of 400 V, 50 Hz with converter switching frequency of 4 kHz.

Stray-load losses, $P_{LL,N,C}$ [W]	180.8
B	77.49
γ	0.9999

Harmonic losses

The stray-load losses $P_{LL,N,C}$ include all load-dependent additional losses. The load-dependent additional harmonic losses $P_{HL,L}$ are determined from the difference between results on converter supply and results on sinusoidal supply according to equation (IEC 2013)

$$P_{\mathrm{HL,L}} = P_{\mathrm{LL,N,C}} - P_{\mathrm{LL,N}}, \tag{3.19}$$

where $P_{LL,N}$ are the stray-load losses on 400 V, 50 Hz sinusoidal supply according to chapter 3.3.4.

No-load additional harmonic losses $P_{HL,0}$ are determined from the difference between the rated voltage constant losses $P_{c,C}$ on converter supply and the rated voltage constant losses P_c on sinusoidal supply (IEC 2013)

$$P_{\mathrm{HL,0}} = P_{\mathrm{c,C}} - P_{\mathrm{c}}\,, \tag{3.20}$$

where $P_{\mathrm{c,C}}$ are according to chapter A2.6 of Appendix 2 and P_{c} are constant losses of the 100 % voltage point of the no-load test on sinusoidal supply.

Total additional harmonic losses of converter-fed motor are the sum of the load-dependent additional harmonic losses and the no-load additional harmonic losses according to equation (IEC 2013)

$$P_{\mathrm{HL}} = P_{\mathrm{HL,L}} + P_{\mathrm{HL,0}}\,. \tag{3.21}$$

The additional harmonic losses of the test converter supply are presented in Table 3.9. The additional harmonic losses are relatively small compared to the other determined motor loss components, which were shown in Table 3.7.

Table 3.9. The segregated time harmonic losses of the 15 kW motor on test converter supply at rated motor load and rated motor fundamental voltage of 400 V, 50 Hz. The switching frequency was 4 kHz.

Load dependent harmonic losses, $P_{\mathrm{HL,L}}$ [W]	23.9
No-load harmonic losses, $P_{\mathrm{HL,0}}$ [W]	61.9
Total harmonic losses, P_{HL} [W]	85.8

3.4.4 Total losses and efficiency of converter-fed motor

Total losses $P_{\mathrm{T,C}}$ of frequency converter driven motor are determined by adding the additional harmonic losses to the fundamental motor losses P_{T} determined on sinusoidal supply (IEC 2013)

$$P_{\mathrm{T,C}} = P_{\mathrm{T}} + P_{\mathrm{HL}}\,. \tag{3.22}$$

The efficiency η_{C} of converter-fed motor is calculated from equation (IEC 2013)

$$\eta_{C} = \frac{P_{2,N}}{P_{2,N} + P_{T,C}}, \quad (3.23)$$

where $P_{2,N}$ is the output power on sinusoidal supply determined from equation (A2.21) of Appendix 2. Harmonic loss ratio r_{HL} is the amount of the additional harmonic losses in relation to the fundamental losses according to equation (IEC 2013)

$$r_{HL} = \frac{P_{HL}}{P_{T}} \cdot 100\,\%. \quad (3.24)$$

The total losses, efficiency and the harmonic loss ratio determined on the test converter supply are presented in Table 3.10. The total losses were 7 % higher and the efficiency correspondingly 0.5 %-unit lower on the test converter supply compared to the results on sinusoidal supply.

Table 3.10. The total losses, efficiency and harmonic loss ratio of the 15 kW motor on test converter supply at rated motor load and rated motor fundamental voltage of 400 V, 50 Hz. The switching frequency was 4 kHz.

Total losses, $P_{T,C}$ [W]	1343
Efficiency, η_{C} [%]	91.84
Harmonic loss ratio, r_{HL} [%]	7

3.5 Input-output method

In the input-output method, the total motor losses are determined from the difference between the input power and the output power. Only one test at the rated load is needed with electrical input power measurement and mechanical output power measurement performed at the same time. The method similar for both sinusoidal supply (method 2-1-1A) and for frequency converter supply (method 2-3-C).

3.5.1 Measurement procedure

There was no need to make separate input-output measurements because the requirements for the input-output method are the same as the requirements for rated load test in summation of losses method. The required values according to IEC (2014a) are terminal voltage U_N, line current I_N, input power $P_{1,N}$, operating speed n_N, mechanical torque T_N and coolant temperature $\theta_{c,N}$, which were recorded at the rated load test. For converter-fed motors, the rated load test is not required. However, the requirements before beginning a load curve test are the same and the recordings for the input-output method were taken at the end of the rated load heat run of the frequency converter measurements.

3.5.2 Determining losses and efficiency

The losses and efficiency are determined from the recorded electric quantities of the motor input and the mechanical quantities of the motor output. The mechanical output power at rated load $P_{2,N}$ is calculated from (IEC 2014a)

$$P_{2,\mathrm{N}} = 2\pi T_{\mathrm{N}} n_{\mathrm{N}}, \tag{3.25}$$

where T_N is the motor torque at rated load and n_N the operating speed at the rated load. The total losses (IEC 2014a)

$$P_{\mathrm{T,I/O}} = P_{1,\mathrm{N}} - P_{2,\mathrm{N}}, \tag{3.26}$$

where $P_{1,N}$ is the input power on rated load. The efficiency of the motor is calculated from equation (IEC 2014a)

$$\eta_{\mathrm{I/O}} = \frac{P_{2,\mathrm{N}}}{P_{1,\mathrm{N}}}. \tag{3.27}$$

Although the presented symbols in equations (3.25) – (3.27) are for sinusoidal test quantities, the same equations apply for frequency converter supply. The results from input-output calculations on the sinusoidal supply and the test converter supply are presented in Table 3.11. In Table 3.12, a comparison between the results from the summation of losses method and the input-output method is shown. The total input-output losses on sinusoidal supply were higher compared to the results from summation of losses method. On test converter supply, the total losses and efficiency determined on both methods were equal.

Table 3.11. The total losses and efficiency of the 15 kW motor determined with the input-output method. The results are at rated motor load and rated motor fundamental voltage of 400 V, 50 Hz. The switching frequency in the test converter measurements was 4 kHz.

	Sinusoidal supply	**Test converter supply**
Total losses, $P_{T,I/O}$ [W]	1276	1343
Efficiency, $\eta_{I/O}$ [%]	92.22	91.84

Table 3.12. The total losses of the 15 kW motor determined with the summation of losses method and with input-output method. The results are at rated motor load and rated motor fundamental voltage of 400 V, 50 Hz. The switching frequency in the test converter measurements was 4 kHz.

	Summation of losses	**Input-output**	**Difference**
Sinusoidal supply	1257 W	1276 W	1.5 %
Test converter supply	1343 W	1343 W	0 %

3.6 Measurements on DTC converter supply

The results from rated fundamental motor voltage measurements on DTC frequency converter supply are presented in this chapter. For comparison, the results from measurements on the test converter supply are included. The test procedures were carried out similarly as with the test converter supply, the only differences being the supplying frequency converter and slight variations in durations of the procedures.

The tests were carried out with risen frequency converter input voltage of 433 V for the fundamental converter output voltage to reach rated motor voltage of 400 V, 50 Hz without overmodulation. The 433 V input of the converter resulted in slightly under 400 V fundamental output voltage and higher input voltage did not have any further effect on the output fundamental voltage. For this reason, the flux reference value of the frequency converter had to be risen from default 100 % to 100.9 % for the fundamental motor voltage to reach 400 V at the rated load.

As mentioned in chapter 1.4, a frequency converter utilizing DTC does not have a fixed switching frequency. An example of harmonic spectrum of the output voltage of the DTC converter used in the measurements was presented in Figure 1.5. It shows that the frequency content of the DTC converter output voltage is spread along the spectrum with only some centralization around the frequency range of 5 kHz – 6 kHz.

The stray-load losses at the rated load and the constants B and γ from linear regression analysis are shown in Table 3.13. The constants B and γ are within the limits specified in chapter 3.3.4, hence the results can be considered reliable based on these values.

Table 3.13. The stray-load losses at rated load DTC converter supply and constants B and γ from the linear regression analysis. The tests were run at rated motor fundamental voltage (400 V, 50 Hz). The switching frequency in the test converter measurements was 4 kHz.

	DTC converter supply	**Test converter supply**
Stray-load losses, $P_{LL,N,C}$ [W]	167.9	180.8
B	72.87	77.49
γ	0.9939	0.9999

Summary of the segregated results from the tests on DTC frequency converter supply is shown in Table 3.14. According to the results, both load-dependent and no-load additional harmonic losses were under half of those determined on the test converter supply.

The results from the input-output measurements on the DTC converter supply are presented in Table 3.15. According to the input-output method, the losses on both test converter supply and DTC supply are similar. Compared to the results from the summation of losses method (Table 3.14), the total losses $P_{T,C}$ and $P_{T,I/O,C}$ on the test converter are similar, but on the DTC converter, there is a 41 W difference in the losses.

Table 3.14. The harmonic losses, total losses and efficiency on DTC frequency converter supply compared to the results on test converter supply. The tests were run at rated motor fundamental voltage (400 V, 50 Hz). The switching frequency in the test converter measurements was 4 kHz.

	DTC Converter supply	**Test converter supply**
Load-dependent harmonic losses, $P_{HL,L}$ [W]	11.0	23.9
No-load harmonic losses, $P_{HL,0}$ [W]	29.7	61.9
Total harmonic losses, P_{HL} [W]	40.7	85.8
Total losses, $P_{T,C}$ [W]	1299	1343
Efficiency, η_C [%]	92.09	91.84
Harmonic loss ratio, r_{HL} [%]	3	7

Table 3.15. The total losses and efficiency of the 15 kW motor determined with the input-output method on DTC frequency converter supply compared to the results on test converter supply. The tests were run at the rated motor fundamental voltage (400 V, 50 Hz). The switching frequency in the test converter measurements was 4 kHz.

	DTC Converter supply	**Test converter supply**
Total losses, $P_{T,I/O,C}$ [W]	1340	1343
Efficiency, $\eta_{I/O,C}$ [%]	91.85	91.84

The discrepancy of the total losses $P_{T,C}$ and $P_{T,I/O,C}$ on DTC converter supply might be caused by slight load-dependence of the DTC converter fundamental voltage. During the measurements, the fundamental voltage altered between 396 V at no-load and 404 V at 125 % load, which affects both load curve test and no-load test. The load-dependent voltage related problems are further discussed in chapter 4.

3.7 Measurements at reduced voltage

The results from the tests at reduced motor voltage are presented in this chapter. The reduced voltages of 350 V and 377 V were the fundamental output voltages of the frequency converters at 50 Hz output, when the motor was running at its rated load and each converter was supplied with 400 V input voltage. All tests were carried out with the same procedures as the rated motor voltage tests in chapters 3.3–3.5. The only differences were the motor fundamental voltages being 350 V, 50 Hz and 377 V, 50 Hz instead of the rated 400 V, 50 Hz.

The tests on reduced motor voltage can be considered as non-standard from the beginning, since the IEC methods state that the tests should be run at the rated motor voltage. However, nothing in the methods prevents performing the tests at reduced motor voltage for determining the motor losses at that specific voltage. The reduced voltage sinusoidal tests were performed for determining the fundamental losses needed in the reduced fundamental motor voltage tests on both converter supplies. Additionally, the reduced voltage sinusoidal tests allow investigating the effect of motor voltage on the segregated and total motor losses.

Usually the motor loadability is considered lower when the motor fundamental voltage is below rated. However to keep the results comparable, the rated load of 15 kW was used also in the reduced voltage tests. When motor voltage is reduced, but the load stays the same, higher current is needed to provide the same power. Therefore, considerable rise in the winding losses and motor temperatures were expected. The stator winding temperature readings ($\theta_{\mathrm{meas,N}}$) were observed during the heat runs to avoid the motor reaching too high temperatures. Summary of the temperature measurements and the temperature rises at the end of the rated load heat run are shown in Table 3.16. For the sinusoidal tests, the stator winding temperature θ_{N} of the rated load test is determined from the extrapolated stator winding resistance R_{N}, hence θ_{N} is also included in the table.

The maximum temperature rise according to the motor manufacturer is 80 °C. The measured stator winding temperature rise was below 80 °C in all tests except the 350 V, 50 Hz test converter measurements. For the sinusoidal supply tests, the stator winding temperature θ_{N} was calculated from the stator winding resistance. The extrapolated θ_{N} values were considerably higher than the measured $\theta_{\mathrm{meas,N}}$ values. For the 350 V sinusoidal rated load test, θ_{N} was 116.3 °C, which results in temperature rise of 92.4 °C. However, all the determined stator winding temperatures, including the calculated temperature of 116.3 °C, are still within acceptable limits for the motor. The maximum allowed ambient temperature for the motor is 40 °C and the maximum temperature rise 80 °C; hence, a worst-case temperature of 120 °C is still allowable.

Table 3.16. The measured stator winding temperature $\theta_{meas,N}$, the ambient (coolant) temperature $\theta_{c,N}$, the stator winding temperature rise θ_{rise} (= $\theta_{meas,N}$–$\theta_{c,N}$) at the end of the rated load heat run of each of the measurements. θ_N is the stator winding temperature determined for the sinusoidal tests from the extrapolated stator winding temperature.

Test run	$\theta_{meas,N}$ **[°C]**	$\theta_{c,N}$ **[°C]**	θ_{rise} **[°C]**	θ_N **[°C]**
350 V, 50 Hz test converter supply	106.4	24.5	81.9	-
350 V, 50 Hz sinusoidal supply	102.9	23.9	79	116.3
377 V, 50 Hz DTC converter supply	99.6	24.6	75	-
377 V, 50 Hz sinusoidal supply	96.3	25.3	71	104.1
400 V, 50 Hz test converter supply	93.9	25.3	68.6	-
400 V, 50 Hz DTC converter supply	92.9	24.7	68.2	-
400 V, 50 Hz sinusoidal supply	89.3	24.9	64.4	97.4

3.7.1 Summation of losses on reduced voltage sinusoidal supplies of 350 V and 377 V

The tests were carried out with the procedures introduced in chapter 3.3 for determining the induction motor losses on sinusoidal supply. The only differences were that motor voltages of 350 V, 50 Hz and 377 V, 50 Hz were used instead of the rated voltage. For the 377 V run, the no-load test voltage points were the same as in the rated voltage tests. For the 350 V run, the no-load test voltage points were calculated from the motor voltage of 350 V, since it differs considerably from the rated voltage of 400 V, 50 Hz.

The main results from the sinusoidal tests at reduced voltages are presented in Tables 3.17 – 3.20. For comparison, the results from the rated voltage measurements are also included. The results from rated load tests are shown in Table 3.17. The coolant air temperature during both tests runs was near 25 °C and therefore the corrections to the reference coolant temperature were very small. The winding losses rise considerably as the motor voltage is reduced.

The results from the no-load tests are presented in Table 3.18. Both friction and windage losses and iron losses were lower in the reduced voltage tests. The reduction in the iron losses is about the same between both voltage reductions from 400 V to 377 V and from 377 V to 350 V. The reduction in the friction and windage losses, however, was unexpectedly large between the 377 V and 350 V tests. The decrease was only 11 % between 400 V and 377 V tests, but between the 377 V and 350 V tests, the friction and windage losses were reduced by 40 %.

Table 3.17. The uncorrected and temperature corrected winding losses.

Quantity	**Reduced sinusoidal voltage 1 (350 V, 50 Hz)**	**Reduced sinusoidal voltage 2 (377 V, 50 Hz)**	**Rated sinusoidal voltage (400 V, 50 Hz)**
Stator winding losses, $P_{s,N}$ [W]	640.8	539.0	485.7
Corrected stator winding losses, $P_{s,N,\theta}$ [W]	642.8	538.5	485.9
Rotor winding losses, $P_{r,N}$ [W]	439.4	353.8	300.0
Corrected rotor winding losses, $P_{r,N,\theta}$ [W]	440.7	353.5	300.1

Table 3.18. The friction and windage losses and iron losses at no-load and at rated load.

Quantity	**Reduced sinusoidal voltage 1 (350 V, 50 Hz)**	**Reduced sinusoidal voltage 2 (377 V, 50 Hz)**	**Rated sinusoidal voltage (400 V, 50 Hz)**
No-load friction and windage losses, $P_{fw,0}$ [W]	58.9	97.2	108.9
Rated load friction and windage losses, $P_{fw,N}$ [W]	54.8	91.8	103.7
No-load iron losses, $P_{fe,0}$ [W]	177.1	200.4	223.5
Rated load iron losses, $P_{fe,N}$ [W]	166.3	188.4	210.5

Some of the reduction can be explained with lower friction of the bearings. The motor, including the bearings, runs hotter in the reduced voltage tests and lubrication typically has less viscosity and friction at higher temperatures. The additional reduction in the friction and windage losses might be explained with the break-in of the motor, since the 377 V test was run several weeks before the 350 V test. The motor was rather new and several other tests were run on the motor between the 377 V and 350 V test runs. In addition, other efficiency tests that were run on the motor during the same period of time show reduction of total losses that is similar to the additional reduction in friction and windage losses in these tests. However, it is still not certain if the friction and windage losses really have changed. The results should be confirmed with additional tests. In addition to the no-load test, the friction and windage losses can be determined by other means. Possibilities are, for instance, torque measurement when rotating the motor with another machine or the retardation test.

The stray-load losses at the rated load and the constants *B* and *γ* from linear regression analysis are shown in Table 3.19. The constants *B* and *γ* are within the limits specified in chapter 3.3.4 in both reduced voltage tests, hence the results can be considered reliable based on these values. The stray-load losses at reduced voltages show similar rise as the winding losses compared to the rated voltage results.

Table 3.19. The stray-load losses at rated load and constants *B* and *γ* from the linear regression analysis.

