भारतीय मानक

Indian Standard

IS/IEC 60034-2-1 : 2024

विद्युत घूर्णीय मशीनें

भाग 2 परीक्षण के द्वारा क्षति और दक्षता का निर्धारण

अनुभाग 1 मानक तरीके (संकर्षण वाहनों की मशीनों को छोड़कर)

(दूसरा पुनरीक्षण)

Rotating Electrical Machines
Part 2 Determining Losses and Efficiency from Tests
Section 1 Standard Methods (Excluding Machines for Traction Vehicles)

(Second Revision)

ICS 29.160.01

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IEC

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December 2024

Price Group 18

Rotating Machinery Sectional Committee, ETD 15

NATIONAL FOREWORD

This Indian Standard (Second Revision) which is identical to IEC 60034-2-1 : 2024 'Rotating electrical machines — Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Rotating Machinery Sectional Committee and approval of the Electrotechnical Division Council.

This standard was originally published in 2011 and subsequently revised in 2023. The second revision (Superseding of IS 15999 (Part 2/Sec 1: 2023) has been undertaken to align it with the latest version of IEC 60034-2-1: 2024.

On the recommendation of the Rotating Machinery Sectional Committee single numbering has been adopted for IEC 60034 series to avoid confusion in use and implementation as experienced by industry, lab and other stakeholders.

This standard is published in various parts. Other parts in this series are:

Part 5	Rotating electrical machines: Part 5 Degrees of protection provided by the integral design of rotating electrical machines (IP Code) — Classification
Part 8	Rotating electrical machines: Part 8 Terminal markings and direction of rotation
Part 27 Section 4	Rotating Electrical Machines: Part 27 Winding insulation of rotating electrical machines, Section 4 Measurement of insulation resistance and polarization index

The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appears referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to International Standards for which Indian Standards also exists. The corresponding Indian Standards, which are to be substituted, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60027-1 Letter symbols to be used in electrical technology — Part 1: General	IS 3722 (Part 1) : 2023/IEC 60027-1 : 1992 Letter symbols and signs used In electrical technology: Part 1 General (*second revision*)	Identical
IEC 60034-1: 2022 Rotating electrical machines — Part 1: Rating and performance	IS 15999 (Part 1) : 2021/IEC 60034-1 : 2017 Rotating electrical machines: Part 1 Rating and performance (under revision with latest Identical IEC)	Identical

International Standard	Corresponding Indian Standard	Degree of Equivalence
IEC 60034-4-1 : 2018 Rotating electrical machines — Part 4-1: Methods for determining electrically excited synchronous machine quantities from tests	IS 15999 (Part 4/Sec 1) : 2023/IEC 60034-4-1 : 2018 Rotating electrical machines: Part 4 Electrically excited synchronous machine quantities Section 1 Test methods (*first revision*)	Identical
IEC 60034-30-1, Rotating electrical machines — Part 30-1: Efficiency classes of line operated AC motors (IE code)	IS 12615 : 2018 Line operated three phase a.c. motors (IE Code) 'Efficiency classes and performance specification' (*third revision*)	Technically Equivalent
IEC 60051(all parts) Direct acting indicating analogue electrical measuring instruments and their accessories	IS 1248 (Part 1) : 2021/IEC 60051-1 : 2016 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 1: Definitions and general requirements common to all parts (*fifth revision*)	Identical
	IS 1248 (Part 2) : 2021/IEC 60051-2 : 2018 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 2: Special requirements for ammeters and voltmeters	Identical
	IS 1248 (Part 3) : 2021/IEC 60051-3 : 2018 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 3: Special requirements for wattmeters and varmeters	Identical
	IS 1248 (Part 4) : 2021/IEC 60051-4 : 2018 Direct acting indicating analogue electrical measuring instruments and their accessories title — Part 4: Special requirements for frequency meters	Identical
	IS 1248 (Part 5) : 2021/IEC60051-5 : 2018 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 5: Special requirements for phase meters power factor meters and synchroscopes	Identical
	IS 1248 (Part 6) : 2021/IEC 60051-6 : 2017 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 6: Special requirements for ohmmeters impedance meters and conductance meters	Identical
	IS 1248 (Part 7) : 2021/IEC 60051-7 : 2017 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 7: Special requirements for multi-function instruments	Identical

International Standard	Corresponding Indian Standard	Degree of Equivalence
IEC 60051(all parts) Direct acting indicating analogue electrical measuring instruments and their accessories	IS 1248 (Part 8) : 2021/ IEC 60051-8 : 2017 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 8: Special requirements for accessories	Identical
	IS 1248 (Part 9) : 2021/IEC 60051-9 : 2019 Direct acting indicating analogue electrical measuring instruments and their accessories — Part 9: Recommended test methods	Identical

The Committee has reviewed the provisions of the following international standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard.