Quantity	**Reduced sinusoidal voltage 1 (350 V, 50 Hz)**	**Reduced sinusoidal voltage 2 (377 V, 50 Hz)**	**Rated sinusoidal voltage (400 V, 50 Hz)**
Stray-load losses, $P_{LL,N}$ [W]	240.5	184.3	156.9
B	12.17	23.98	35.82
γ	0.9987	0.9995	0.9998

Table 3.20 gives summary of the segregated losses, total losses and efficiency. Although the friction and windage losses and the iron losses were reduced, the increases from winding losses and stray-load losses were significantly higher. Therefore, the total losses increased as the motor voltage was decreased. The increase in the total losses when fundamental voltage was reduced from 377 V to 350 V was almost twice the increase from the voltage reduction of 400 V to 377 V. The motor efficiency drop was correspondingly 0.6 % between the 400 V and 377 V measurements and 1.1 % between the 377 V and 350 V measurements.

Table 3.20. Summary of the segregated losses, total losses and efficiency on sinusoidal supply with different motor voltages.

Quantity	Reduced sinusoidal voltage 1 (350 V, 50 Hz)	Reduced sinusoidal voltage 2 (377 V, 50 Hz)	Rated sinusoidal voltage (400 V, 50 Hz)
Stator winding losses, $P_{s,N,\theta}$ [W]	642.8	538.5	485.9
Rotor winding losses, $P_{r,N,\theta}$ [W]	440.7	353.5	300.1
Friction and windage losses, $P_{fw,N}$ [W]	54.8	91.8	103.7
Iron losses, $P_{fe,N}$ [W]	166.3	188.4	210.5
Stray-load losses, $P_{LL,N}$ [W]	240.5	184.3	156.9
Total losses, P_T [W]	1545	1357	1257
Efficiency, η [%]	90.64	91.74	92.33

3.7.2 Summation of losses on test converter supply of 350 V, 50 Hz

During the 350 V, 50 Hz measurements, the test converter fundamental output voltage U_{fund} was not constant. U_{fund} was heavily dependent on motor load as shown in Table 3.21. Therefore, the results from the summation of losses method on 350 V test converter supply cannot be considered valid. Load dependently varying motor voltage affects both the load curve test and the no-load test. However, the results from the reduced voltage tests on the test converter supply are presented in Tables 3.22 and 3.23. For comparison, the results from the standard rated voltage tests are also included. The stray-load losses on the 350 V fundamental voltage test converter supply and the constants B and γ from the linear regression analysis are presented in Table 3.22.

Table 3.21. The test converter fundamental output voltage $U_{L,fund}$ on different motor loads at 50 Hz.

	Motor load (in % of rated load)						
	0 % (no-load)	25 %	50 %	75 %	100 %	115 %	125 %
$U_{L,fund}$	377	368	363	356	350	347	344

Table 3.22. The stray-load losses at rated load on 350 V, 50 Hz fundamental voltage test converter supply and constants B and γ from the linear regression analysis. The rated motor voltage results are included for comparison. The converter switching frequency was 4 kHz.

Quantity	**Reduced voltage (Test converter, 350 V, 50 Hz)**	**Rated voltage (Test converter, 400 V, 50 Hz)**
Stray-load losses, $P_{LL,N,C}$ [W]	254.6	180.8
B	83.23	77.49
γ	0.9828	0.9999

The determined stray-load loss value is probably erroneous because of the load-dependent fundamental motor voltage. In addition, although the values of B and γ are within the required limits (specified in chapter 3.3.4), the residual loss points form a rather curve-like than a linear relationship. The load-dependent voltage is further discussed in chapter 4.

Summary of the segregated results from the tests on 350 V, 50 Hz test converter supply is shown in Table 3.23. Because of the varying fundamental motor voltage, the values of load-dependent harmonic losses $P_{HL,L}$ and no-load harmonic losses $P_{HL,0}$ are probably erroneous. The results are also illogical. At reduced voltages, all load dependent losses tend to rise and no-load losses tend to drop. This should be the case with harmonic losses too, but the values shown in Table 3.23 would indicate just the opposite, if they were correct.

Table 3.23. The harmonic losses, total losses and efficiency on 350 V, 50 Hz fundamental voltage test converter supply. The rated motor voltage results are included for comparison. The converter switching frequency was 4 kHz.

Quantity	**Reduced voltage (Test converter, 350 V, 50 Hz)**	**Rated voltage (Test converter, 400 V, 50 Hz)**
Load-dependent harmonic losses, $P_{HL,L}$ [W]	14.1	23.9
No-load harmonic losses, $P_{HL,0}$ [W]	72.6	61.9
Total harmonic losses, P_{HL} [W]	86.7	85.8
Total losses, $P_{T,C}$ [W]	1632	1343
Efficiency, η_C [%]	90.17	91.84
Harmonic loss ratio, r_{HL} [%]	6	7

Although the results with summation of losses method at the 350 V, 50 Hz fundamental voltage test converter supply are probably incorrect, the input-output results are still usable. The input-output method is not affected by the changing fundamental voltage since the load is constant during input-output measurements. The input-output results from all reduced motor voltage measurements are presented in chapter 3.7.4.

3.7.3 Summation of losses on DTC frequency converter supply of 377 V, 50 Hz

The results from the reduced voltage tests on the DTC frequency converter supply are shown in Tables 3.24 and 3.25. For comparison, the results from the rated voltage tests are included.

As was noted considering the rated fundamental motor voltage DTC converter tests, the results of the summation of losses method with the DTC converter supply might be inaccurate. The fundamental motor voltage was somewhat load-dependent also in the 377 V tests. For some reason though, while the fundamental motor voltage increased with load in the 400 V DTC measurements, in the 377 V DTC tests the fundamental voltage decreased when the load was increased.

The stray-load losses on the DTC converter supply and the constants B and γ from the linear regression analysis are presented in Table 3.24. The values of B and γ are within the required limits specified in chapter 3.3.4. Stray-load losses $P_{LL,N,C}$ on reduced voltage show notable rise in comparison to the rated voltage value. $P_{LL,N,C}$ were higher also compared to the stray-load losses $P_{LL,N}$ on sinusoidal supply at same fundamental voltages (Table 3.19). The difference between $P_{LL,N}$ and $P_{LL,N,C}$ was higher in the 377 V tests.

Table 3.24. The stray-load losses at the rated load on 377 V, 50 Hz DTC frequency converter supply and constants B and γ from the linear regression analysis. The rated motor voltage results are included for comparison.

Quantity	**Reduced voltage (DTC, 377 V, 50 Hz)**	**Rated voltage (DTC, 400 V, 50 Hz)**
Stray-load losses, $P_{LL,N,C}$ [W]	202.5	167.9
B	75.46	72.87
γ	0.9989	0.9939

Summary of the segregated results from the tests on DTC frequency converter supply at reduced voltage is shown in Table 3.25. Both load-dependent and no-load additional harmonic losses were higher in reduced voltage tests compared to the rated voltage tests. The total losses were 127 W higher and the efficiency was 0.74 % lower in the reduced voltage tests. Although the results with the summation of losses method on DTC converter supply are uncertain, the input-output results are still comparable. The input-output results are presented in the next chapter.

Table 3.25. The harmonic losses, total losses and efficiency on 377 V, 50 Hz DTC frequency converter supply. The rated motor voltage results are included for comparison.

Quantity	Reduced voltage (DTC, 377 V, 50 Hz)	Rated voltage (DTC, 400 V, 50 Hz)
Load dependent harmonic losses, $P_{HL,L}$ [W]	18.2	11.0
No-load harmonic losses, $P_{HL,0}$ [W]	50.0	29.7
Total harmonic losses, P_{HL} [W]	68.1	40.7
Total losses, $P_{T,C}$ [W]	1425	1298
Efficiency, η_C [%]	91.36	92.09
Harmonic loss ratio, r_{HL} [%]	5	3

3.7.4 Input-output losses at reduced voltage tests

The input-output results from the tests at reduced motor voltage are presented in Table 3.26. The results from the rated motor voltage tests are listed for comparison. In Table 3.27 is shown comparison from all of the results determined with both summation of losses and input-output methods on different fundamental voltage sinusoidal, test converter and DTC converter supplies.

According to the input-output results, the total losses on test converter supply were 79 W higher than on sinusoidal supply at 350 V, 50 Hz, while on 400 V, 50 Hz the corresponding difference was 67 W. On DTC supply, the total losses were 77 W higher than on sinusoidal supply at 377 V, 50 Hz. On 400 V, 50 Hz the difference between DTC supply and sinusoidal supply was 64 W.

Table 3.26. Total losses and efficiencies on sinusoidal supply, on test converter supply, and on DTC converter supply determined with the input-output method at reduced fundamental motor voltages. The rated motor voltage results are included for comparison. The test converter switching frequency was 4 kHz.

Quantity	**Reduced voltage (350 V, 50 Hz)**	**Reduced voltage (377 V, 50 Hz)**	**Rated voltage (400 V, 50 Hz)**
Total losses on sinusoidal supply, $P_{I/O}$ [W]	1529	1374	1276
Efficiency on sinusoidal supply, $\eta_{I/O}$ [%]	90.73	91.64	92.22
Total losses on test converter supply, $P_{I/O,C}$ [W]	1608	-	1343
Efficiency on test converter supply, $\eta_{I/O,C}$ [%]	90.29	-	91.84
Total losses on DTC supply, $P_{I/O,C}$ [W]	-	1451	1340
Efficiency on DTC supply, $\eta_{I/O,C}$ [%]	-	91.20	91.85

Table 3.27. Comparison of the total losses on sinusoidal supply, on test converter supply, and on DTC converter supply determined with the summation of losses method and the input-output method. The rated motor voltage results are included for comparison. The test converter switching frequency was 4 kHz.

Supply voltage	**Summation of losses**	**Input-output method**	**Difference**
Sinusoidal 400 V, 50 Hz	1257 W	1276 W	1.5 %
Sinusoidal 377 V, 50 Hz	1357 W	1374 W	1.3 %
Sinusoidal 350 V, 50 Hz	1545 W	1529 W	-1.0 %
Test converter 400 V, 50 Hz	1343 W	1343 W	0.0 %
Test converter 350 V, 50 Hz	1632 W	1608 W	-1.5 %
DTC 400 V, 50 Hz	1298 W	1340 W	3.2 %
DTC 377 V, 50 Hz	1425 W	1451 W	1.8 %

Compared to the results with the summation of losses method, the total losses on sinusoidal supply determined with input-output method were 1.5 % higher on 400 V and 1.3 % higher on 377 V but 1 % lower on 350 W. The input-output results on test converter supply at 350 V were relatively close to the results from summation of losses, considering that there were problems at the 350 V summation of losses measurements. At 400 V test converter supply both methods gave exactly same results. On DTC converter supply, the 3.2 % difference between the methods at 400 V tests was reduced to a difference of 1.8 % at reduced voltage of 377 V.

4 CHALLENGES AND UNCERTAINTIES

The measurement procedures of the summation of losses methods are quite complex, and therefore, susceptible to unexpected problems and human errors. The accuracy of the indirect loss segregation method, however, is relatively high. The input-output method, as contrast, is very simple for the measurement part, but the accuracy of the method is very sensitive to on the input electric power and output mechanical power measurement uncertainties.

The summation of losses measurements at the rated motor fundamental voltage on the test converter supply and on sinusoidal supply were performed with the least problems. The same measurements seemed to give also the most reliable results. In addition, the measurements at reduced voltage sinusoidal supply of 377 V gave stable results. The DTC converter supply measurements were also mostly non-problematic, but the results from the summation of losses method might be unreliable because of the converter properties not fully supporting the measurement accuracy.

The accuracy of the measurements depends on several factors. The accuracy, quality and stability of the power supply can affect the results considerably. The accuracy of the measured quantities is limited by the accuracy of the instruments. The stability of temperature and humidity during the tests can also affect the accuracy. In addition, if the method used is not suitable for the purpose, it can produce erroneous results even though the measurements and calculations might seem valid.

4.1 Problems that occurred during the measurements

Several problems were faced during the measurements. Most of the difficulties in the measurement procedures were related to the measurement setup and not directly to the methods. The measurements on frequency converter supply had their own additional hitches and the IEC methods for converter-fed motors were not entirely clear at all points. The rated motor voltage measurements had the least difficulties.

The summation of losses method is rather complex utilizing three separate tests, which are performed immediately in the correct order without any unnecessary interruptions and with minimal delays. The recording of test data was almost fully automated, but several procedures had to be performed manually. These included the decoupling of the load machine, the four-wire resistance measurement, adjusting the load torque during the load curve test and adjusting the motor voltage during the sinusoidal supply no-load test. A couple of times the whole test procedure had to be stopped because of problems during the tests. Once, difficulties with decoupling the load machine between the load curve test and the no-load test caused too long delay and therefore the test run had to be stopped. During another test run, loose couplings caused invalid readings in the resistance measurement. The results from the failed test runs were discarded and the measurements were redone successfully.

The stability of the mains supply voltage caused problems in the measurements. Although the voltage was adjusted to the required value, i.e. 400 V, from the variable transformer, it altered by ± 3–6 V during the heat run a few times. Usually, this was noticed and the voltage was readjusted at an early stage of the heat run or shortly after the change was happened. Once or twice, however, the voltage change was not noticed until the measurements were supposed to be performed. Since the motor voltage affects the motor temperature, the required thermal stability had to be re-established before beginning the tests. An example of the effect of a smaller voltage fluctuation can be seen in Figure 3.3 around the 22 h mark, where the winding temperature suddenly increased by 0.2 °C. In addition to the sudden changes of voltage level, the mains supply voltage was somewhat load-dependent. Difference between supply voltage values on 25 % and 125 % load points were 1.5–2.9 V in the sinusoidal supply tests. A separate stable sinusoidal supply should solve the problem of fluctuating network voltage.

Most problems with the measurements on the test converter supply were related to the frequency converter parameters. Several parameters had to be adjusted for the converter to fulfill the requirements of the test converter operation. Some of these parameters switched automatically to their default values when the frequency converter was switched off and they had to be rechecked and readjusted every time. In addition, for the 400 V fundamental voltage measurements, a few settings controlling DC-link (over)voltage had to be tuned. Although the input voltage of 460 V was within the input voltage limits of the frequency converter, the risen DC-link voltage caused some unwanted behavior at default converter settings.

In the reduced fundamental voltage measurements on the test converter supply, the fundamental output voltage was heavily dependent on load. This makes the summation of losses method results practically unusable. The fundamental voltage was somewhat load-dependent on DTC converter supply, too. The DTC converter fundamental voltage was slightly increased when the load was increased at the rated motor fundamental voltage tests. At the reduced motor voltage tests, on the contrary, the fundamental voltage was slightly reduced when the load was increased. Aside from the varying fundamental voltage, the DTC converter measurements were performed without any specific problems.

4.1.1 Ambiguities in the IEC procedures

The IEC procedures for converter-fed motors were not entirely clear at few points. The method refers directly to the procedures of the method 2-1-1B, but when measurements are performed according to them, some parts seem unnecessary. In addition, setting the input voltage of the test converter was problematic with the IEC (2013) instructions, at least in the case of the frequency converter used. However, it should be noted that IEC (2013) is not a completed standard and currently only released as a technical specification.

According to IEC (2013), the load curve tests is supposed to be performed with the procedures of method 2-1-1B of IEC (2014a). The load curve test includes resistance measurements before and after the test, although in the determination of converter-fed motor losses, the resistance values are not needed at all. However, when the resistance measurements are made similarly to the measurements on sinusoidal supply, the motor temperature curve is also similar in the converter supply tests. This can be counted beneficial to the accuracy, since the losses determined on sinusoidal supply represent the fundamental losses of the converter-fed motor. If the load curve test were started directly from the rated load heat run without stopping for resistance measurement, the winding temperature would rise significantly higher than during the sinusoidal supply test.

IEC (2013) instructs to set the test converter input voltage to a just high enough value for allowing rated motor voltage to be applied without overmodulation. When this was done at the rated motor load, problems were encountered at 115 % and 125 % load points. The converter input voltage needed for rated motor load was 454 V, but for the converter to operate appropriately at also the 125 % load, the input voltage had to be risen to 460 V. It is not clear in the technical specification if a voltage high enough for all test points should be used or if the supply should be adjusted load point by load point.

4.2 Instrumentation accuracy

The instruments used for measuring each of the quantities are listed in Table 4.1. In Table 4.1 are also shown the calculated uncertainties and the IEC accuracy requirements for each quantity. The calculated overall reading uncertainties are for rated motor load of 15 kW and rated motor voltage of 400 V. Calculating the uncertainties is presented in chapter A2.7 of Appendix 2. The instrument accuracies from Table 3.2 were used in the calculations.

Only the accuracies of torque and temperature measurements fulfill the IEC requirements. The accuracies of the voltage, current and power measurements are slightly outside the IEC limits. Since Yokogawa WT1600 is a power analyzer, the accuracy of measured power is actually better than it would be, if the power was calculated from voltage, current and power factor indirectly. The fundamental voltage, rotational speed and stator winding resistance measurements have over twice the allowed uncertainty.

The IEC accuracy requirements are very strict. For comparison, the previous edition of the standard has only the accuracy class 0.2 requirement for measurements of electric quantities and 0.1 % or 1 rpm accuracy requirement for the rotational speed (IEC 2007). Especially the new requirement of 0.1 rpm accuracy for speed measurement is a huge step from the previous 1 rpm requirement. The 0.1 rpm uncertainty in case of a 1500 rpm machine results in 0.007 % speed measurement accuracy demand which is not practical.

Table 4.1. The overall accuracy of the measurement instruments at rated motor load and rated motor voltage measurements. The IEC (2014a; IEC 2013) accuracy requirements for each quantity are also included. Calculating the overall accuracies is presented in chapter A2.7 of Appendix 2.

Quantity	**Instrument**	**Calculated overall uncertainty**	**IEC required accuracy**
Power	Yokogawa WT1600	0.24 % (Power factor 1.0)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
Voltage	Yokogawa WT1600	0.22 % (Power factor 1.0)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
Current	Yokogawa WT1600	0.26 % (Power factor 1.0)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
	Hitec CURACC		
Fundamental voltage	Yokogawa PZ4000	0.54 % (Power factor 1.0)	Class 0.2 & overall uncertainty of 0.2 % of reading at power factor 1.0
Torque	HBM T12	0.06 %	Class 0.2
Rotational speed	HBM T12	0.23 rpm	0.1 rpm
Ambient (coolant) temperature	Keithley 2701	0.21 °C	1 K
	Pt100 Class A		
Winding temperature	Keithley 2701	0.75 °C	1 K
	Pt100 Class B		
Resistance	Keithley 2701	0.56 %	Class 0.2 & overall uncertainty of 0.2 % of reading

4.3 Other sources of inaccuracy and error

Several sources may cause inaccuracy and error in induction motor measurements. The power supply voltage and frequency affect the motor operation and therefore the losses and results. Similarly, the test conditions need to be stable. In addition, variations in the measurement procedures and, obviously, possible errors in the measurements may cause in inaccurate results.