International Standard	Title
IEC 60034-19	Rotating electrical machines — Part 19: Specific test methods for DC machines on conventional and rectifier-fed supplies
IEC 60034-29	Rotating electrical machines — Part 29: Equivalent loading and superposition techniques — Indirect testing to determine temperature rise

Only English language text has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in the International Standard.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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CONTENTS

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ROTATING ELECTRICAL MACHINES

PART 2 DETERMINING LOSSES AND EFFICIENCY FROM TESTS

SECTION 1 STANDARD METHODS (EXCLUDING MACHINES FOR TRACTION VEHICLES)

(Second Revision)

1 Scope

This part of IEC 60034 is intended to establish methods of determining efficiencies from tests, and also to specify methods of obtaining specific losses.

This document applies to DC machines and to AC synchronous and induction machines of all sizes within the scope of IEC 60034-1 rated for mains operation.

NOTE   These methods may be applied to other types of machines such as rotary converters, AC commutator motors and single-phase induction motors.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60027-1, *Letter symbols to be used in electrical technology – Part 1: General*

IEC 60034-1:2022, *Rotating electrical machines – Part 1: Rating and performance*

IEC 60034-4-1:2018, *Rotating electrical machines – Part 4-1: Methods for determining electrically excited synchronous machine quantities from tests*

IEC 60034-19, *Rotating electrical machines – Part 19:Specific test methods for DC machines on conventional and rectifier-fed supplies*

IEC 60034-29, *Rotating electrical machines – Part 29: Equivalent loading and superposition techniques – Indirect testing to determine temperature rise*

IEC 60034-30-1, *Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code)*

IEC 60051(all parts), *Direct acting indicating analogue electrical measuring instruments and their accessories*

IEC 60051-1, *Direct acting indicating analogue electrical measuring instruments and their accessories – Part 1: Definitions and general requirements common to all parts*

3   Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60034-1, IEC 60051-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
efficiency
ratio of output power to input power expressed in the same units and usually given as a percentage

3.2
direct efficiency determination
method by which the determination of efficiency is made by measuring directly the input power and the output power

3.3
dual-supply back-to-back test
test in which two identical machines are mechanically coupled together, and the total losses of both machines are calculated from the difference between the electrical input to one machine and the electrical output of the other machine

3.4
indirect efficiency determination
method by which the determination of efficiency is made by measuring the input power or the output power and determining the total losses. Those losses are added to the output power, thus giving the input power, or subtracted from the input power, thus giving the output power

3.5
single-supply back-to-back test
test in which two identical machines are mechanically coupled together and are both connected electrically to the same power system. The total losses of both machines are taken as the input power drawn from the system

3.6
no-load test
test in which a machine is run as a motor providing no useful mechanical output from the shaft, or if run as a generator with its terminals open-circuited

3.7
zero power factor test
no-load test on a synchronous machine, which is over-excited and operates at a power factor very close to zero

3.8
equivalent circuit method
test on an induction machine in which the losses are determined by help of an equivalent circuit model

3.9
test with rotor removed and reverse rotation test
combined test on an induction machine in which the additional load losses are determined from a test with rotor removed and a test with the rotor running in reverse direction to the rotating magnetic field of the stator

3.10
short-circuit test
test on a synchronous machine in which a machine is run as a generator with its terminals short-circuited

3.11
locked rotor test
test in which the rotor is locked to prevent rotation

3.12
Eh-star test
test in which the motor is run in star connection on unbalanced voltage

3.13
losses

3.13.1
total losses
P_T
difference between the input power and the output power, equivalent to the sum of the constant losses (see 3.13.2), the load losses (see 3.13.4), the additional load losses (see 3.13.5) and the excitation circuit losses (see 3.13.3)

3.13.2
constant losses
P_c
losses incorporating the sum of windage, friction and iron losses

Note 1 to entry: Although these losses change with voltage and load, they are historically called "constant" losses and the name is retained in this document.