4.3.1 Test setup

In addition to the uncertainties of the measuring instruments, the test setup contains several other equipment that could cause inaccuracy in the tests. The variable transformer, which is used for supplying the mains voltage in all the measurements, is adjustable between 0–720 V. However, the transformer voltage adjustment is not very accurate, and the smallest adjustable voltage step is about 1 – 1.5 V. In the measurements, the voltage was targeted between –0.5 – +1V range of the required voltage.

The stator winding temperature of the motor was measured with a B-class Pt100 sensor installed on the winding surface with thermal adhesive. The temperature information provided by the sensor is sufficient for establishing the thermal stability before the rated load tests. However, the accuracy of the temperature readings cannot be confirmed. The resistance extrapolation method gave higher results than the sensor, but the differences were not consistent. In addition, the resistance measurement had its own problems, which are discussed in chapter 4.3.4.

Two ball bearings are located between the tested motor and the torque transducer. The torque loss of the bearings was measured by driving the decoupled axle with the load machine. The measured torque was very low and therefore the accuracy of the torque transducer might be questionable. A torque transducer of a lower rating would be more accurate when determining the loss of the bearings. Additionally, the friction of the bearings may be different when they are coupled with the machine, if the alignment is not optimal. The temperature of the bearings may also cause the torque loss to vary between the measurements.

The accuracy of the torque measurement is especially important for the input-output method. In the summation of losses method, on the contrary, the importance of the mechanical torque measurement is minimized. For example considering the 15 kW motor tests, an offset error of 1 Nm in the torque measurement causes an error of 154 W in the input-output losses, but only an error of 3 W in the total losses of the summation of losses method.

4.3.2 Power supply quality and stability

In addition to the instrument accuracies, the supply frequency, harmonic voltage factor and symmetry have limits defined by IEC (2014a). The average supply frequency of all tests and test points, except during some test points on the 350 V sinusoidal supply, was within the limits of ±0.1 % of the frequency of 50 Hz. The harmonic voltage factor and symmetry of the supply were not observed during these tests.

The mains supply voltage was not very stable in the tests. During measurements on sinusoidal supply, the voltage difference between lowest and highest load points was 1.5–2.9 V depending on the test run. The voltage was lowest at the highest load points. The altering voltage may cause some error in the determination of the stray-load losses.

In the frequency converter tests, the motor supply frequency was very exact. The voltage value was also very accurate in the 400 V, 50 Hz fundamental voltage measurements on test converter supply. Although the converter fundamental voltage was stable, the slightly load-dependent sinusoidal voltage may affect the results. The additional load-dependent losses $P_{\mathrm{HL,L}}$ are determined as difference of the stray-load losses $P_{\mathrm{LL,N,C}}$ on converter supply and $P_{\mathrm{LL,N}}$ on sinusoidal supply according to equation (3.19). Therefore possible errors in $P_{\mathrm{LL,N}}$ are transferred to the value of $P_{\mathrm{HL,L}}$.

In the other frequency converter measurements, the fundamental voltage was more or less load-dependent. The fundamental voltage of 350 V, 50 Hz test converter measurements was heavily load-dependent. The stray-load loss determination for the 350 V test converter measurements is shown in Figure 4.1. The residual losses seem to form a relationship that looks more like an exponential curve than a straight line. It is obvious that the residual loss method will not give accurate stray-load loss value in this type of a situation. Similar, but much less pronounced behavior can be noticed in the 377 V, 50 Hz DTC test and sinusoidal tests. In these tests, the motor voltage dropped slightly when the load was increased. In the 400 V, 50 Hz DTC test, the voltage increased when the load was increased and the residual losses showed correspondingly opposite behavior, which is shown in Figure 4.2. Therefore, the load-dependent voltage is the probable cause for this behavior. The errors in the stray-load losses $P_{\mathrm{LL,N,C}}$ affect the additional harmonic load losses $P_{\mathrm{HL,L}}$ value according to equation (3.19).

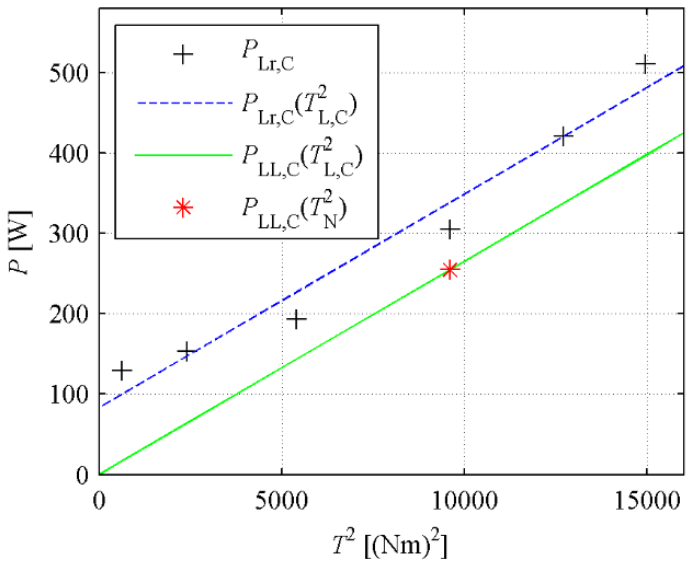

Figure 4.1. Determining the stray-load losses with the residual loss method on the 350 V, 50 Hz test converter supply. The dashed line is the smoothed linear relationship of the residual loss points. However, the loss points seem to form more like an exponential curve.

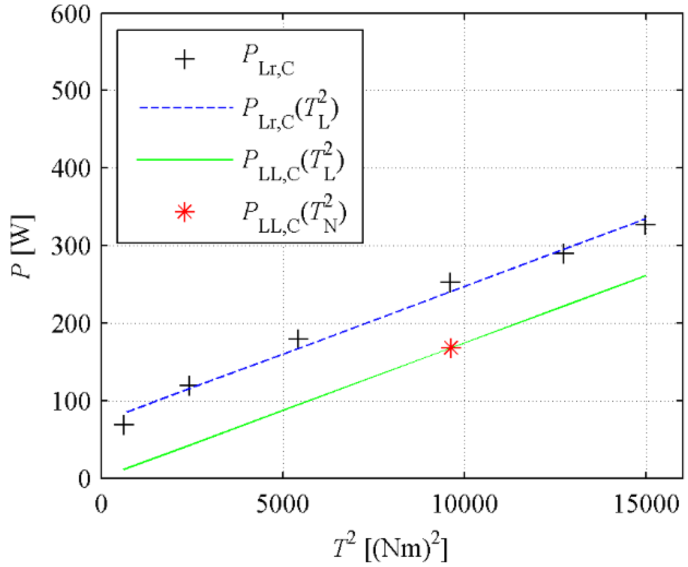

Figure 4.2. Determining the stray-load losses with the residual loss method on the 400 V, 50 Hz DTC converter supply. The dashed line is the smoothed linear relationship of the residual loss points. The residual loss points seem to be arranged in just the opposite manner when compared to Figure 4.1.

In addition to $P_{HL,L}$, the load-dependent fundamental voltage causes error in the determination of the no-load additional harmonic losses $P_{HL,0}$. For example, in the test converter measurements on 350 V, 50 Hz fundamental motor voltage, the no-load test voltage was 377 V instead of 350 V. The motor voltage in the 100 % voltage point of the no-load test on sinusoidal supply was 349 V. Since $P_{HL,0}$ are determined as difference of no-load losses on converter and on sinusoidal supply according to equation (3.20), and the constant losses P_c and $P_{c,C}$ both are increased with voltage, the calculated $P_{HL,0}$ value ends up too small. This was partly corrected by interpolating the sinusoidal P_c at the voltage of 377 V. Still however, the determined $P_{HL,0}$ value is the no-load additional harmonic loss value at the voltage of 377 V instead of 350 V. Hence, the determined value of $P_{HL,0}$ is probably higher than it would be at 350 V.

4.3.3 Test temperature and thermal stability

The IEC summation of losses and input-output methods have requirements for thermal state of the motor under test. Before rated load measurements, the temperature rise rate of the motor is allowed to be one kelvin per half hour at most. In addition, the load-curve test has to be performed immediately after the rated load test, or if that is not possible, the winding temperature has to be within 5 K of the rated load test value before beginning the test. The no-load test, in turn, has to be run immediately after the load curve test on hot motor. Same instructions apply to the load curve test and no-load test on converter supply. (IEC 2014a; IEC 2013.)

During the sinusoidal supply tests, the rated load, load curve and no-load tests were carried out consecutively without any unnecessary interruptions. For the frequency converter tests, the rated load test is not required, but the motor was run to thermal equilibrium before starting the load curve test. Since the motor losses on converter supply are higher than the losses on sinusoidal supply, the winding temperature was slightly higher in the converter tests. However, the winding temperature was within the required 5 K of the corresponding rated load test temperature in the beginning of load curve test in all the measurements, except in measurements on the 350 V, 50 Hz sinusoidal supply. The measured stator winding temperatures in the beginning of all load curve tests compared with the rated load test temperature are listed in Table 4.2. The no-load test temperatures were considerably lower than the rated load temperatures. The winding temperatures during no-load test points were 12–21 °C lower than the rated load test temperatures.

Table 4.2. The stator winding temperature at the beginning of the load curve test compared to the rated load test temperature.

	Rated load test	**Beginning of load curve test on sinusoidal supply**	**Beginning of load curve test on test converter supply**	**Beginning of load curve test on DTC converter supply**
400 V tests	89.3 °C	85.4 °C (–3.9 °C)	87.4 °C (–1.9 °C)	86.9 °C (–2.4 °C)
377 V tests	96.9 °C	92.1 °C (–4.8 °C)	-	94.7 °C (–2.2 °C)
350 V tests	102.9 °C	96.8 °C (–6.1 °C)	98.7 °C (–4.2 °C)	-

The duration of the test points was longer than what is instructed by IEC (2014a; IEC 2013). The duration of 45 seconds for each of the load and voltage points has been in regular use in the laboratory. As a shorter duration might have caused additional changes in laboratory procedures, it was not applied at this point. In addition, the sampling interval of one second would result in relatively low amount of samples for each load point. The purpose of the requirement for short duration of the measurement points is to minimize variations caused by changes in the motor temperature.

An example of temperature curve during the whole measurement run of the 400 V sinusoidal measurements is shown in Figure 4.3. During the performed load curve tests, the maximum variations of the stator winding temperature were around 5 °C. Using load points of 15 s would decrease the temperature variation but bringing the shorter duration into use and investigating its effects on the results was left for future work. However, shorter load points will not decrease the temperature drop during the resistance measurement between rated load test and load curve test. Shorter resistance measurement in turn, is not practical since extrapolating the stator winding resistance to the stopping moment needs enough recordings. However, if the resistance measurement were substituted with temperature based resistance determination, the load curve test could be started directly from the rated load test without stopping the motor.

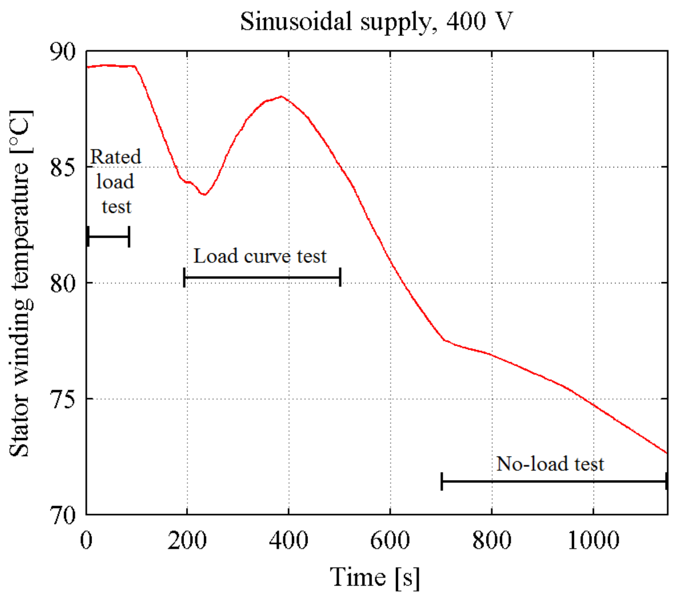

Figure 4.3. The measured stator winding temperature curve during the 400 V, 50 Hz test run on sinusoidal supply.

4.3.4 Stator winding resistance measurement

When analyzing the test data, problems were discovered with the four-wire resistance measurement. Illogical resistance values were noticed from the recorded measurement data of some tests. The resistance values recorded during the tests were investigated further by comparing the measurement-based values with values calculated from stator winding temperature rise. The comparisons are presented in chapter A3.2 of Appendix 3 and they show that the four-wire measurement gives inconsistent stator winding resistance values during most of the test runs. Two examples of the stator winding resistance measurement data are shown in Figure 4.4.

According to Keithley (2004), a probable source for these variations are thermoelectric voltages, which are caused by temperature differences in the measurement circuit. Methods for cancelling the effect of the thermoelectric voltages are proposed by Keithley (2004 & 2013, pp. 3-20–3-25). However, none of these methods is well suitable for measuring resistance of high inductance loads such as induction motor windings.

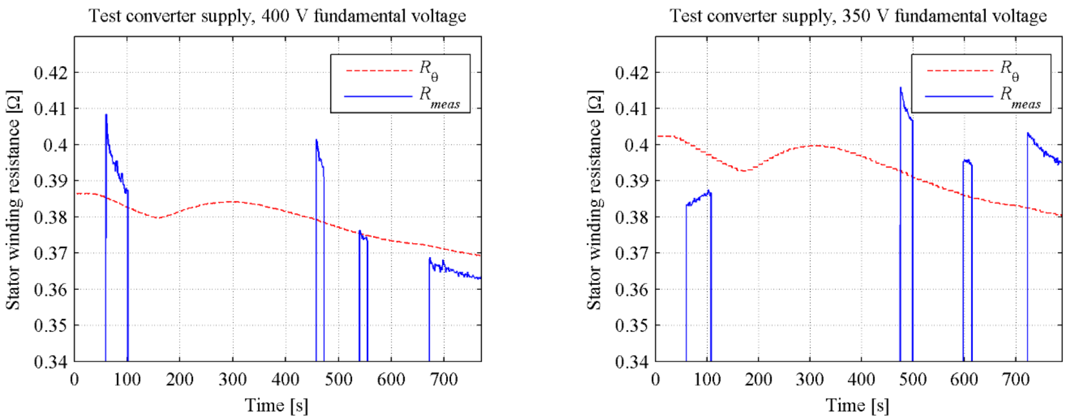

Figure 4.4 Stator winding resistance curves during the measurements on test converter supply of 400 V and 350 V. The resistance R_{meas} is determined from the 4-wire measurement between the tests. The resistance R_{θ} is calculated from the stator winding temperature. The plots show that the 4-wire resistance measurement gives inconsistent results.

Considering the problematic resistance measurement, the alternative option of determining the stator winding resistance from the stator winding temperature might seem a better option. However, the temperature sensors give the temperature only at certain spots of the windings and the values do not necessarily represent the (average) winding temperature very well. For example in the tests of this thesis – although the accuracy of the resistance measurement is uncertain – the stator winding temperatures from the resistance method were notably higher than the direct temperature measurements from the winding surface. Hence, the accuracy of the stator winding resistance might not be any better than the accuracy of direct resistance measurement. IEC (2014a; 2013) allows the stator winding resistance of the load curve test points and the no-load test points to be determined from the temperature measurement, but the resistance measurement (with extrapolation) is required for the rated load test. Since the resistance drifting seems much more pronounced in the measurements on converter supply (Figure A3.2 compared to Figure A3.1), the no-load test stator winding resistance on converter supply might be more accurate when determined from the measured winding temperature.

4.4 Accuracy of the results

The means to evaluate the accuracy of the results are limited. Methods exist to calculate the measurement uncertainty for the loss results, but they are out of the scope of this thesis.

In addition, the measurement uncertainty does not take into account additional sources of error and uncertainty discussed in chapter 4.3.

The measurement uncertainty of the summation of losses and input-output methods has been investigated by Aarniovuori et. al. (2014). In the study, the calculated uncertainty of total losses of a 15 kW induction motor was 1.4 % when determined with the loss segregation method, and 5.2 % when determined with input-output method (Aarniovuori et. al. 2014). These numbers cannot be assumed to apply directly to the loss determinations in this thesis, but they give some guidelines for the relative accuracies of the two methods.

One way to investigate the correctness of the results would be to determine the losses with a more accurate method. For example the calorimetric concept presented by Kosonen et. al. (2013) would fit for the purpose. The calorimetric method suggested by them allows measuring losses of 500 W to 2 kW with the uncertainty of only 0.4 % (Kosonen et. al 2013).

4.4.1 Tests on sinusoidal supply

The summation of losses (2-1-1B) and input-output (2-1-1A) methods gave acceptable results at the sinusoidal supply of 400 V. The efficiency determined with the 2-1-1B method was close to the value given by the manufacturer. The efficiency of 92.3 % determined for the motor is 0.4 %-units less than the IEC efficiency of 92.7 % given by the motor manufacturer. According to IEC (2010a) the tolerance for the motor losses is 15 % of the total losses, which means that the efficiency of a single tested motor should be between 91.58 % and 93.64 %. Hence, the determined efficiency is well within the tolerance. The input-output efficiency of the 400 V sinusoidal supply test was 92.2 %, which is also relatively close to the efficiency from the 2-1-1B method.

At reduced sinusoidal voltages, the results were mixed. At 377 V, everything seemed fine and the results from the methods 2-1-1B and 2-1-1A were expected in comparison to the 400 V results. The total losses were higher than at 400 V, but there was similar difference in the determined losses between the two methods. At 350 V however, the results from the 2-1-1B method seem inaccurate. While the total losses from method 2-1-1A were 1.5 % higher at 400 V and 1.3 % higher at 377 V, at 350 V the total losses from the method 2-1-

1A were 1.0 % lower. In addition, the residual losses from 350 V tests showed the most nonlinear behavior among the sinusoidal tests.