3.13.2.1
iron losses
P_{fe}
losses in active iron and additional no-load losses in other magnetic and conductive parts

3.13.2.2
friction and windage losses
P_{fw}
losses incorporating the sum of windage and friction

3.13.2.2.1
friction losses
losses due to friction (bearings and brushes, if not lifted at rated conditions) not including any losses in a separate lubricating system

3.13.2.2.2
windage losses
total losses due to aerodynamic friction in all parts of the machine, including power absorbed in shaft mounted fans, and in auxiliary machines forming an integral part of the machine

Note 1 to entry: Losses in a separate ventilating system should be listed separately.

Note 2 to entry: For machines indirectly or directly cooled by hydrogen, see IEC 60034-1.

3.13.3
excitation circuit losses
3.13.3.1
excitation circuit losses
P_e
sum of the excitation winding losses (see 3.13.3.2), the exciter losses (see 3.13.3.3) and, for synchronous machines, electrical brush loss (see 3.13.3.5), if any

3.13.3.2
excitation winding losses
P_f
excitation (field) winding losses are equal to the product of the exciting current I_e and the excitation voltage U_e

3.13.3.3
exciter losses
P_{Ed}
exciter losses for the different excitation systems (see Annex B) are defined as follows:

a) shaft driven exciter

exciter losses are the power absorbed by the exciter at its shaft (reduced by friction and windage losses) plus the power P_{1E} drawn from a separate source at its excitation winding terminals, minus the useful power which the exciter provides at its terminals. The useful power at the terminals of the exciter is equal to the excitation winding losses as per 3.13.3.2 plus (in the case of a synchronous machine) the electrical brush losses as per 3.13.3.5.

Note 1 to entry: If the exciter can be decoupled and tested separately its losses can be determined according to 7.1.3.2.1.5.

Note 2 to entry: Whenever the exciter makes use of separate auxiliary supplies, their consumptions are to be included in the exciter losses unless they are considered together with the main machine auxiliaries consumption.

b) brushless exciter

exciter losses are the power absorbed by the exciter at its shaft, reduced by friction and windage losses (when the relevant test is performed on the set of main machine and exciter), plus the electrical power P_{1E} from a separate source (if any) absorbed by its field winding or its stator winding (in the case of an induction exciter), minus the useful power which the exciter provides at the rotating power converter terminals.

Note 3 to entry: Whenever the exciter makes use of separate auxiliary supplies their consumptions are to be included in the exciter losses unless they are considered together with the main machine auxiliaries consumption.

Note 4 to entry: If the exciter can be decoupled and tested separately, its losses can be determined according to 7.1.3.2.1.

c) separate rotating exciter

exciter losses are the difference between the power absorbed by the driving motor, plus the power absorbed by separate auxiliary supplies, of both driving and driven machines, including the power supplied by separate source to their excitation winding terminals, and the excitation power supplied as per 3.13.3.2 and 3.13.3.4. The exciter losses may be determined according to 7.1.3.2.1.

d) static excitation system

static exciter

excitation system losses are the difference between the electrical power drawn from its power source, plus the power absorbed by separate auxiliary supplies, and the excitation supplied as per 3.13.3.2 and 3.13.3.4.

Note 5 to entry: In the case of systems fed by transformers, the transformer losses shall be included in the exciter losses.

e) excitation from auxiliary winding

auxiliary winding exciter

exciter losses are the copper losses in the auxiliary (secondary) winding and the additional iron losses produced by increased flux harmonics. The additional iron losses are the difference between the losses which occur when the auxiliary winding is loaded and when it is unloaded.

Note 6 to entry: Because separation of the excitation component of losses is difficult, it is recommended to consider these losses as an integral part of the stator losses when determining overall losses.

In the cases c) and d) no allowance is made for the losses in the excitation source (if any) or in the connections between the source and the brushes (synchronous machine) or between the source and the excitation winding terminals (DC machine).

If the excitation is supplied by a system having components as described in b) to e) the exciter losses shall include the relevant losses of the components pertaining to the categories listed in Annex B as applicable.

3.13.3.4
separately supplied excitation power
P_{1E}
excitation power P_{1E} supplied from a separate power source is:

–   for exciter types a) and b) the exciter excitation power (DC or synchronous exciter) or stator winding input power (induction exciter). It covers a part of the exciter losses P_{Ed} (and further losses in induction exciters) while a larger part of P_e is supplied via the shaft;

–   for exciter types c) and d) equal to the excitation circuit losses, $P_{1E} = P_e$;

–   for exciter type e) $P_{1E} = 0$, the excitation power being delivered entirely by the shaft. Also, $P_{1E} = 0$ for machines with permanent magnet excitation.