4.4.2 Test converter measurements

The test converter measurements according to the IEC methods 2-3-A and 2-3-C at rated voltage gave very stable results. The total losses of the motor on 400 V, 50 Hz test converter supply were the same with both methods. At reduced voltage of 350 V, 50Hz, in turn, the results from the method 2-3-A are probably erroneous, since the converter fundamental output voltage was not constant. Additionally, the sinusoidal tests at 350 V, 50 Hz voltage gave mixed results, which may further affect the 350 V, 50 Hz test converter results in the 2-3-A method. The accuracy of the input-output measurement is limited, but there was no reason to suspect any additional uncertainties or errors considering the input-output method 2-3-C.

4.4.3 Measurements on DTC Converter supply

The summation of losses method 2-3-B was noticed to be uncertain when used for the DTC converter measurements. Since the fundamental voltage of the DTC converter was somewhat load-dependent in the tests, the results of both load curve test and no-load test are probably inaccurate. In addition, the voltage waveform of a specific converter is not necessarily constant with different loads, which may also affect the results.

The input-output method 2-3-C, on the other hand, is fully usable with any specific frequency converter supply. The input-output losses are determined in a single load point and therefore the results are unaffected with any load-dependent behavior. The limited accuracy of the input-output measurement is, however, the downside of the method also in the case of a specific converter supply.

5 CONCLUSIONS

The main interest of this thesis was to investigate determining the losses of a converter-fed induction motor with the IEC summation of losses method 2-3-A. As IEC requires, all measurements were made at the motor rated frequency of 50 Hz. Sinusoidal supply tests are part of the method 2-3-A, hence the measurements with the recently updated IEC summation of losses method 2-1-1B were performed also. The method 2-3-A utilizes a specific test converter, which is a frequency converter with a fixed output waveform. The test converter waveform differs from those of typical commercial frequency converters. Therefore, the differences between the motor losses on the test converter supply and on a typical DTC frequency converter supply were another focus of this work. Additionally, the method 2-3-A requires that the tests are run at the rated fundamental motor voltage. However, the fundamental converter output voltage is typically lower and reaching the rated motor voltage requires the converter input voltage to be risen considerably, which sounds pretty artificial from the practice point of view. Hence, the differences between the motor losses at rated motor fundamental voltage and at the lower, converter specific fundamental voltage were investigated. For comparison, total motor losses from all the measurements were determined with also the input-output method.

The IEC 2-3-A method of summation of losses on test converter supply gave very promising results. The basic principle of determining the additional harmonic losses from the differences between results on the test converter supply and sinusoidal supply is simple and useful, but it makes the method rather complex to apply. The test converter seemed to work as supposed to, and the measurement results of converter-fed motor were very stable. However, the method requires also a clean and stable sinusoidal supply to give accurate results. In addition, since the measurements are made at two parts on the sinusoidal and on the test converter supply, the test conditions during both measurements need to be similar. Although the sinusoidal mains supply used in these tests was not optimal, the method gave satisfactory results. The total motor losses were the same determined with the method 2-3-A and the input-output method. The only problem with the method 2-3-A is that the results do not give any realistic estimate of the motor losses with a specific converter supply in a final application. The motor voltage, load and frequency are all rarely at their rated values when considering an electric drive system. However, the ability to compare the losses and efficiencies of different induction motors is often more important than determining the actual losses.

Comparing the test converter supply and the DTC converter supply was practically limited to comparing the input-output results. Determined with the input-output method, the motor losses on the test converter and the DTC converter were similar. Determined with the loss segregation method, the harmonic motor losses on DTC converter supply were less than half of the harmonic losses on the test converter supply, but the results have to be considered as uncertain. The fundamental DTC converter output voltage was load-dependent, which causes error in the 2-3-B method. To determine the motor losses and efficiency accurately with the summation of losses method, the motor fundamental voltage and the voltage waveform need to be stable. With a specific frequency converter with a manufacturer specific control method – such as DTC – the operation may alter depending on motor load. However, although the DTC converter operation might be possible to configure to be more suitable for the summation of losses method, the converter operation at that point might be far from normal. Since the original intention was to investigate motor losses on a typical DTC converter supply in comparison to the test converter, the purpose of such tests would be questionable. It seems that the summation of losses method 2-3-B on a specific converter supply cannot be recommended for determining induction motor losses based on these results. At least not without confirming the suitability of the method for the specific converter that is going to be used in the tests. The most reliable methods for determining the losses on a specific frequency converter would be the direct methods, where only a single load measurement is needed.

The method 2-3-B used in the DTC measurements is intended for a specific converter supply in final application. However, the procedure is exactly similar to the method 2-3-A with the only difference being usage of a specific converter instead of the test converter. The similarities include the requirements of the rated motor fundamental voltage and the rated motor load. In final application, the motor fundamental voltage is usually lower and typically, the motor loadability at frequency converter supply is typically considered lower, too. In addition, naturally, when utilizing a frequency converter, one of the main purposes is the ability to alter the motor speed – and fundamental frequency – from their rated values. The original intention with method 2-3-B might have been determining the losses in final application conditions, but at its current form, the purpose of the method is left unclear.

The measurements at reduced motor fundamental voltages gave mixed results. Of the results with summation of losses method, only the 377 V sinusoidal supply results seemed comparable. The fundamental output voltages of both the test converter and the DTC converter were load-dependent, when the 400 V converter input voltage was used. As mentioned above, this makes the summation of losses results unreliable. However, the 400 V and 377 V results from the method 2-1-1B and all input-output results showed that the induction motor losses are significantly higher at fundamental voltage levels of normal frequency converter operation, than at the rated motor voltage.

The IEC/TS 60034-2-3 method 2-3-A and the test converter supply seem to be usable for comparing losses and efficiency of different induction motors at the operating point of rated voltage, rated frequency and rated load, but the measurements do not give any prediction of the motor losses at final application. The same applies to the method 2-3-B with a specific converter supply. Apparently, the release of IEC 60034-2-3 as a technical specification instead of a final standard for now was justified, since the practical relevance of the main methods is questionable. According to rumors, alternative approaches to determining the converter-fed motor losses are being explored and the development of IEC 60034-2-3 might be actually taking another direction after all.

5.1 Future work

The results of the performed tests should be confirmed with a more accurate method since several factors affect the accuracy of the used methods. The method 2-3-A looks very promising, and although both methods 2-3-A and 2-3-C gave the same results, the means to estimate the accuracy of the results are limited. The correctness of the results cannot be appropriately evaluated without additional measurements of higher accuracy. For example, a specific calorimetric measurement concept would fit the purpose.

The summation of losses method 2-3-B on a specific converter supply may not give accurate loss values, but the results between different motors tested on the same converter might be comparable. The method 2-3-A on test converter supply is intended for determining losses to compare different motors, not to give any realistic loss values in final application. Similarly, although the losses determined with method 2-3-B on a specific converter supply might be inaccurate, but the results could still be comparable between different motors tested on that same specific converter supply. At least between motors of same rated voltage and rated power. However, confirming this would require extensive tests.

The fundamental motor voltage altered between the load curve test points in several measurements. In all tests on sinusoidal supply, there was only slight load-dependence in the motor voltage, but it may still have some effect on the results. The effect of the load dependent load curve test voltage on the stray-load loss results should be further investigated.

The fundamental output voltage of the test converter supply was very load-dependent at the 350 V tests. However, with appropriately changed motor parameters, the correct test converter operation at reduced voltages should be achieved. In addition, though, the 350 V results on sinusoidal supply were not very reliable either. However, by using slightly higher fundamental motor voltages and risen converter input voltage, investigating the dependence of the harmonic losses from the fundamental motor voltage might be possible.

Measuring the stator winding resistance and stator winding temperature proved to be challenging during the measurements. The 4-wire method used in these tests seems quite unreliable for determining the stator winding resistance. Other option would be to calculate the resistance from the stator winding temperature. The temperature measurement, in turn is very sensitive to the location of the sensor. In addition, the temperature differences between different parts of the stator winding might be considerable. The real need (effect on the accuracy of the 2-1-1B and 2-3-A methods) and possibilities to a more accurate and reliable resistance or temperature measurement or determination should be surveyed.

The second edition of the standard IEC 60034-2-1 (IEC 2014a), introduces a relatively strict limit for the length of the load points compared to the first edition. These tests were carried out with 45 s load points instead of the new 15 s limit. The effect of the length of the load points along with the minimal practical length of load points should be investigated.

The determined 40 % drop in friction and windage losses between the 377 V and 350 V measurements was left without confirmation. The break-in of a new induction motor and the friction and windage losses should be investigated. In addition, the friction and windage losses are probably somewhat dependent on the motor temperature and that should be looked at too. For determining friction and windage losses, several methods exist and comparison between those could be made.

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Appendix 1 – EQUIPMENT USED IN THE MEASUREMENT SETUP

Table A1.1. The induction machines used in the measurements.

	Tested induction motor	**Load machine (induction motor)**
Manufacturer	ABB	ABB
Type	M3BP 160 MLB 4	M3KP 225SMB 4
Rating plate data (400 V, Δ)	50 Hz, 15.0 kW, 1474 r/min, 27.8 A, cos φ =0.84 Insulation class F Temperature rise class B Efficiency class: IE3 50 Hz: 92.7 (100 % load)	50 Hz, 37 kW, 1480 r/min, 69 A, cos φ =0.84 Insulation class F

Table A1.2. The power analyzers used in the measurements.

	Power, voltage and current	**Harmonics**
Manufacturer	Yokogawa	Yokogawa
Model	WT1600	PZ4000
Main features	Frequency power range: DC, 0.5 Hz – 1 MHz Basic power accuracy: ±0.1 % Current input range: 10 mA – 5 A Voltage input range: 1.5 V – 1000 V 50 ms data storing interval	Measurement bandwidth: DC – 2 MHz Maximum sampling rate: 5 MS/s Harmonic analysis: Up to 500th order FFT functions for spectrum analysis

Table A1.3. Current sensor and torque transducer.

	Current sensor	**Torque transducer**
Manufacturer	Hitec	HBM
Type	CURACC	T12
Main features	Rated current (primary / secondary): 100 A / 1 A Bandwidth: DC – 100 kHz	Nominal (rated) torque: 200 Nm Nominal (rated) rotational speed: 15000 r/min Accuracy class: 0.03

Table A1.4. The multimeters used in resistance and temperature measurements.

	Resistance measurement	**Temperature reading**
Manufacturer	Keithley	Keithley
Model	2701 Digital Multimeter Data Acquisition and Datalogging System	2701 Digital Multimeter Data Acquisition and Datalogging System
Main features	Combined DMM, switch system and datalogger 22 bit resolution Ethernet communication cababilities	Combined DMM, switch system and datalogger 22 bit resolution Ethernet communication cababilities

Appendix 2 – EQUATIONS AND CALCULATIONS

A2.1 Stator winding resistance of cool motor

All three line-to-line resistances were measured and temperature during the measurements was recorded. The measured line-to-line resistances and temperature during measurement of each resistance value is presented in Table A2.1. The resistance and temperature values are arithmetic average of several consecutive readings. The stator winding (line-to-line) resistance is the arithmetic average of the three line-to-line resistance values. The average values shown in Table A2.1 are the stator winding resistance R_{cool} and stator winding temperature θ_{cool} of cool motor.

Table A2.1. The measured line-to-line resistances of cool motor, and the measured winding temperature during of each resistance measurement.

	R_{cool} [Ω]	θ_{cool} [°C]
Measured from terminals U1 and V1	0.2899	22.18
Measured from terminals V1 and W1	0.2915	22.19
Measured from terminals U1 and W1	0.3279	22.20
Average	**0.3031**	**22.19**

A2.2 Rated load test

A2.2.1 Temperature rise and thermal time constant

The temperature rise of an electric motor is calculated from the motor temperature – in this case the measured stator winding temperature $\theta_{\mathrm{meas,N}}$ – and coolant temperature $\theta_{\mathrm{c,N}}$

$$\theta_{\mathrm{rise}} = \theta_{\mathrm{N,meas}} - \theta_{\mathrm{c}} \,. \tag{A2.1}$$

The temperature rise after time t from the beginning of the heat run can be represented with equation

$$\theta_{\mathrm{rise}} = \theta_{\mathrm{rise,end}} - \left(\theta_{\mathrm{rise,end}} - \theta_{\mathrm{rise,0}}\right) \cdot e^{-\frac{t}{\tau}} \,, \tag{A2.2}$$

where $\theta_{\text{rise,end}}$ is the stator winding temperature rise at rated load thermal equilibrium, $\theta_{\text{rise,0}}$ is the stator winding temperature rise at the beginning of the heatrun, and τ is the thermal time constant. After time $t = \tau$, the temperature rise

$$\theta_{\text{rise}} = \theta_{\text{rise,end}} - \left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right) \cdot e^{-1} = \theta_{\text{rise,end}} - \left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right) \cdot 0.368 \ . \qquad \text{(A2.3)}$$

The measured stator winding temperature at the end of the rated load heat run of the 400 V sinusoidal measurement was $\theta_{\text{meas,N}}$ = 89.3 °C and the ambient temperature θ_{c} = 24.9 °C. In the beginning of the heatrun the stator winding temperature was 22.3 °C and the ambient temperature 18.8 °C, hence the temperature rise at $t = \tau$ was

$$\theta_{\text{rise}}(t = \tau) = 64.4\,°\text{C} - \left(64.4\,°\text{C} - 3.5\,°\text{C}\right) \cdot 0.368 \approx 42.0\ °\text{C} \ . \qquad \text{(A2.4)}$$

According to the recorded test data, the stator winding temperature rise was 42 °C at approximately 54 min after beginning the heat run, hence τ = 54 min. Now, the stator winding temperature (at each point of the heatrun) can be calculated from equations (A2.1) and (A2.2)

$$\theta_{\text{meas,N,fit}} = \theta_{\text{c}} + \theta_{\text{rise,end}} - \left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right) \cdot e^{-\frac{t}{\tau}} = \theta_{\text{c}} + 64.4\,°\text{C} - \left(60.9\,°\text{C}\right) \cdot e^{-\frac{t}{54\,\text{min}}} \ . \qquad \text{(A2.5)}$$

Since the ambient temperature changed during the heatrun, a constant value of θ_{c} cannot be used and the fitted temperature needs to be calculated for each measurement point separately in order to compare the fitted temperature curve with the measured temperature curve. When $\theta_{\text{meas,N,fit}}$ is calculated for the whole heatrun from equation (A2.5), the rate of change of $\theta_{\text{meas,N,fit}}$ falls permanently below 1 K after 235 minutes.

If the changing ambient temperature is left out of the calculations, the minimum time needed for the rate of change of the stator winding temperature rise θ_{rise} to fall to 1 K / 30 min can be estimated with the equations above. The requirement for the temperature rise rate can be expressed by

$$\theta_{\text{rise}}(t_1) - \theta_{\text{rise}}(t_1 - 30\,\text{min}) = 1\,°\text{C}, \qquad \text{(A2.6)}$$

From equations (A2.2) and (A2.6) we get

$$\theta_{\text{rise,end}} - \left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right)\cdot e^{-\frac{t_1}{\tau}} - \left(\theta_{\text{rise,end}} - \left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right)\cdot e^{-\frac{t_1 - 30\,\text{min}}{\tau}}\right) = 1\,°\text{C} \qquad \text{(A2.7)}$$

$$-\left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right)\cdot e^{-\frac{t_1}{\tau}} + \left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right)\cdot e^{-\frac{t_1 - 30\,\text{min}}{\tau}} = 1\,°\text{C} \qquad \text{(A2.8)}$$

$$e^{-\frac{t_1}{\tau}} e^{\frac{30\,\text{min}}{\tau}} - e^{-\frac{t_1}{\tau}} = \frac{1\,°\text{C}}{\theta_{\text{rise,end}} - \theta_{\text{rise,0}}} \qquad \text{(A2.9)}$$

$$e^{-\frac{t_1}{\tau}}\left(e^{\frac{30\,\text{min}}{\tau}} - 1\right) = \frac{1\,°\text{C}}{\theta_{\text{rise,end}} - \theta_{\text{rise,0}}} \qquad \text{(A2.10)}$$

$$-\frac{t_1}{\tau} = \ln\left(\frac{1\,°\text{C}}{\left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right)\cdot\left(e^{\frac{30\,\text{min}}{\tau}} - 1\right)}\right) \qquad \text{(A2.11)}$$

$$t_1 = -\tau\cdot\ln\left(\frac{1\,°\text{C}}{\left(\theta_{\text{rise,end}} - \theta_{\text{rise,0}}\right)\cdot\left(e^{\frac{30\,\text{min}}{\tau}} - 1\right)}\right) = -54\,\text{min}\cdot\ln\left(\frac{1\,°\text{C}}{60.9\,°\text{C}\cdot\left(e^{\frac{30\,\text{min}}{54\,\text{min}}} - 1\right)}\right) \approx 206\ \text{min}, \qquad \text{(A2.12)}$$

which is the calculated time, when the rate of change of θ_{rise} falls to 1 K / 30 min, but it does not take into account changes in ambient temperature.

A2.2.2 Extrapolation method for determining winding resistance

There is always a delay between stopping the load and beginning of resistance measurement. The resistance drops relatively fast when windings begin to cool down and IEC (2014) recommends extrapolation method described in IEC (2010) for determining the rated load stator winding line-to-line resistance R_{N}.

The line-to-line resistance R_{U1V1} between terminals U1 and V1 was recorded after stopping the motor. In the extrapolation method, the recorded resistance is plotted as a function of time after stopping the load and the recorded plot is extrapolated to the stopping moment (IEC 2010). An example of the method is shown in Figure A2.1.