Exciter types shall be in accordance with 3.13.3.3.

3.13.3.5
brush losses (excitation circuit)
P_b
electrical brush loss (including contact loss) of separately excited synchronous machines

3.13.4
load losses

3.13.4.1
load losses
P_L
sum of the winding (I^2R) losses (see 3.13.4.2) and the electrical brush losses (see 3.13.3.5), if any

3.13.4.2
winding losses
winding losses are I^2R losses:

– in the armature circuit of DC machines;

– in the stator and rotor windings of induction machines;

– in the armature and field windings of synchronous machines

3.13.4.3
brush losses
P_b
electrical brush loss (including contact loss) in the armature circuit of DC machines and in wound-rotor induction machines

3.13.5
additional load losses
P_{LL}
losses produced in active iron and other magnetic and conductive parts by alternating stray fluxes when the machine is loaded; eddy current losses in winding conductors caused by load current-dependent flux pulsations and additional brush losses caused by commutation

Note 1 to entry: These losses do not include the additional no-load losses of 3.13.2.2.

3.13.6
short-circuit losses
P_{sc}
current-dependent losses in a synchronous machine and in a DC machine when the armature winding is short-circuited

3.14
test quantities <polyphase AC machines>

3.14.1
terminal voltage
for polyphase AC machines, the arithmetic average of line voltages

3.14.2
line current
for polyphase AC machines, the arithmetic average of line currents

3.14.3
line-to-line resistance
for polyphase AC machines, the arithmetic average of resistances measured between each pair of terminals

Note 1 to entry: For Y-connected three-phase machines, the phase-resistance is 0,5 times the line-to-line resistance. For Δ-connected machines, the phase-resistance is 1,5 times the line-to-line resistance.

Note 2 to entry: In Clauses 6 and 7 explanations and formulae given are for three-phase machines, unless otherwise indicated.

3.14.4
temperature rise
is the machine temperature minus the cooling medium (coolant) temperature as defined by IEC 60034-1

4 Symbols and abbreviated terms

4.1 Symbols

$\cos\varphi$	is the power factor[1]
f	is the supply frequency, Hz
I	is the line current (average of all phases), A
k_θ	is the temperature correction factor
n	is the operating speed, s^{-1}
p	is the number of pole pairs
P	is the power, W
P_0	is the input power at no-load, W
P_1	is the input power, excluding excitation[2], W
P_2	is the output power, W
P_b	is the brush loss, W
P_D	is the output power (shaft power) of a drive motor, W
P_e	is the excitation circuit losses, W
P_{1E}	is the excitation power supplied by a separate source, W
P_{Ed}	is the exciter losses, W
P_{el}	is the electrical power, excluding excitation, W
P_f	is the excitation (field) winding losses, W
P_{fe}	is the iron losses, W
P_{fw}	is the friction and windage losses, W
P_c	is the constant losses, W
P_L	is the load losses, W
P_{Lr}	is the residual losses, W
P_{LL}	is the additional-load losses, W
P_{sc}	is the short-circuit losses, W
P_{mech}	is the mechanical power, W
P_T	is the total losses, W
P_w	is the winding losses, W, where subscript w is generally replaced by a, f, e, s or r (see 4.2)
R	is a winding resistance, Ω
R_{eh}	is the actual value of the auxiliary resistor for the Eh-star test (see 6.2.5), Ω
R'_{eh}	is the typical value of the auxiliary resistor, Ω
R_f	is the field winding resistance, Ω

_____

[1] This definition assumes sinusoidal voltage and current.

[2] Unless otherwise indicated, the tests in this document are described for motor operation, where P_1 and P_2 are electrical input and mechanical output power, respectively.