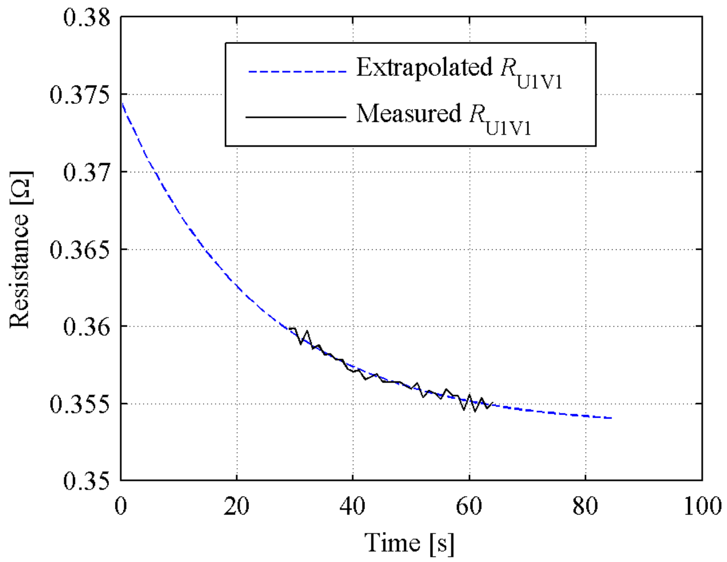

Figure A2.1. The measured and extrapolated curves for R_{U1V1} as function of time at the end of rated load test. At t = 0 s, the motor was stopped from rated load. The value of extrapolated R_{U1V1}-curve at t = 0 s is the rated load value $R_{\mathrm{U1V1,N}}$.

The extrapolation can be done by forming an equation of exponential decaying for the resistance

$$R_{\mathrm{U1V1}}(t) = R_{\mathrm{b}} + (R_{\mathrm{a}} - R_{\mathrm{b}}) \cdot e^{-\lambda t}. \tag{A2.13}$$

The constants R_b, R_a and λ of the equation are adjusted to match the resulting curve with the measured resistance curve. The resistance $R_{U1V1,N}$ at the stopping moment is calculated from equation (A2.13) at t = 0 s, giving

$$R_{U1V1,N} = R_{U1V1}(0) = R_b + (R_a - R_b) \cdot e^0 = R_a \, . \qquad \text{(A2.14)}$$

The resistance $R_{U1V1,N}$ is the rated load line-to-line resistance between terminals U1 and V1. The stator winding resistance R_N can be calculated from $R_{U1V1,N}$ with equation (A3.1) of Appendix 3.

A2.2.3 Rated load winding temperature

According to IEC (2014), the rated load winding temperature θ_N shall be determined from the extrapolated rated load resistance. The rated load winding temperature (IEC 2010)

$$\theta_N = \frac{R_N - R_{cool}}{R_{cool}} \cdot (235 + \theta_{cool}) + \theta_{cool}, \qquad \text{(A2.15)}$$

where R_N is the stator winding resistance at rated load, R_{cool} is the stator winding resistance of cool motor and θ_{cool} is the stator winding temperature of cool motor (the temperature during the measurement of R_{cool}).

A2.2.4 Correcting the rated load winding losses to reference coolant temperature of 25 °C

Winding material specific temperature correction factor is required for correcting resistive losses to the reference coolant temperature of 25 °C. For copper windings, the temperature correction factor

$$k_\theta = \frac{235 + \theta + 25 - \theta_c}{235 + \theta}, \qquad \text{(A2.16)}$$

where θ is the winding temperature and θ_c is the inlet coolant temperature in degrees Celsius, the number 235 in equation is the temperature constant for copper. (IEC 2014.)

For rated load test, in equation (A2.16) $\theta = \theta_N$ is the rated load stator winding temperature and $\theta_c = \theta_{c,N}$ is the coolant temperature during rated load test. The stator winding losses in reference coolant temperature

$$P_{s,N,\theta} = P_{s,N} \cdot k_\theta \,, \tag{A2.17}$$

where $P_{s,N}$ are the uncorrected stator winding losses with the coolant temperature θ_c (IEC 2014).

The corrected rotor winding losses are calculated in similar way as the rotor winding losses $P_{r,N}$ in chapter 3.3.1, using the corrected stator winding losses and temperature corrected slip instead of actual values. The corrected rotor winding losses

$$P_{r,N,\theta} = \left(P_{1,N} - P_{s,N,\theta} - P_{fe,N}\right) \cdot s_{N,\theta} \,, \tag{A2.18}$$

where $P_{1,N}$ is the input power of the motor, $P_{fe,N}$ are the rated load iron losses determined from no-load test and temperature corrected per-unit slip

$$s_{N,\theta} = s_N \cdot k_\theta \,, \tag{A2.19}$$

where s_N is the per-unit slip at rated load. (IEC 2014.)

Increased winding losses cause equal rise in input power. Corrected input power in the reference coolant temperature is calculated according to equation (IEC 2014)

$$P_{1,N,\theta} = P_{1,N} - \left(P_{s,N} - P_{s,N,\theta} + P_{r,N} - P_{r,N,\theta}\right), \tag{A2.20}$$

where $P_{r,N}$ is the uncorrected rotor winding loss.

A2.2.5 Output power

The rated load output power on sinusoidal supply (IEC 2014)

$$P_{2,\mathrm{N}} = 2\pi T_{\mathrm{N}} n_{\mathrm{N}} \,, \tag{A2.21}$$

where T_N is the motor torque at rated load and n_N is the operating speed at rated load.

A2.3 Load curve test

A2.3.1 Determining resistance R_L for each load point

The stator winding resistance values before and after the load curve test are calculated from the measured values of $R_{U1V1,L}$ with the method presented in Appendix 3.

IEC (2014) defines that the resistance value determined before the test is used for 125 %, 115 %, 100 % load points. For load points less than 100 %, the resistance is interpolated with load using the resistance measured before the test for the highest load and the resistance determined after the test for the 25 % load. (IEC 2014). Summary of resistance selection is shown in Table A2.2

Table A2.2 Load curve test stator winding resistance R_L determination for the load points.

Load point	**Resistance value**
125 %	Measured before the test
115 %	Measured before the test
100 %	Measured before the test
75 %	Measured before the test
50 %	Interpolated with load from values measured before and after the test
25 %	Measured after the test

Resistance R_L for 50 % load can be calculated by linear interpolation with equation

$$R_{\mathrm{L,50}} = \frac{(T_{\mathrm{L,50}} - T_{\mathrm{L,25}})(R_{\mathrm{L,75}} - R_{\mathrm{L,25}})}{T_{\mathrm{L,75}} - T_{\mathrm{L,25}}} + R_{\mathrm{L,25}}, \qquad \text{(A2.22)}$$

where $R_{\mathrm{L,25}}$ and $R_{\mathrm{L,75}}$ are the resistance values and $T_{\mathrm{L,25.}}$ $T_{\mathrm{L,50}}$ and $T_{\mathrm{L,75}}$ the load torque values for load points of percentages indicated by the subscripts.

A2.4 No-load test

A2.4.1 Interpolating the winding resistance for the voltage points

The stator winding resistance values before and after the test are calculated from the measured values of $R_{\mathrm{U1V1,0}}$ with the method presented in Appendix 3.

According to IEC (2014), the resistance for each of the voltage points of no-load test shall be interpolated linearly from the measured resistances with the input power. Interpolating can be done with equation

$$R_{\mathrm{0,VP}} = \frac{(P_{\mathrm{1,0,VP}} - P_{\mathrm{1,0,30\%}})(R_{\mathrm{0,before}} - R_{\mathrm{0,after}})}{P_{\mathrm{1,0,110\%}} - P_{\mathrm{1,0,30\%}}} + R_{\mathrm{0,after}}, \qquad \text{(A2.23)}$$

where:

$R_{\mathrm{0,before}}$ is the stator winding resistance before the no-load test,
$R_{\mathrm{0,after}}$ is the stator winding resistance after the no-load test,
$P_{\mathrm{1,0,110\%}}$ is the input power of the 110 % voltage point,
$P_{\mathrm{1,0,30\%}}$ is the input power of the 30 % voltage point,
$P_{\mathrm{1,0,VP}}$ is the input power of VP % voltage point and
$R_{\mathrm{0,VP}}$ is the stator winding resistance for the VP % voltage point.

A2.4.2 Friction and windage losses

For determination of friction and windage losses, a linear relationship of constant losses as function of voltage squared $P_{\mathrm{c}}(U_0^2)$ is developed from the 30 % – 60 % voltage points. This can be done by linear regression analysis, which is presented in Appendix 4. For applying the method of Appendix 4 for constant losses, $y = P_c$ and $x = U_0^2$, hence the equation is form

$$P_c(U_0^2) = A \cdot U_0^2 + B\,, \tag{A2.24}$$

where A and B are constants determined from the linear regression analysis. No-load friction and windage losses $P_{fw,0}$ are the value of P_c at zero voltage

$$P_{fw,0} = P_c(U_0 = 0) = B\,. \tag{A2.25}$$

A2.4.3 Iron losses

To determine the rated load iron losses, voltage U_i that takes the voltage drop in the stator winding into account is calculated at rated load from equation

$$U_i = \sqrt{\left(U_N - \frac{\sqrt{3}}{2} I_N R_N \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} I_N R_N \sin\varphi\right)^2}\,, \tag{A2.26}$$

where

$$\cos\varphi = \frac{P_{1,N}}{\sqrt{3} U_N I_N} \tag{A2.27}$$

and

$$\sin\varphi = \sqrt{1 - \cos^2\varphi}\,. \tag{A2.28}$$

In equations (A2.26) and (A2.27), U_N, I_N and R_N are according to the rated load test. (IEC 2014.)

According to IEC (2014), the rated load iron losses $P_{fe,N}$ are interpolated from the curve of no-load iron losses as function of voltage $P_{fe,0}(U_0)$ at the inner voltage U_I (see Figure 3.8 of chapter 3.3.3). However, IEC does not define any particular method for the interpolation. The interpolation curve $P_{\mathrm{fe,0}}(U_0)$ was determined by forming a second order equation that best fits all four voltage points. The resulted relationship has two parts separated by a threshold voltage U_{T}:

$$P_{\mathrm{fe,0}}(U_0) = A \cdot U_0^2, \text{ when } U_0 < U_{\mathrm{T}}$$
$$P_{\mathrm{fe,0}}(U_0) = A \cdot U_0^2 + B(U_0 - U_{\mathrm{T}}), \text{ when } U_0 > U_{\mathrm{T}}, \tag{A2.29}$$

where A and B are constants. A, B and U_{T} were determined by manually finding suitable values. The rated load iron losses

$$P_{\mathrm{fe,N}} = P_{\mathrm{fe,0}}(U_{\mathrm{i}}), \tag{A2.30}$$

where U_{i} is determined from equation (A2.26) (IEC 2014).

As example, the values for the rated voltage test run are shown in Table A2.3. The curve $P_{\mathrm{fe,0}}(U_0)$ drawn with the values of Table A2.3 is shown in Figure 3.8 of chapter 3.3.3.

Table A2.3 Values of the constants and threshold voltage U_{T} for the rated voltage test run.

A	0.001373
B	0.0047
U_{T} [V]	380

The resulting relationship is with the values of Table A2.3 is

$$P_{\mathrm{fe,0}}(U_0) = 0.001373 \cdot U_0^2, \text{ when } U_0 < 380$$
$$P_{\mathrm{fe,0}}(U_0) = 0.001373 \cdot U_0^2 + 0.0047 \cdot (U_0 - 380), \text{ when } U_0 > 380. \tag{A2.31}$$

A2.5 Stray-load losses

For determining the stray-load losses with the residual loss method, output power and all other loss components (except the stray-load losses) are calculated for the six load points of the load curve test.

Output power $P_{2,\mathrm{L}}$, stator winding losses $P_{\mathrm{s,L}}$ and rotor winding losses $P_{\mathrm{r,L}}$ are determined from the load curve test. Output power $P_{2,\mathrm{L}}$ for each load point is calculated from the torque and the rotation speed of the motor from equation

$$P_{2,\mathrm{L}} = 2\pi T_{\mathrm{L}} n_{\mathrm{L}}\,, \tag{A2.32}$$

where T_{L} is the motor torque and n_{L} is the operating speed of each load point. The stator winding losses

$$P_{\mathrm{s,L}} = 1{,}5 \cdot I_{\mathrm{L}}^{2} R_{\mathrm{L}}\,, \tag{A2.33}$$

where I_{L} is the line current and R_{L} is the stator winding line-to-line resistance of each load point. The rotor winding losses

$$P_{\mathrm{r,L}} = \left(P_{1,\mathrm{L}} - P_{\mathrm{s,L}} - P_{\mathrm{fe,N}}\right) \cdot s_{\mathrm{L}}\,, \tag{A2.34}$$

where $P_{1,\mathrm{L}}$ is the input power of each load point, $P_{\mathrm{s,L}}$ is according to equation (A2.33), $P_{\mathrm{fe,N}}$ is determined from the no-load test and s_{L} is per-unit slip for each load point from

$$s_{\mathrm{L}} = 1 - \frac{n_{\mathrm{L}}\, p}{f_{\mathrm{L}}}\,, \tag{A2.35}$$

where n_{L} is the operating speed of each load point, f_{L} is the supply frequency of each load point and p is the number of pole pairs of the motor. (IEC 2014.)

Friction and windage losses $P_{\mathrm{fw,L}}$ and iron losses $P_{\mathrm{fe,L}}$ are determined from the results of the no-load test. Friction and windage losses are dependent of the rotation speed of the rotor and since rotor speed decreases with load, they need to be adjusted for each load point with equation (IEC 2014)

$$P_{\mathrm{fw,L}} = P_{\mathrm{fw,0}}(1 - s_{\mathrm{L}})^{2.5}, \tag{A2.36}$$

where $P_{\mathrm{fw,0}}$ are the friction and windage losses at no-load and s_{L} is according to (A2.35). According to IEC (2014), iron losses $P_{\mathrm{fe,N}}$ for rated load are used for all load points

$$P_{\mathrm{fe,L}} = P_{\mathrm{fe,N}} . \tag{A2.37}$$

A2.6 Constant losses on frequency converter supply

The constant losses $P_{\mathrm{c,C}}$ of converter-fed motor are determined from

$$P_{\mathrm{c,C}} = P_{\mathrm{1,0,C}} - P_{\mathrm{s,0,C}} . \tag{A2.38}$$

where $P_{\mathrm{1,0,C}}$ is the no-load input power and $P_{\mathrm{s,0,C}}$ are no-load stator winding losses according to

$$P_{\mathrm{s,0,C}} = 1.5 \cdot I_{\mathrm{0,C}}^{2} R_{\mathrm{0,C}} , \tag{A2.39}$$

where $I_{\mathrm{0,C}}$ is the line current and $R_{\mathrm{0,C}}$ the stator winding line-to-line resistance from the no-load test on converter supply. (IEC 2014.)

A2.7 Instrumentation uncertainty

IEC (2014) requires that the overall uncertainty of measuring instruments for electrical quantities is 0.2 % of reading at power factor of 1.0. The uncertainties are calculated here at rated motor voltage and rated motor load.

Voltage

According to Yokogawa (2008), the WT1600 accuracy of voltage measurement is 0.1 % of reading + 0.05 % of range. The reading at rated voltage was approximately 230 V and the used range was 300 V, hence the uncertainty at rated voltage was

$$0.0015 \times 230\ \mathrm{V} + 0.0005 \times 300\ \mathrm{V} = 0.495\ \mathrm{V}\,, \tag{A2.40}$$

which as percentage of the reading is

$$\frac{0.495\ \mathrm{V}}{230\ \mathrm{V}} \approx 0.002152 \approx 0.22\,\%\,. \tag{A2.41}$$

Current

According to Yokogawa (2009), the accuracy of the CURACC-system is 0.01 % of reading + 0.005 % of range. The rated current of the CURACC is 100 A and the current transfer ratio is 100:1. Therefore the rated output current is 1 A and the actual output current of CURACC at rated motor load was approximately 0.287 A. Therefore the uncertainty of CURACC at rated load was

$$0.0001 \times 0.287\ \mathrm{A} + 0.00005 \times 1\ \mathrm{A} = 0.3370\ \mathrm{mA}\,, \tag{A2.42}$$

According to Yokogawa (2008), the one-year accuracy of current measurement is 0.15 % of reading + 0.05 % of range. The transfer ratio of the CURACC was taken into account by using the multiplier of 100 for the current measurement. The used range was 500 mA and the current reading at rated load approximately 0.287 A before the multiplication. Hence, the WT1600 current uncertainty at rated load was

$$0.0015 \times 0.287\ \mathrm{A} + 0.0005 \times 0.5\ \mathrm{A} = 0.6805\ \mathrm{mA}\,. \tag{A2.43}$$

The combined uncertainty of Hitec and Yokogawa corrected with the transfer ratio of 100 was

$$100 \times \sqrt{(0.3370\ \text{mA})^2 + (0.6805\ \text{mA})^2} \approx 0.0759\ \text{A}\ , \tag{A2.44}$$

which as percentage of the reading is

$$\frac{0.0759\ \text{A}}{28.7\ \text{A}} \approx 0.002645 \approx 0.26\ \% \,. \tag{A2.45}$$

Power

According to Yokogawa (2008), the WT1600 accuracy of power measurement is 0.15 % of reading + 0.05 % of range. The power reading at rated load was approximately 16400 W. The range of power measurement is calculated by multiplying the voltage range by the current range and the number of phases (Yokogawa 2008). The voltage range at the measurements was 300 V and the current range was 500 mA with a multiplier of 100, hence the power measurement range was

$$300\ \text{V} \times 50\ \text{A} \times 3 = 45000\ \text{W}\,. \tag{A2.46}$$

The power uncertainty at rated load was

$$0.0015 \times 16400\ \text{W} + 0.0005 \times 45000\ \text{W} = 47.1\ \text{W}\,, \tag{A2.47}$$

which as percentage of the reading is

$$\frac{47.1\ \text{W}}{16400\ \text{W}} \approx 0.00287 \approx 0.29\ \% \,. \tag{A2.48}$$

Fundamental motor voltage

The fundamental motor voltage was observed with Yokogawa PZ4000 power analyzer. The one-year accuracy of PZ4000 harmonic voltage measurement is 0.15 % of reading + 0.075 % of range (Yokogawa 1999). The voltage reading was approximately 230 V and the voltage range was 1200 V, hence the uncertainty of fundamental voltage measurement was

$$0.0015 \times 230\ \text{V} + 0.00075 \times 1200\ \text{V} = 1.245\ \text{V}\,, \tag{A2.49}$$

which as percentage of reading is

$$\frac{1.245\ \text{V}}{230\ \text{V}} \approx 0.00541 \approx \pm 0.54\,\%\,. \tag{A2.50}$$