R_{ll}	is the line-to-line-resistance (average of all phases), Ω
R_{ph}	is the phase-resistance (average of all phases), Ω
s	is the slip, in per unit value of synchronous speed
T	is the machine torque, N·m
T_d	is the reading of the torque measuring device, N·m
U	is the terminal voltage (average of all phases), V
U_0	is the terminal voltage at no-load (average of all phases), V
U_N	is the rated terminal voltage, V
X	is the reactance, Ω
$\underline{Z} = R + j \times X$	is the notation for a complex quantity (impedance as example)
$Z = \lvert \underline{Z} \rvert = \sqrt{R^2 + X^2}$	is the absolute value of a complex quantity (impedance as example)
Z	is the impedance, Ω
α	is a temperature coefficient
η	is the efficiency
θ_0	is the initial winding temperature, °C
θ_a	is the ambient temperature, °C
θ_c	primary coolant inlet temperature, °C
θ_w	is the winding temperature, °C
τ	is a time constant, s

4.2 Additional subscripts

The following subscripts may be added to symbols to clarify the machine function and to differentiate values.

Machine components:

a	armature
e	excitation
f	field winding
r	rotor
s	stator
w	winding
U,V,W	phase designations

Machine categories:

B	booster
E	exciter
G	generator
M	motor

Operating conditions:

0	no-load
1	input
2	output
av	average, mean
d	dissipated
el	electrical
i	internal
sc	short circuit
L	test load
lr	locked rotor
mech	mechanical
N	rated
red	at reduced voltage
t	test
zpf	zero power factor test
θ	corrected to a reference coolant temperature.

NOTE   Further additional subscripts are introduced in relevant subclauses.

5   Basic requirements

5.1   Direct and indirect efficiency determination

Tests can be grouped into the three following categories:

a) input-output power measurement on a single machine. This involves the direct measurement of electrical or mechanical power into, and mechanical or electrical power out of a machine;

b) electrical input and output measurement on two identical machines mechanically connected back-to-back. This is done to eliminate the measurement of mechanical power into or out of the machine;

c) determination of the actual loss in a machine under a particular condition. This is usually not the total loss but comprises certain loss components.

The methods for determining the efficiency of machines are based on a number of assumptions. Therefore, it is not recommended that a comparison be made between the values of efficiency obtained by different methods, because the figures may not necessarily agree.

5.2   Uncertainty

Uncertainty as used in this standard is the uncertainty of determining a true efficiency. It reflects variations in the test procedure and the test equipment.

Although uncertainty shall be expressed as a numerical value, such a requirement needs sufficient testing to determine representative and comparative values.

5.3   Preferred methods and methods for customer-specific acceptance tests, field-tests or routine-tests

It is difficult to establish specific rules for the determination of efficiency. The choice of test to be made depends on the information required, the accuracy required, the type and size of the machine involved and the available field test equipment (supply, load or driving machine).

In the following, the test methods suitable for asynchronous and synchronous machines are separated into preferred methods and methods for customer-specific acceptance tests, field-tests or routine tests.

5.4 Power supply

5.4.1 Voltage

The supply voltage shall be in accordance with 7.2 (and 8.3.1 for thermal tests) of IEC 60034-1:2022.

5.4.2 Frequency

During tests, the average supply frequency shall be within ±0,1 % of the frequency required for the test being conducted.

5.5 Instrumentation

5.5.1 General

Environmental conditions shall be within the recommended range given by the instrument manufacturer. If appropriate, temperature corrections according to the instrument manufacturer's specification shall be made.

Digital instruments shall be used whenever possible.

For analogue instruments accuracy is generally expressed as a percentage of full scale, the range of the instruments chosen shall be as small as practical.

The full scale of the instrument, particularly the current sensors, shall be adapted to the power of the machine under test.

For analogue instruments the observed values should be in the upper third of the instrument range.

When testing electric machines under load, slow fluctuations in the output power and other measured quantities may be unavoidable. Therefore, for each load point many readings (typically many hundred readings) shall be taken automatically by a suitable digital meter over a period of several fluctuation cycles, at least 5 s but not more than 60 s and this average shall be used for the determination of efficiency.

5.5.2 Measuring instruments for electrical quantities

The measuring instruments shall have the equivalent of an accuracy class of 0,2 in case of a direct test and 0,5 in case of an indirect test in accordance with IEC 60051. The measuring equipment shall reach a maximum overall uncertainty of 0,2 % of reading at power factor 1,0 and shall include all errors of instrument transformers or transducers, if used.

NOTE   For a routine test as described in IEC 60034-1 an accuracy class of 0,5 is sufficient.

In the case of AC machines, unless otherwise stated in this standard, the arithmetic average of the line currents and voltages shall be used.