Torque

The accuracy class of HBM T12 is 0.03, hence the base accuracy is 0.03 % of the rated 200 Nm torque of the transducer (HBM 2011). Although such additional factors as temperature and used data transfer method have an effect on the total accuracy of torque measurement, those are not taken in account in this calculation. The torque reading at rated motor load was approximately 98.1 Nm. Therefore the uncertainty of torque measurement was

$$0.0003 \times 200\ \text{Nm} = 0.06\ \text{Nm}\,, \tag{A2.51}$$

which as percentage of reading is

$$\frac{0.06\ \text{Nm}}{98.1\ \text{Nm}} = 0.0006116 \approx 0.061\,\%\,. \tag{A2.52}$$

Rotational speed

The rotational speed was measured with HBM T12. The accuracy of HBM speed measurement is 150 ppm and the resolution 0.1 rpm (HBM 2011). The rated load speed of the motor was approximately 1472 rpm, hence the uncertainty of the rotational speed measurement was

$$\frac{150}{1000000} \times 1472\ \text{rpm} \approx 0.22\ \text{rpm} \tag{A2.53}$$

and the uncertainty due to the measurement resolution was

$$\frac{0.1\,\text{rpm}}{2} = 0.05\,\text{rpm}. \tag{A2.54}$$

The combined uncertainty of the speed measurement was therefore

$$\sqrt{(0.22\,\text{rpm})^2 + (0.05\,\text{rpm})^2} \approx 0.23\,\text{rpm}. \tag{A2.55}$$

Ambient temperature

The ambient temperature, which is also the coolant temperature, was measured with Keithley 2701 multimeter and Pt100 Class A sensor. The accuracy of Keithley 2701 temperature measurement with Pt100 sensor is ± 0.06 °C and the accuracy of a Pt100 Class A sensor is ± (0.15 + 0.002| t |) °C (Keithley 2002; Thermibel 2015). The ambient temperature during the measurements was approximately 25 °C. Hence the uncertainty of temperature measurement was

$$\sqrt{(0.06\,°\text{C})^2 + ((0.15 + 0.002 \times 25)\,°\text{C})^2} \approx 0.21\,°\text{C}. \tag{A2.56}$$

Winding temperature

The winding temperature was measured with Keithley 2701 multimeter and Pt100 Class B sensor. The accuracy of Keithley 2701 temperature measurement with Pt100 sensor is ± 0.06 °C and the accuracy of a Pt100 Class B sensor is ± (0.30 + 0.005| t |) °C (Keithley 2002; Thermibel 2015). At rated load, the measured stator winding temperature was approximately 89 °C. Hence, the uncertainty of temperature measurement was

$$\sqrt{(0.06\,°\text{C})^2 + ((0.30 + 0.005 \times 89)\,°\text{C})^2} \approx 0.75\,°\text{C}. \tag{A2.57}$$

Stator winding resistance

The stator winding resistance was measured with Keithley 2701 multimeter. The resistance accuracy of Keithley 2701 is 0.01 % of reading + 0.002 % of range (Keithley 2002). The Keithley 2701 minimum resistance range of 100 Ω was used and the measured resistance value was approximately 0.366 Ω, hence the uncertainty of resistance measurement was

$$0.0001 \times 0.366\,\Omega + 0.00002 \times 100\,\Omega \approx 2.04\,\text{m}\Omega\,, \tag{A2.58}$$

which as percentage of reading is

$$\frac{2.04\,\text{m}\Omega}{366\,\text{m}\Omega} \approx 0.00556 \approx 0.56\,\%\,. \tag{A2.59}$$

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Appendix 3 – STATOR WINDING RESISTANCE OF HOT MOTOR

A3.1 Determining the stator winding resistance of hot motor

According to IEC (2014), the stator winding resistance values used in calculations of the summation of losses method are averages of the three line-to-line to resistance values. During tests, only one line-to-line resistance R_{U1V1} is measured between terminals U1 and V1. To determine the stator winding resistance of hot motor, the stator winding resistance R_{cool} of cool motor and corresponding $R_{\mathrm{U1V1,Cool}}$ are required. All three line-to-line resistances $R_{\mathrm{U1V1,Cool}}$, $R_{\mathrm{V1W1,Cool}}$, $R_{\mathrm{U1W1,Cool}}$ were measured from cool motor before the tests. R_{cool} is the arithmetic average of the three line-to-line resistance values.

When the relationship of the resistances $R_{\mathrm{U1V1,Cool}}$ and R_{cool} is known, the resistance of hot motor can be calculated from

$$\frac{R_{\mathrm{hot}}}{R_{\mathrm{U1V1,hot}}} = \frac{R_{\mathrm{cool}}}{R_{\mathrm{U1V1,cool}}} = \frac{0.3031\ \Omega}{0.2899\ \Omega}, \qquad \text{(A3.1)}$$

where R_{hot} is the stator winding resistance of hot motor:

R_{N} for rated load test,
R_{L} for load curve test,
R_0 for no-load test on sinusoidal supply, or
$R_{0,\mathrm{C}}$ for no-load test on converter supply

and the values of $R_{\mathrm{U1V1,cool}} = 0.2899\ \Omega$ and $R_{\mathrm{cool}} = 0.3031\ \Omega$ are from Table A2.1.

Another possibility is to determine the stator winding resistance of hot motor from the measured stator winding temperature with equation (IEC 2010)

$$\frac{\theta_{\mathrm{hot}} + 235}{\theta_{\mathrm{cool}} + 235} = \frac{R_{\mathrm{hot}}}{R_{\mathrm{cool}}}, \qquad \text{(A3.2)}$$

where θ_{cool} is the stator winding temperature of cool motor, R_{cool} is the stator winding resistance of cool motor, θ_{hot} is the stator winding temperature of hot motor and R_{hot} is the stator winding resistance of hot motor.

A3.2 Problems related to the stator winding resistance measurement

The 4-wire measurement of the stator winding resistance seems to give somewhat inconsistent results. Figure A3.1 shows the stator winding resistances values determined with two different methods for the sinusoidal supply tests. The stator winding resistance R_θ, which covers the whole test procedure, is determined from the stator winding temperature with equation (A3.2). The stator winding resistance R_{meas}, is determined from the 4-wire measurement; hence the data is only available only for four short periods. The R_{meas} measurement points from left to right in each plot are after the rated load test, after the load curve test, after decoupling the load machine and after the no-load test.

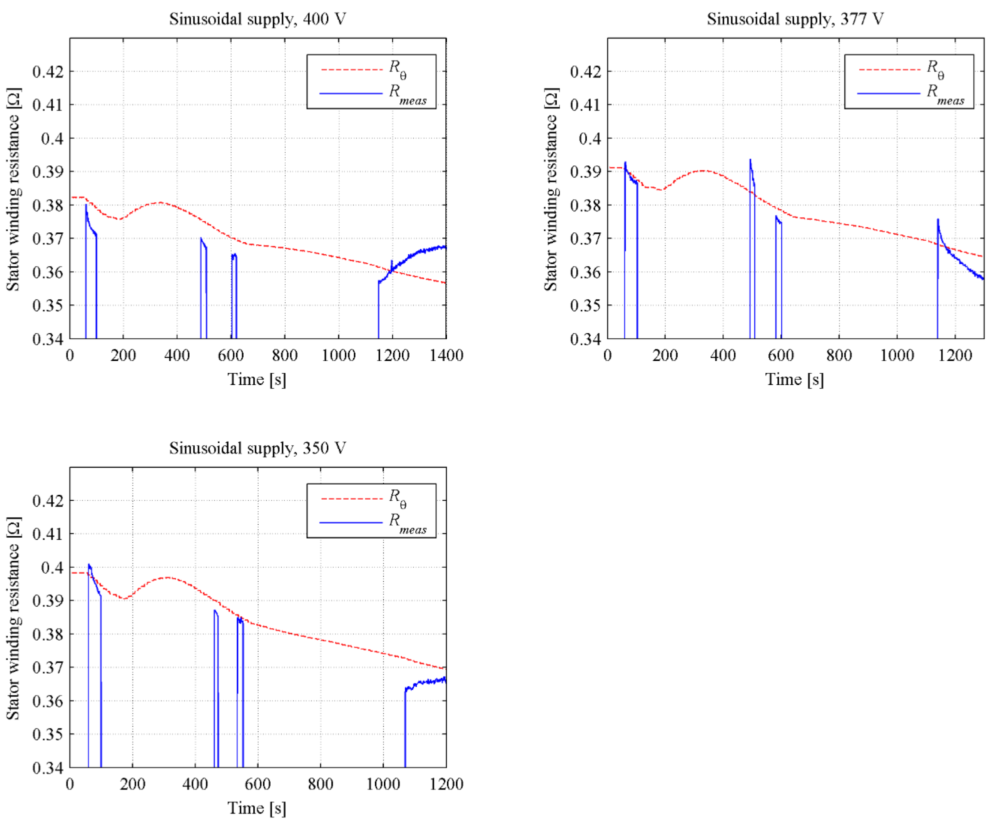

Figure A3.1 Stator winding resistance curves during the sinusoidal supply tests of 400 V, 377 V and 350 V. The resistance R_{meas} is determined from the 4-wire measurement between the tests. The resistance R_θ is calculated from the stator winding temperature. The plots show that the 4-wire resistance measurement gives inconsistent results.

In Figure A3.1, the resistance R_θ behaves in all the plots as could be expected. At about 40 seconds it starts decreasing when the motor is stopped for the rated load test resistance measurement, and starts rising again when the motor is restarted for the load curve test at around 200 seconds. After the load curve test and throughout the no-load test, R_θ keeps decreasing. The resistance R_{meas}, in turn, seems to behave illogically between some of the measurement points and compared to the resistance R_θ-curve. For example during both load curve test and no-load tests at 400 V and 350 V the resistance R_{meas} decreases slightly as would be expected, but at the 377 V the resistance R_{meas} stays about the same. In addition, at 400 V and 350 V the R_{meas}-curve starts rising after the no-load test, while at 377 V it decreases rapidly.

At converter supply, the inconsistencies in the resistance measurement are even more pronounced. The stator winding resistance curves during the test converter measurements are shown in Figure A3.2. Especially the first resistance measurement values are peculiar, showing that the resistance at 350 V would be lower than at 400 V, while the R_θ-curve shows 0.015 Ω higher value at 350 V, than at 400 V. Additionally, the first resistance R_{meas}-curve at 350 V is rising, while it should be decreasing.

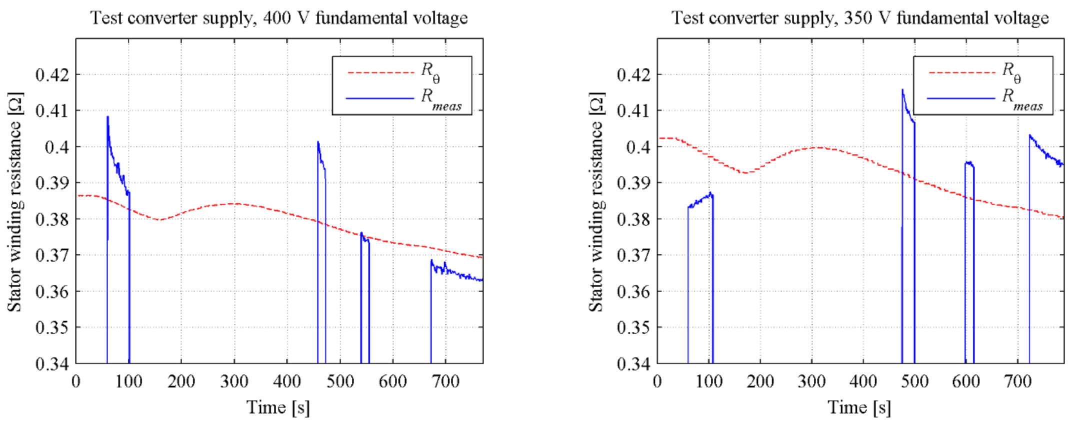

Figure A3.2 Stator winding resistance curves during the measurements on test converter supply of 400 V and 350 V. The resistance R_{meas} is determined from the 4-wire measurement between the tests. The resistance R_θ is calculated from the stator winding temperature. The plots show that the 4-wire resistance measurement gives inconsistent results.

REFERENCES for Appendix 3

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IEC (2014), *IEC 60034-2-1 Edition 2.0: Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*. International standard.

Appendix 4 – LINEAR REGRESSION ANALYSIS

The linear regression analysis method shown here is according to the procedure introduced in IEC (2014) method 2-1-1B for smoothing residual loss data. Linear relationship of *y* as the function of *x* is formed for a group of known points as shown in Figure A4.1.

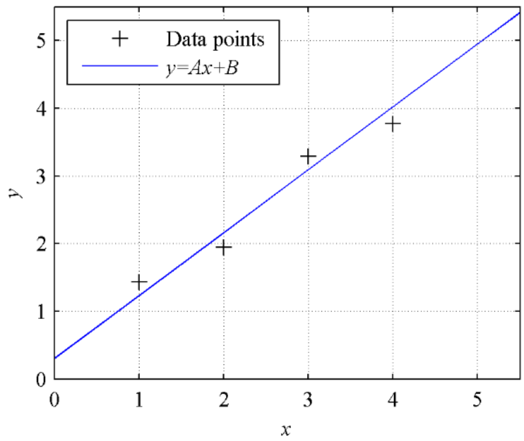

Figure A4.1 Linear regression analysis. A linear relationship *y*=*Ax*+*B* is formed from the known points marked with “+”.

In the example shown in Figure A4.1, linear regression is applied to a group of four known points. The relationship is a first order equation

$$y(x) = A \cdot x + B, \tag{A4.1}$$

where *A* and *B* are constants, which are determined from the known points according to equations

$$\mathrm{A} = \frac{i \cdot \sum (y \cdot x) - \sum y \cdot \sum x}{i \cdot \sum x^2 - \left(\sum x\right)^2} \tag{A4.2}$$

and

$$B = \frac{\sum y}{i} - \mathrm{A} \cdot \frac{\sum x}{i}, \tag{A4.3}$$

where i is the number of the known points summed. (IEC 2014.)

The correlation coefficient γ shows how well the points form a linear relationship. γ is calculated from equation (IEC 2014)

$$\gamma = \frac{i \cdot \sum(y \cdot x) - \sum y \cdot \sum x}{\sqrt{\left(i \cdot \sum x^2 - \left(\sum x\right)^2\right) \cdot \left(i \cdot \sum y^2 - \left(\sum y\right)^2\right)}}. \tag{A4.4}$$

REFERENCES for Appendix 4

IEC (2014), IEC 60034-2-1 Edition 2.0: Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

Appendix 5 – TEST DATA

Results from measurements and calculations of all tests are presented in Tables A5.2 – A5.65.

The stator winding line-to-line resistances of cool motor are shown in Table A5.1. Stator winding resistance is the arithmetic average of all three line-to-line resistances. The values of R_{cool} and θ_{cool} shown in Table A5.1 were used in calculations of all tests.

Table A5.1. Cool motor: Stator winding (line-to-line) resistances and stator winding temperature during the resistance measurements.

Quantity	**Symbol**	**Value**
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,cool}$	0.290
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,cool}$	0.291
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,cool}$	0.328
Stator winding resistance [Ω]	R_{cool}	0.303
Stator winding temperature [°C]	θ_{cool}	22.2

A5.1 Tests on rated motor voltage (400 V)

The results from tests on rated motor voltage of 400 V are presented in Tables A5.2 – A5.27. IEC (2014; 2013) defines that rated motor voltage shall be used in the losses and efficiency tests.

A5.1.1 Results on sinusoidal supply voltage of 400 V (rated motor voltage)

The results of measurements and calculations with 400 V sinusoidal supply are shown in Tables A5.2 – A5.13.