5.5.3 Torque measurement

The torque measuring device shall have a minimum class of 0,2. The minimum torque measured shall be at least 10 % of the torque meter's nominal torque. This applies also to part load measurements, because of increased instrument uncertainty at small readings. If a better class instrument is used, the allowed torque range can be extended accordingly.

NOTE For example class 0,1 means 5 % of the torque meter's nominal torque.

Allowed torque measuring device are an inline torque meter or a reaction torque sensor between the machine and its base. In the latter case the machine is directly coupled to the load. See Figure 2.
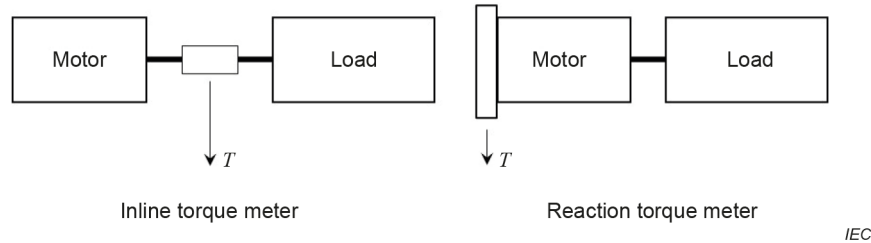
Figure 1 – Torque measuring devices

It shall be noted that the temperature of the torque sensor (i.e., due to proximity to the rotor) may be higher than the ambient temperature and is acknowledged to have a significant contribution to overall uncertainty. In that case the contribution of temperature to the uncertainty shall be limited to 0,15 % of full scale. If that is not practical, an appropriate temperature correction shall be applied.

Parasitic loads should be minimized by shaft alignment and the use of flexible couplings.

5.5.4 Speed and frequency measurement

The instrumentation used to measure supply frequency shall have an accuracy of ±0,1 % of full scale. The speed measurement should be accurate within 0,1 revolution per minute.

NOTE For asynchronous machines, the measurement of slip by a suitable method may replace speed measurement (see Annex C).

5.5.5 Temperature measurement

The instrumentation used to measure temperatures shall have an accuracy of ±1 K.

5.6 Units

Unless otherwise specified, the units of values are SI-units as listed in IEC 60027-1.

5.7 Resistance

5.7.1 Test resistance

Winding resistance R is the ohmic value, determined by appropriate methods.

For DC machines, R is the total resistance of all windings carrying armature current (armature, commutation, compensating winding, compound winding).

For DC and synchronous machines, R_f is the field winding resistance.

For polyphase AC machines, $R = R_{||}$ is the line-to-line average resistance of the stator or armature winding according to 3.14.3. In the case of wound rotor induction machines, $R_{r,||}$ is the rotor line-to-line average resistance.

The measured resistance at the end of the thermal test shall be determined as soon as possible but not after more than twice the interval as specified in Table 6 of IEC60034-1:2022. Additional readings shall be taken at intervals of approximately 1 min until these readings have begun a distinct decline from their maximum value. A curve of these readings shall be plotted as a function of time and extrapolated to zero. The value of temperature thus obtained shall be considered as the temperature at shutdown.

The measured temperature of windings shall be determined according to 5.7.2.

5.7.2 Winding temperature

The measured winding temperature shall be determined by one of the following methods (shown in order of preference):

a) temperature determined from the rated load test resistance R_N by the extrapolation procedure as described in 5.7.1;

b) temperature measured directly by either ETD or thermocouple; if the temperature is measured by more than one ETD or thermocouple, the average of all readings shall be taken;

c) temperature determined according to a) on a duplicate machine of the same construction and electrical design;

d) if load capability is not available, determine operating temperature according to IEC 60034-29;

e) if the rated load test resistance R_N cannot be measured directly, the winding temperature shall be assumed to be equal to the reference temperature of the rated thermal class as given in Table 1.

Table 1 – Reference temperature

Thermal class of the insulation system	Reference temperature °C
130 (B)	95
155 (F)	115
180 (H)	135

If the rated temperature rise or the rated temperature is specified as that of a lower thermal class than that used in the construction, the reference temperature shall be that of the lower thermal class.

Motors that are subject to check testing for regulatory purposes are not to be dismantled. In that case, measurement of winding temperature shall be by the change of resistance method;

5.7.3 Correction to reference coolant temperature

If required, the winding resistance values recorded during test shall be referred to a standard reference temperature of 25 °C. The correction factor to adjust the winding resistance (and the slip in the case of cage induction machines) to a standard reference coolant temperature of 25 °C shall be determined by

$$k_\theta = \frac{235 + \theta_w + 25 - \theta_c}{235 + \theta_w} \tag{1}$$

where

k_θ is the temperature correction factor for windings;

θ_c is the primary coolant temperature during test;

θ_w is the winding temperature according to 5.7.2.

The temperature constant 235 is for copper; this should be replaced by 225 for aluminium conductors.

For machines with water as the primary or secondary coolant, the water reference temperature shall be 25 °C according to Table 5 of IEC 60034-1:2022. Alternative values may be specified by agreement.

5.8   State of the machine under test and test categories

Tests shall be conducted on an assembled machine with the essential components in place, to obtain test conditions equal or very similar to normal operating conditions.

For handling of sealing systems for efficiency classification related measurements see IEC 60034-30-1.

It is preferable that the machine be selected randomly from series production without special considerations.

The sub-tests that make up a test procedure shall be performed in the sequence listed. It is not essential that the tests be carried out immediately one after another. However, if the sub-tests are performed with delay, then the specified thermal conditions shall be re-established prior to obtaining the test data.

For machines with adjustable brushes, the brushes shall be placed in the position corresponding to the specified rating. For induction motors with wound rotor having a brush lifting device, the brushes shall be lifted during tests, with the rotor winding short-circuited. For measurements on no-load, the brushes shall be placed in the neutral axis on DC machines.

For machines having brushes, during the rated load test, and prior to any measurement, a visual inspection shall be done to check if the brushes are fully bedded, and a proper skin is developed.

The bearing losses depend on the operating temperatures of the bearings, the type of lubricant and lubricant temperature.

If the losses in a separate lubricating system of bearings are required these should be listed separately.

In the case of motors which are furnished with thrust bearings, only that portion of the thrust bearing loss produced by the motor itself shall be included in the total losses.

Friction losses due to thrust load may be included by agreement.

If the tested machine uses direct flow cooling of the bearings, these losses are distributed between the tested machine and any other one coupled to it mechanically, such as a turbine, in proportion to the masses of their rotating parts. If there is no direct flow cooling, the distribution of bearing losses shall be determined from empirical formulae by agreement.

5.9 Excitation circuit measurements

Determination of voltage U_e and current I_e (see 3.13.3.2) depends on the configurations of the excitation system (see 3.13.3.3). Where applicable, test data shall be recorded according to the following:

a) for machines excited by shaft driven, separate rotating, static and auxiliary winding exciters (see 3.13.3.3 a), c), d) and e)), voltage U_e and current I_e are measured:

   – at the excitation winding terminals of DC machines;

   – at the field winding slip-rings of synchronous machines;

b) for machines excited by brushless exciters (see 3.13.3.3 b)), test data shall be recorded by either of the following methods:

   – voltage U_e measured using auxiliary (provisional) slip-rings connected to the field winding ends. From the voltage and resistance R_e determine the field winding current $I_e = \dfrac{U_e}{R_e} = \dfrac{U_f}{R_f}$. The field winding resistance is to be measured after switching off the machine using the extrapolation procedure according to 5.7.1;

   – voltage U_e and current I_e measured using power slip-rings suitable for direct measurement of field winding current.

NOTE   The difference between U_e and U_f (voltage drop of brushes) is in practice almost negligible.

Voltages and currents shall be measured at stabilized temperatures.

The excitation circuit losses P_e are determined according to 7.1.3.2.1.5 (synchronous machines) or 8.3.2.1.5 (DC machines).

5.10 Ambient temperature during testing

The ambient temperature should be in the range of 15 °C to 40 °C.

6 Test methods for the determination of the efficiency of induction machines

6.1 Preferred testing methods

6.1.1 General

This document defines three different preferred methods with low uncertainty within the given range of application, see Table 2. The specific method to be used depends on the type or rating of the machine under test:

Method 2-1-1A: Direct measurement of input and output power by using a torque measuring device. To be applied for all single phase machines.

Method 2-1-1B: Summation of separate losses. Additional load loss determined by the method of residual loss. To be applied for all three phase machines with rated output power up to 2 MW. See also Annex D.

Method 2-1-1C: Summation of separate losses. Additional load loss determined by the method of assigned value. To be applied for all three phase machines with rated output power greater than 2 MW.