Table A5.2. Rated load test results

Quantity	**Symbol**	**Value**
Input power [W]	$P_{1,\mathrm{N}}$	16391
Line current [A]	I_{N}	28.75
Terminal voltage [V]	U_{N}	399.1
Supply frequency [Hz]	f_{N}	50.02
Coolant temperature [°C]	$\theta_{\mathrm{c,N}}$	24.9
Machine torque [Nm]	T_{N}	98.07
Operating speed [1/s]	n_{N}	24.53
Measured stator winding temperature [°C]	$\theta_{\mathrm{meas,N}}$	89.3
Stator winding resistance [Ω]	R_{N}	0.392
Stator winding temperature [°C] (Extrapolated)	θ_{N}	97.4
Temperature correction factor	k_{θ}	1.0004
Slip [%]	s_{N}	1.91
Corrected slip [%]	s_{θ}	1.91
Stator winding losses [W]	$P_{\mathrm{s,N}}$	485.7
Corrected stator winding losses [W]	$P_{\mathrm{s,N,\theta}}$	485.9
Rotor winding losses [W]	$P_{\mathrm{r,N}}$	300.0
Corrected rotor winding losses [W]	$P_{\mathrm{r,N,\theta}}$	300.1
Corrected input power [W]	$P_{1,\mathrm{N,\theta}}$	16391

Table A5.3. Rated load test: Resistance extrapolation and line-to-line resistances

Quantity	Symbol	Value
Resistance curve constant [Ω]	R_b	0.3535
Resistance curve constant [Ω]	R_a	0.3746
Exponential decay constant	λ	0.042
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,N}$	0.375
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,N}$	0.377
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,N}$	0.424

Table A5.4. Load curve test results

		Load point (in % of rated load)					
Quantity	**Symbol**	**25 %**	**50 %**	**75 %**	**100 %**	**115 %**	**125 %**
Input power [W]	$P_{1,L}$	4384	8309	12308	16380	18890	20530
Line current [A]	I_L	13.23	17.41	22.70	28.67	32.57	35.16
Terminal voltage [V]	U_L	402.5	401.9	401.3	400.5	399.8	399.8
Supply frequency [Hz]	f_L	50.01	50.00	50.01	49.99	50.00	49.99
Machine torque [Nm]	T_L	24.98	49.28	73.67	98.05	112.8	122.4
Operating speed [1/s]	n_L	24.89	24.78	24.66	24.52	24.45	24.39
Measured stator winding temperature [°C]	$\theta_{L,meas}$	85.4	86.9	87.9	87.7	86.4	84.4
Stator winding resistance [Ω]	R_L	0.370	0.374	0.378	0.378	0.378	0.378
Stator winding losses [W]	$P_{s,L}$	97.17	170.1	292.0	465.9	601.0	700.5
Slip [%]	s_L	0.446	0.896	1.38	1.89	2.22	2.44
Rotor winding losses [W]	$P_{r,L}$	18.2	71.0	162.4	296.4	402.0	479.2
Output power [W]	$P_{2,L}$	3906	7672	11415	15109	17327	18754
Friction and windage losses [W]	$P_{fw,L}$	107.6	106.4	105.1	103.8	102.9	102.3
Residual losses [W]	P_{Lr}	44.3	79.0	122.4	192.3	243.1	280.8
Stray-load losses [W]	P_{LL}	10.2	39.6	88.5	156.8	207.6	244.4
*Stray-load losses at T_N [W]	$P_{LL,N}$				156.9		

*Calculated using T_N from the rated load test

Table A5.5. Load curve test: Linear regression of residual losses

Constant	Value
A	0.01631
B	35.82
γ	0.9998

Table A5.6. Load curve test: Line-to-line resistances and stator winding resistance before and after the test

Quantity	Symbol	Before the test	After the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,L}$	0.361	0.354
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,L}$	0.363	0.356
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,L}$	0.409	0.401
Stator winding resistance [Ω]	R_L	0.378	0.370

Table A5.7. No-load test results for voltage points

		Voltage point (in % of rated voltage)							
Quantity	Symbol	30 %	40 %	50 %	60 %	90 %	95 %	100 %	110 %
Input power [W]	P_0	133.4	153.9	178.9	207.7	336.3	365.0	399.6	485.4
Line current [A]	I_0	2.902	3.799	4.789	5.817	9.541	10.27	11.10	12.94
Terminal voltage [V]	U_0	120.8	160.4	200.3	238.7	360.1	380.1	401.6	441.1
Supply frequency [Hz]	f_0	50.03	50.00	50.02	49.98	50.03	50.00	50.01	50.00
Measured stator winding temperature [°C]	$\theta_{0.meas}$	73.1	73.9	74.6	75.4	76.0	76.4	76.9	77.2
Stator winding resistance [Ω]	R_0	0.358	0.359	0.359	0.360	0.363	0.363	0.364	0.365
Stator winding losses [W]	$P_{s,0}$	4.527	7.769	12.36	18.27	49.49	57.46	67.20	91.86
Constant losses [W]	P_c	129.0	146.1	166.6	189.4	286.8	307.5	332.4	393.6
No-load iron losses [W]	$P_{fe,0}$	20.0	37.2	57.7	80.6	178.0	198.6	223.5	284.7

Table A5.8. No-load test: More results

Quantity	Symbol	Value
No-load friction and windage losses [W]	$P_{fw,0}$	108.9
Rated load friction and windage losses [W]	$P_{fw,N}$	103.7
Inner voltage on rated load [V]	U_i	391.1
Rated load iron losses [W]	$P_{fe,N}$	210.5

Table A5.9. No-load test: Constants of the iron losses interpolation curve $P_{fe}(U_0)$.

Constant	Value
A	0.001373
B	0.0047
U_T [V]	380.0

Table A5.10. No-load test: Linear regression of friction and windage losses

Constant	Value
A	0.001423
B	108.9
γ	0.9996

Table A5.11. No-load test: Line-to-line resistances and stator winding resistance before and after the test

Quantity	Symbol	Before the test	After the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,0}$	0.350	0.343
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,0}$	0.352	0.345
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,0}$	0.395	0.388
Stator winding resistance [Ω]	R_0	0.365	0.358

Table A5.12. Rated load losses and efficiency on 400 V sinusoidal supply: Summation of losses

Quantity	**Symbol**	**Value**
Stator winding losses at θ_c = 25 °C [W]	$P_{s,N,\theta}$	485.9
Rotor winding losses at θ_c = 25 °C [W]	$P_{r,N,\theta}$	300.1
Friction and windage losses [W]	$P_{fw,N}$	103.7
Iron losses [W]	$P_{fe,N}$	210.5
Stray-load losses [W]	$P_{LL,N}$	156.9
Total losses [W]	P_T	1257
Efficiency [%]	η	92.33

Table A5.13. Rated load losses and efficiency on 400 V sinusoidal supply: Input-output method

Quantity	**Symbol**	**Value**
Input power [W]	$P_{1,N}$	16391
Output power [W]	$P_{2,N}$	15115
Total losses [W]	$P_{T,I/O}$	1276
Efficiency [%]	$\eta_{I/O}$	92.22

A5.1.2 Results on test converter supply with 400 V fundamental voltage (rated motor voltage)

The results of measurements and calculations with test converter supply of 400 V fundamental voltage are shown in Tables A5.14 – A5.20.

Table A5.14. Rated load measurements (test converter)

Quantity	Symbol	Values
Input power [W]	$P_{1,N,C}$	16457
Supply frequency [Hz]	$f_{N,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{N,C,meas}$	92.9
Coolant temperature [°C]	$\theta_{c,N,C}$	25.3
Machine torque [Nm]	$T_{N,C}$	98.10
Operating speed [1/s]	$n_{N,C}$	24.52
Fundamental voltage [V]	$U_{N,C,fund}$	400

Table A5.15. Load curve test results (test converter)

		Load point (in % of rated load)					
Quantity	**Symbol**	**25 %**	**50 %**	**75 %**	**100 %**	**115 %**	**125 %**
Input power [W]	$P_{1,L,C}$	4 434	8 361	12 366	16 450	18 960	20 607
Line current [A]	$I_{L,C}$	13.23	17.39	22.67	28.63	32.49	35.09
Fundamental voltage [V]	$U_{L,C,fund}$	400	400	400	400	400	400
Supply frequency [Hz]	$f_{L,C}$	50.00	50.00	50.00	50.00	50.00	50.00
Measured stator winding temperature [°C]	$\theta_{L,C,meas}$	88.6	90.1	90.8	90.5	89.3	87.4
Torque [Nm]	$T_{L,C}$	25.03	49.32	73.71	98.11	112.8	122.4
Operating speed [1/s]	$n_{L,C}$	24.89	24.77	24.65	24.52	24.44	24.38
Output power [W]	$P_{2,L,C}$	3 913	7 677	11 417	15 116	17 327	18 755
Residual losses [W]	$P_{Lr,C}$	87.7	125.8	179.4	257.5	316.1	360.1
Stray-load losses [W]	$P_{LL,C}$	11.8	45.7	102.1	180.9	239.3	281.7
Stray-load losses at T_N [W]	$P_{LL,C,N}$				180.8		

*Calculated using T_N from the rated load test

Table A5.16. Load curve test: Linear regression of residual losses (test converter)

Constant	Value
A	0.01879
B	77.49
γ	0.9999

Table A5.17. No-load test results (test converter)

Quantity	Symbol	Value
Input power [W]	$P_{0,C}$	464.5
Line current [A]	$I_{0,C}$	11.17
Fundamental voltage [V]	$U_{0,C,fund}$	400
Supply frequency [Hz]	$f_{0,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{0,C,meas}$	81.6
Stator winding resistance [Ω]	$R_{0,C}$	0.375
Stator winding losses [W]	$P_{s,0,C}$	70.2
Constant losses [W]	$P_{c,C}$	394.3

Table A5.18. No-load test (test converter): Line-to-line resistances and stator winding resistance before the test

Quantity	Symbol	Before the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,0}$	0.359
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,0}$	0.361
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,0}$	0.406
Stator winding resistance [Ω]	R_0	0.375

Table A5.19. Rated load losses and efficiency on 400 V test converter supply: Summation of losses

Quantity	**Symbol**	**Value**
Load dependent harmonic losses [W]	$P_{HL,L}$	23.9
No-load harmonic losses [W]	$P_{HL,0}$	61.9
Total harmonic losses [W]	P_{HL}	85.8
Total losses [W]	$P_{T,C}$	1343
Efficiency [%]	η_{C}	91.84
Harmonic loss ratio [%]	r_{HL}	7

Table A5.20. Rated load losses and efficiency on 400 V test converter supply: Input-output method

Quantity	**Symbol**	**Value**
Input power [W]	$P_{1,N,C}$	16457
Output power [W]	$P_{2,N,C}$	15114
Total losses [W]	$P_{T,I/O,C}$	1343
Efficiency [%]	$\eta_{I/O,C}$	91.84

A5.1.3 Results with DTC frequency converter supply of 400 V fundamental voltage (rated motor voltage)

The results of measurements and calculations with DTC converter supply of 400 V fundamental voltage are shown in Tables A5.21 – A5.27.

Table A5.21. Rated load measurements (DTC)

Quantity	Symbol	Values
Input power [W]	$P_{1,N,C}$	16445
Supply frequency [Hz]	$f_{N,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{N,C,meas}$	92.8
Coolant temperature [°C]	$\theta_{c,N,C}$	24.7
Machine torque [Nm]	$T_{N,C}$	98.06
Operating speed [1/s]	$n_{N,C}$	24.51
Fundamental voltage [V]	$U_{N,C,fund}$	400.0

Table A5.22. Load curve test results (DTC)

		Load point (in % of rated load)					
Quantity	**Symbol**	**25 %**	**50 %**	**75 %**	**100 %**	**115 %**	**125 %**
Input power [W]	$P_{1,L,C}$	4402	8341	12352	16435	18933	20573
Line current [A]	$I_{L,C}$	12.79	17.39	22.88	28.75	32.40	34.96
Fundamental voltage [V]	$U_{L,C,fund}$	397.7	399.3	398.0	401.4	404.2	403.8
Supply frequency [Hz]	$f_{L,C}$	50.00	50.00	50.00	50.00	50.00	50.00
Measured stator winding temperature [°C]	$\theta_{NLC,meas}$	88.5	90.0	90.8	90.6	89.2	86.9
Torque [Nm]	$T_{L,C}$	24.95	49.26	73.66	98.05	112.8	122.4
Operating speed [1/s]	$n_{L,C}$	24.88	24.76	24.64	24.52	24.45	24.39
Output power [W]	$P_{2,L,C}$	3900	7663	11403	15105	17327	18753
Residual losses [W]	$P_{Lr,C}$	68.5	119.4	179.6	252.7	289.5	326.8
Stray-load losses [W]	$P_{LL,C}$	10.9	42.4	94.7	167.8	222.1	261.4
Stray-load losses at T_N [W]	$P_{LL,C,N}$				167.9		

*Calculated using T_N from the rated load test

Table A5.23. Load curve test: Linear regression of residual losses (DTC)

Constant	Value
A	0.01746
B	72.87
γ	0.9939

Table A5.24. No-load test results (DTC)

Quantity	Symbol	Value
Input power [W]	$P_{0,\mathrm{C}}$	421.5
Line current [A]	$I_{0,\mathrm{C}}$	10.31
Fundamental voltage [V]	$U_{0,\mathrm{C,fund}}$	395.9
Supply frequency [Hz]	$f_{0,\mathrm{C}}$	50.00
Measured stator winding temperature [°C]	$\theta_{0,\mathrm{C,meas}}$	79.8
Stator winding resistance [Ω]	$R_{0,\mathrm{C}}$	0.374
Stator winding losses [W]	$P_{\mathrm{s},0,\mathrm{C}}$	59.5
Constant losses [W]	$P_{\mathrm{c,C}}$	362.0

Table A5.25. No-load test (DTC): Line-to-line resistances and stator winding resistance before the test

Quantity	Symbol	Before the test
Resistance between terminals U1 and V1 [Ω]	$R_{\mathrm{U1V1},0}$	0.357
Resistance between terminals V1 and W1 [Ω]	$R_{\mathrm{V1W1},0}$	0.359
Resistance between terminals U1 and W1 [Ω]	$R_{\mathrm{U1W1},0}$	0.404
Stator winding resistance [Ω]	R_0	0.374

Table A5.26. Rated load losses and efficiency on 400 V DTC converter supply: Summation of losses

Quantity	**Symbol**	**Value**
Load dependent harmonic losses [W]	$P_{HL,L}$	11.0
No-load harmonic losses [W]	$P_{HL,0}$	29.7
Total harmonic losses [W]	P_{HL}	40.7
Total losses [W]	$P_{T,C}$	1298
Efficiency [%]	η_C	92.09
Harmonic loss ratio [%]	r_{HL}	3

Table A5.27. Rated load losses and efficiency on 400 V DTC converter supply: Input-output method

Quantity	**Symbol**	**Value**
Input power [W]	$P_{1,N,C}$	16445
Output power [W]	$P_{2,N,C}$	15105
Total losses [W]	$P_{T,I/O,C}$	1340
Efficiency [%]	$\eta_{I/O,C}$	91.85

A5.2 Tests on reduced motor voltage of 377 V

The results from 377 V test run are shown in Tables A5.28 – A5.46. The voltage of 377 V is the fundamental output voltage of the frequency converter used for the DTC-tests, when the converter is supplied with 400 V mains voltage and the motor is running on rated load. Stator winding resistance values of cool motor are shown in Table A5.1.

A5.2.1 Results on reduced sinusoidal supply voltage of 377 V

The results of measurements and calculation from tests on 377 V sinusoidal supply are shown in Tables A5.28 – A5.39.

Table A5.28. Rated load test results (377 V)

Quantity	Symbol	Values
Input power [W]	$P_{1,N}$	16433
Line current [A]	I_N	29.99
Terminal voltage [V]	U_N	376.8
Supply frequency [Hz]	f_N	50.01
Coolant temperature [°C]	$\theta_{c,N}$	25.3
Machine torque [Nm]	T_N	98.07
Operating speed [1/s]	n_N	24.44
Measured stator winding temperature [°C]	$\theta_{meas,N}$	96.9
Stator winding resistance [Ω]	R_N	0.400
Stator winding temperature [°C] (Extrapolated)	θ_N	104.1
Temperature correction factor	k_θ	0.9992
Slip [%]	s_N	2.25
Corrected slip [%]	s_θ	2.25
Stator winding losses [W]	$P_{s,N}$	539.0
Corrected stator winding losses [W]	$P_{s,N,\theta}$	538.5
Rotor winding losses [W]	$P_{r,N}$	353.8
Corrected rotor winding losses [W]	$P_{r,N,\theta}$	353.5
Corrected input power [W]	$P_{1,N,\theta}$	16432

Table A5.29. Rated load test (377 V): Resistance extrapolation and line-to-line resistances

Quantity	Symbol	Value
Resistance curve constant [Ω]	R_b	0.3684
Resistance curve constant [Ω]	R_a	0.3822
Exponential decay constant	λ	0.036
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,N}$	0.382
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,N}$	0.384
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,N}$	0.432

Table A5.30. Load curve test results (377 V)

		Load point (in % of rated load)					
Quantity	**Symbol**	**25 %**	**50 %**	**75 %**	**100 %**	**115 %**	**125 %**
Input power [W]	$P_{1,L}$	4343	8281	12313	16432	18989	20676
Line current [A]	I_L	12.56	17.42	23.41	30.07	34.43	37.42
Terminal voltage [V]	U_L	376.1	375.6	375.5	375.6	375.1	374.6
Supply frequency [Hz]	f_L	50.04	50.02	50.03	50.00	50.02	50.03
Machine torque [Nm]	T_L	24.96	49.27	73.67	98.04	112.8	122.4
Operating speed [1/s]	n_L	24.89	24.75	24.60	24.43	24.34	24.27
Measured stator winding temperature [°C]	$\theta_{L,meas}$	92.9	94.8	95.9	95.8	94.5	92.1
Stator winding resistance [Ω]	R_L	0.396	0.397	0.397	0.397	0.397	0.397
Stator winding losses [W]	$P_{s,L}$	93.8	180.7	326.4	538.5	706.2	834.3
Slip [%]	s_L	0.527	1.06	1.64	2.27	2.68	2.97
Rotor winding losses [W]	$P_{r,L}$	21.4	84.2	194.0	355.9	485.3	583.9
Output power [W]	$P_{2,L}$	3903	7661	11389	15052	17248	18667
Friction and windage losses [W]	$P_{fw,L}$	95.9	94.6	93.2	91.8	90.8	90.1
Residual losses [W]	P_{Lr}	39.8	71.3	122.4	205.3	270.4	312.9
Stray-load losses [W]	P_{LL}	11.9	46.6	104.1	184.3	244.0	287.3
*Stray-load losses at T_N [W]	$P_{LL,N}$				184.4		

*Calculated using T_N from the rated load test

Table A5.31. Load curve test (377 V): Linear regression of residual losses

Constant	Value
A	0.01918
B	23.98
γ	0.9995

Table A5.32. Load curve test (377 V): Line-to-line resistances and stator winding resistance before and after the test

Quantity	Symbol	Before the test	After the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,L}$	0.380	0.379
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,L}$	0.382	0.381
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,L}$	0.430	0.429
Stator winding resistance [Ω]	R_L	0.397	0.396

Table A5.33. No-load test results (377 V)

		Voltage point (in % of rated voltage)							
Quantity	**Symbol**	**30 %**	**40 %**	**50 %**	**60 %**	**90 %**	**95 %**	**100 %**	**110 %**
Input power [W]	P_0	122.0	142.6	168.7	199.0	327.9	356.3	390.1	479.6
Line current [A]	I_0	2.86	3.75	4.77	5.83	9.49	10.20	10.96	12.83
Terminal voltage [V]	U_0	120.6	159.9	200.7	240.5	360.3	380.0	399.5	440.3
Supply frequency [Hz]	f_0	50.04	50.04	50.04	50.02	50.03	50.04	50.02	50.02
Measured stator winding temperature [°C]	$\theta_{0,meas}$	79.1	80.7	80.7	81.5	82.2	82.8	83.5	84.0
Stator winding resistance [Ω]	R_0	0.376	0.376	0.376	0.376	0.376	0.376	0.376	0.376
Stator winding losses [W]	$P_{s,0}$	4.60	7.93	12.8	19.1	50.8	58.7	67.7	92.9
Constant losses [W]	P_c	117.4	134.6	155.9	179.9	277.2	297.6	322.4	386.7
No-load iron losses [W]	$P_{fe,0}$	20.2	37.5	58.8	82.7	180.0	200.4	225.3	289.5

Table A5.34. No-load test (377 V): More results

Quantity	Symbol	Value
No-load friction and windage losses [W]	$P_{fw, 0}$	97.2
Rated load friction and windage losses [W]	$P_{fw,N}$	91.8
Inner voltage on rated load [V]	U_i	368.2
Rated load iron losses [W]	$P_{fe,N}$	188.4
Iron losses on voltage *$U_{0,C,fund}$ [W]	$P_{fe}(U_{0,C,fund})$	197.2
Constant losses on *$U_{0,C,fund}$ [W]	$P_c(U_{0,C,fund})$	294.3

* Voltage of the no-load test on DTC converter supply

Table A5.35. No-load test (377 V): Constants of the iron losses interpolation curve $P_{fe}(U_0)$

Constant	Value
A	0.001390
B	0.0047
U_T [V]	375.0

Table A5.36. No-load test (377 V): Linear regression of friction and windage losses

Constant	Value
A	0.00144
B	97.17
γ	0.9996

Table A5.37. No-load test (377 V): Line-to-line resistances and stator winding resistance before and after the test

Quantity	Symbol	Before the test	After the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,0}$	0.360	0.359
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,0}$	0.362	0.361
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,0}$	0.407	0.407
Stator winding resistance [Ω]	R_0	0.376	0.376

Table A5.38. Rated load losses and efficiency on 377 V sinusoidal supply: Summation of losses

Quantity	**Symbol**	**Value**
Stator winding losses at θ_c = 25 °C [W]	$P_{s,N,\theta}$	538.5
Rotor winding losses at θ_c = 25 °C [W]	$P_{r,N,\theta}$	353.5
Friction and windage losses [W]	$P_{fw,N}$	91.79
Iron losses [W]	$P_{fe,N}$	188.4
Stray-load losses [W]	$P_{LL,N}$	184.3
Total losses [W]	P_T	1357
Efficiency [%]	η	91.74

Table A5.39. Rated load losses and efficiency on 377 V sinusoidal supply: Input-output method

Quantity	**Symbol**	**Value**
Input power [W]	$P_{1,N}$	16433
Output power [W]	$P_{2,N}$	15059
Total losses [W]	$P_{T,I/O}$	1374
Efficiency [%]	$\eta_{I/O}$	91.64

A5.2.2 Results with DTC frequency converter supply of 377 V fundamental voltage

The results of measurements and calculations with DTC converter supply of 377 V fundamental voltage are shown in Tables A5.40 – A5.46.

Table A5.40. Rated load measurements (DTC 377 V)

Quantity	Symbol	Values
Input power [W]	$P_{1,N,C}$	16493
Motor fundamental voltage [V]	$U_{N,fund}$	377
Supply frequency [Hz]	$f_{N,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{N,C,meas}$	99.6
Coolant temperature [°C]	$\theta_{c,N,C}$	24.6
Machine torque [Nm]	$T_{N,C}$	98.00
Operating speed [1/s]	$n_{N,C}$	24.43

Table A5.41. Load curve test results (DTC 377 V)

		Load point (in % of rated load)					
Quantity	**Symbol**	**25 %**	**50 %**	**75 %**	**100 %**	**115 %**	**125 %**
Input power [W]	$P_{1,L,C}$	4390.8	8330.4	12358	16490	19045	20765
Line current [A]	$I_{L,C}$	12.67	17.40	23.34	30.07	34.46	37.51
Supply frequency [Hz]	$f_{L,C}$	50.00	50.00	50.00	50.01	50.00	50.00
Measured stator winding temperature [°C]	$\theta_{L,C,meas}$	94.5	97.0	99.0	99.4	97.7	94.7
Torque [Nm]	$T_{L,C}$	24.94	49.24	73.61	98.01	112.7	122.6
Operating speed [1/s]	$n_{L,C}$	24.87	24.74	24.59	24.43	24.32	24.25
Output power [W]	$P_{2,L,C}$	3897	7654	11374	15044	17229	18672
Residual losses [W]	$P_{Lr,C}$	94.5	128.0	181.4	271.7	345.1	396.2
Stray-load losses [W]	$P_{LL,C}$	13.1	51.1	114.1	202.3	267.6	316.3
*Stray-load losses at T_N [W]	$P_{LL,N}$				202.5		

*Calculated using T_N from the rated load test

Table A5.42. Load curve test: Linear regression of residual losses (DTC 377 V)

Constant	Value
A	0.02106
B	75.46
γ	0.9989

Table A5.43. No-load test results (DTC 377 V)

Quantity	Symbol	Value
Input power [W]	$P_{0,C}$	400.6
Line current [A]	$I_{0,C}$	10.14
Fundamental voltage [V]	$U_{0,C,fund}$	377
Supply frequency [Hz]	$f_{0,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{0,C,meas}$	83.5
Stator winding resistance [Ω]	$R_{0,C}$	0.365
Stator winding losses [W]	$P_{s,0,C}$	56.4
Constant losses [W]	$P_{c,C}$	344.3

Table A5.44. No-load test (DTC 377 V): Line-to-line resistances and stator winding resistance

Quantity	Symbol	Before the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,0,C}$	0.349
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,0,C}$	0.351
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,0,C}$	0.395
Stator winding resistance [Ω]	$R_{0,C}$	0.365

Table A5.45. Rated load losses and efficiency on 377 V DTC converter supply: Summation of losses

Quantity	Symbol	Value
Load dependent harmonic losses [W]	$P_{HL,L}$	18.2
No-load harmonic losses [W]	$P_{HL,0}$	50.0
Total harmonic losses [W]	P_{HL}	68.1
Total losses [W]	$P_{T,C}$	1425
Efficiency [%]	η_C	91.36
Harmonic loss ratio [%]	r_{HL}	5

Table A5.46. Rated load losses and efficiency on 377 V DTC converter supply: Input-output method

Quantity	Symbol	Value
Input power [W]	$P_{1,N,C}$	16493
Output power [W]	$P_{2,N,C}$	15041
Total losses [W]	$P_{T,I/O,C}$	1451
Efficiency [%]	$\eta_{I/O,C}$	91.20

A5.3 Tests on reduced motor voltage of 350 V

The results from 350 V test run are shown in Tables A5.47 – A5.65. The voltage of 350 V is the fundamental output voltage of the frequency converter (used as test converter), when the converter is supplied with 400 V mains voltage and the motor is running on rated load. Stator winding resistance values of cool motor are shown in Table A5.1.

A5.3.1 Results on reduced sinusoidal supply voltage of 350 V

The results of measurements and calculations from tests on 350 V sinusoidal supply are shown in Tables A5.47 – A5.58.

Table A5.47. Rated load test results (350 V)

Quantity	Symbol	Values
Input power [W]	$P_{1,N}$	16500
Line current [A]	I_N	32.12
Terminal voltage [V]	U_N	348.6
Supply frequency [Hz]	f_N	50.05
Coolant temperature [°C]	$\theta_{c,N}$	23.9
Machine torque [Nm]	T_N	97.97
Operating speed [1/s]	n_N	24.32
Measured stator winding temperature [°C]	$\theta_{meas,N}$	102.9
Stator winding resistance [Ω]	R_N	0.414
Stator winding temperature [°C] (Extrapolated)	θ_N	116.3
Temperature correction factor	k_θ	1.003
Slip [%]	s_N	2.80
Corrected slip [%]	s_θ	2.81
Stator winding losses [W]	$P_{s,N}$	640.8
Corrected stator winding losses [W]	$P_{s,N,\theta}$	642.8
Rotor winding losses [W]	$P_{r,N}$	439.4
Corrected rotor winding losses [W]	$P_{r,N,\theta}$	440.7
Corrected input power [W]	$P_{1,N,\theta}$	16504

Table A5.48. Rated load test (350 V): Resistance extrapolation and line-to-line resistances

Quantity	Symbol	Value
Resistance curve constant [Ω]	R_b	0.3682
Resistance curve constant [Ω]	R_a	0.396
Exponential decay constant	λ	0.025
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,N}$	0.396
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,N}$	0.398
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,N}$	0.448

Table A5.49. Load curve test results (350 V)

		Load point (in % of rated load)					
Quantity	**Symbol**	**25 %**	**50 %**	**75 %**	**100 %**	**115 %**	**125 %**
Input power [W]	$P_{1,L}$	4256	8222	12303	16507	19141	20874
Line current [A]	I_L	12.03	17.68	24.55	32.26	37.37	40.87
Terminal voltage [V]	U_L	349.1	348.6	347.9	347.1	346.6	346.2
Supply frequency [Hz]	f_L	50.04	50.08	50.08	50.05	50.08	50.07
Machine torque [Nm]	T_L	24.88	49.18	73.58	97.97	112.7	122.3
Operating speed [1/s]	n_L	24.86	24.72	24.53	24.32	24.19	24.09
Measured stator winding temperature [°C]	$\theta_{L,meas}$	98.1	100.2	101.5	101.3	99.4	96.8
Stator winding resistance [Ω]	R_L	0.387	0.395	0.402	0.402	0.402	0.402
Stator winding losses [W]	$P_{s,L}$	84.1	185.1	363.6	627.7	842.0	1007.1
Slip [%]	s_L	0.631	1.28	2.02	2.82	3.39	3.77
Rotor winding losses [W]	$P_{r,L}$	25.3	100.8	237.2	443.9	614.0	743.2
Output power [W]	$P_{2,L}$	3887	7639	11342	14968	17130	18512
Friction and windage losses [W]	$P_{fw,L}$	57.9	57.0	55.9	54.8	54.0	53.5
Residual losses [W]	P_{Lr}	36.2	73.4	137.3	246.0	333.9	391.6
Stray-load losses [W]	P_{LL}	15.5	60.6	135.7	240.5	318.3	374.7
*Stray-load losses at T_N [W]	$P_{LL,N}$				240.5		

*Calculated using T_N from the rated load test

Table A5.50. Load curve test (350 V): Linear regression of residual losses

Constant	Value
A	0.02506
B	12.17
γ	0.9987

Table A5.51. Load curve test (350 V): Line-to-line resistances and stator winding resistance before and after the test

Quantity	Symbol	Before the test	After the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,L}$	0.385	0.370
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,L}$	0.387	0.372
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,L}$	0.435	0.419
Stator winding resistance [Ω]	R_L	0.402	0.387

Table A5.52. No-load test results (350 V)

		Voltage point (in % of rated voltage)							
Quantity	Symbol	30 %	40 %	50 %	60 %	90 %	95 %	100 %	110 %
Input power [W]	P_0	78.8	95.3	115.8	140.7	239.0	258.1	282.6	335.0
Line current [A]	I_0	2.429	3.212	4.048	4.930	7.975	8.439	9.036	10.24
Terminal voltage [V]	U_0	104.3	139.6	174.7	209.3	315.5	331.3	349.4	383.6
Supply frequency [Hz]	f_0	50.06	50.06	50.07	50.09	50.04	50.06	50.09	50.05
Measured stator winding temperature [°C]	$\theta_{0,meas}$	82.3	83.2	84.2	85.2	86.0	86.7	87.6	88.4
Stator winding resistance [Ω]	R_0	0.364	0.366	0.367	0.369	0.377	0.379	0.381	0.385
Stator winding losses [W]	$P_{s,0}$	3.22	5.66	9.03	13.5	36.0	40.5	46.6	60.6
Constant losses [W]	P_c	75.6	89.6	106.7	127.2	203.0	217.6	236.0	274.5
No-load iron losses [W]	$P_{fe,0}$	16.7	30.8	47.9	68.3	144.2	158.8	177.1	215.6

Table A5.53. No-load test (350 V): More results

Quantity	Symbol	Value
No-load friction and windage losses [W]	$P_{fw, 0}$	58.9
Rated load friction and windage losses [W]	$P_{fw,N}$	54.8
Inner voltage on rated load [V]	U_i	338.9
Rated load iron losses [W]	$P_{fe,N}$	166.3
Iron losses on voltage *$U_{0,C,fund}$ [W]	$P_{fe}(U_{0,C,fund})$	207.6
Constant losses on *$U_{0,C,fund}$ [W]	$P_c(U_{0,C,fund})$	266.4

* Voltage of the no-load test on DTC converter supply

Table A5.54. No-load test (350 V): Constants of the iron losses interpolation curve $P_{fe}(U_0)$

Constant	Value
A	0.001448
B	0.0013
U_T [V]	340

Table A5.55. No-load test (350 V): Linear regression of friction and windage losses

Constant	Value
A	0.001563
B	58.87
γ	0.9999

Table A5.56. No-load test (350 V): Line-to-line resistances and stator winding resistance before and after the test

Quantity	Symbol	Before the test	After the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,0}$	0.368	0.348
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,0}$	0.370	0.350
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,0}$	0.417	0.394
Stator winding resistance [Ω]	R_0	0.385	0.364

Table A5.57. Rated load losses and efficiency on 350 V sinusoidal supply: Summation of losses

Quantity	**Symbol**	**Value**
Stator winding losses at θ_c = 25 °C [W]	$P_{s,N,\theta}$	642.8
Rotor winding losses at θ_c = 25 °C [W]	$P_{r,N,\theta}$	440.7
Friction and windage losses [W]	$P_{fw,N}$	54.8
Iron losses [W]	$P_{fe,N}$	166.3
Stray-load losses [W]	$P_{LL,N}$	240.5
Total losses [W]	P_T	1545
Efficiency [%]	η	90.64

Table A5.58. Rated load losses and efficiency on 350 V sinusoidal supply: Input-output method

Quantity	**Symbol**	**Value**
Input power [W]	$P_{1,N}$	16500
Output power [W]	$P_{2,N}$	14971
Total losses [W]	$P_{T,I/O}$	1529
Efficiency [%]	$\eta_{I/O}$	90.73

A5.3.2 Results on test converter supply at 350 V fundamental voltage

The results of measurements and calculations with test converter supply of 350 V fundamental voltage are shown in Tables A5.59 – A5.65

Table A5.59. Rated load measurements (test converter 350 V)

Quantity	Symbol	Values
Input power [W]	$P_{1,N,C}$	16568
Fundamental motor voltage [V]	$U_{N,C,fund}$	350
Supply frequency [Hz]	$f_{N,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{N,C,meas}$	106.4
Coolant temperature [°C]	$\theta_{c,N,C}$	24.5
Machine torque [Nm]	$T_{N,C}$	97.97
Operating speed [1/s]	$n_{N,C}$	24.30

Table A5.60. Load curve test results (test converter 350 V)

		Load point (in % of rated load)					
Quantity	Symbol	25 %	50 %	75 %	100 %	115 %	125 %
Input power [W]	$P_{1,L,C}$	4350	8293	12353	16561	19196	20948
Line current [A]	$I_{L,C}$	12.41	17.44	24.05	31.87	37.26	41.05
Fundamental voltage [V]	$U_{L,C,fund}$	368	363	356	350	347	344
Supply frequency [Hz]	$f_{L,C}$	50.00	50.00	50.00	50.00	50.00	50.00
Measured stator winding temperature [°C]	$\theta_{L,C,meas}$	100.8	102.8	104.0	103.7	101.6	98.7
Torque [Nm]	$T_{L,C}$	24.89	49.16	73.57	97.97	112.69	122.28
Operating speed [1/s]	$n_{L,C}$	24.86	24.71	24.53	24.31	24.15	24.04
Output power [W]	$P_{2,L,C}$	3887	7631	11337	14963	17100	18467
Residual losses [W]	$P_{Lr,C}$	129.4	153.1	192.9	305.1	420.4	510.8
Stray-load losses [W]	$P_{LL,C}$	16.4	64.1	143.6	254.6	336.9	396.7
*Stray-load losses at T_N [W]	$P_{LL,N}$				254.6		

*Calculated using T_N from the rated load test

Table A5.61. Load curve test: Linear regression of residual losses (test converter 350 V)

Constant	Value
A	0.02653
B	83.23
γ	0.9828

Table A5.62. No-load test results (test converter 350 V)

Quantity	Symbol	Value
Input power [W]	$P_{0,C}$	400.9
Line current [A]	$I_{0,C}$	10.20
Fundamental voltage [V]	$U_{0,C,fund}$	377
Supply frequency [Hz]	$f_{0,C}$	50.00
Measured stator winding temperature [°C]	$\theta_{0,C,meas}$	90.5
Stator winding resistance [Ω]	$R_{0,C}$	0.396
Stator winding losses [W]	$P_{s,0,C}$	61.8
Constant losses [W]	$P_{c,C}$	339.1

Table A5.63. No-load test (test converter 350 V): Line-to-line resistances and stator winding resistance

Quantity	Symbol	Before the test
Resistance between terminals U1 and V1 [Ω]	$R_{U1V1,0,C}$	0.379
Resistance between terminals V1 and W1 [Ω]	$R_{V1W1,0,C}$	0.381
Resistance between terminals U1 and W1 [Ω]	$R_{U1W1,0,C}$	0.428
Stator winding resistance [Ω]	$R_{0,C}$	0.396

Table A5.64. Rated load losses and efficiency on 350 V test converter supply: Summation of losses

Quantity	Symbol	Value
Load dependent harmonic losses [W]	$P_{HL,L}$	14.1
No-load harmonic losses [W]	$P_{HL,0}$	72.6
Total harmonic losses [W]	P_{HL}	86.7
Total losses [W]	$P_{T,C}$	1632
Efficiency [%]	η_{C}	90.17
Harmonic loss ratio [%]	r_{HL}	6

Table A5.65. Rated load losses and efficiency on 350 V test converter supply: Input-output method

Quantity	Symbol	Value
Input power [W]	$P_{1,N,C}$	16568
Output power [W]	$P_{2,N,C}$	14960
Total losses [W]	$P_{T,I/O,C}$	1608
Efficiency [%]	$\eta_{I/O,C}$	90.29

REFERENCES for Appendix 5

IEC (2013), IEC/TS 60034-2-3 Edition 1.0: Rotating electrical machines – Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors

IEC (2014), IEC 60034-2-1 Edition 2.0: Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)