Table 2 – Induction machines: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-1A	**Direct measurement:** **Input-output**	Torque measurement	6.1.2	All single phase machines	Torque measuring device for full-load
2-1-1B	**Summation of losses:** **Residual losses**	P_{LL} determined from residual loss	6.1.3	Three phase machines with rated output power up to 2 MW	Torque measuring device for 1,25 × full-load, or load machine for 1,25 × full-load with torque measuring device
2-1-1C	**Summation of losses:** **Assigned value**	P_{LL} from assigned value	6.1.4	Three phase machines with rated output power greater than 2 MW	

6.1.2   Method 2-1-1A – Direct measurement of input and output

6.1.2.1   General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the stator is measured in the same test.

Input and output power are:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 2);   (2)

in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$ (3)
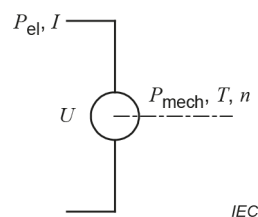
Figure 2 – Sketch for torque measurement test

For an overview, Figure 3 provides a flowchart for efficiency determination by this test method.
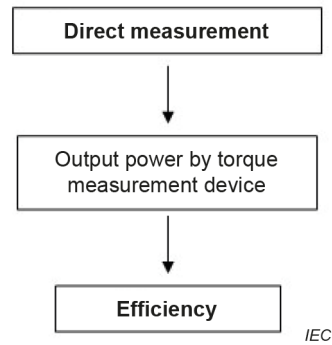
Figure 3 – Efficiency determination according to method 2-1-1A

6.1.2.2   Test procedure

Couple the machine under test to a load machine with torque measuring device. Operate the machine under test at the required load until thermal equilibrium is achieved (rate of change 1 K or less per half hour).

Record U, I, P_{el}, n, T, θ_c.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

6.1.2.3   Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1} \tag{4}$$

Input power P_1 and output power P_2 are:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$; $\tag{5}$

in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$ $\tag{6}$

where

$$P_{mech} = 2\pi \times T \times n \tag{7}$$

6.1.3 Method 2-1-1B – Summation of losses, additional load losses according to the method of residual loss

6.1.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

– iron loss;

– windage and friction losses;

– stator and rotor copper losses;

– additional load losses.

For an overview, Figure 4 provides a flowchart for efficiency determination by this test method.

```
┌─────────────────────────┐
│   Indirect measurement  │
└─────────────────────────┘
             │
             ▼
      ┌──────────────┐
      │ Separate losses │
      └──────────────┘
             │
             ▼
┌───────────────────────────────────────┐
│ Winding resistances at ambient temperature │
└───────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────┐
│    6.1.3.2.1 Rated load test        │
│ Winding resistances at rated load test │
└─────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────┐
│     6.1.3.2.2 Load losses           │
│  Stator and rotor winding losses    │
└─────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────┐
│    6.1.3.2.3 Load curve test        │
│  with measurement of torque, speed  │
│     and winding resistances         │
└─────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────┐
│     6.1.3.2.4 No-load test          │
│  Winding resistances at no-load test │
└─────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────┐
│    6.1.3.2.5 Constant losses        │
│   Friction and windage losses       │
│          Iron losses                │
└─────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────┐
│ 6.1.3.2.6 Additional load losses    │
│       from residual loss            │
└─────────────────────────────────────┘
             │
             ▼
   ┌──────────────────────────┐
   │ 6.1.3.3.1 Total losses   │
   └──────────────────────────┘
             │
             ▼
      ┌──────────────┐
      │  6.1.3.2.2   │
      └──────────────┘
```

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Figure 4 – Efficiency determination according to method 2-1-1B

6.1.3.2   Test procedure

6.1.3.2.1   Rated load test

Before this load test, measure the temperature and the winding resistance of the motor with the motor at ambient temperature.

The machine shall be loaded by suitable means with rated output power and operated until thermal equilibrium is achieved (rate of change 1 K or less per half hour). Record the following quantities:

- P_1, T, I, U, n, f, θ_c, θ;

- $R_N = R$ (the test resistance for rated load according to 5.7.1);

18

— θ (the winding temperature at rated load according to 5.7.2).

Immediately after the load test, the drift of the torque transducer shall be checked. In case of a deviation above the allowed tolerance of the transducer, adjust it and repeat the measurements.

6.1.3.2.2 Load losses

6.1.3.2.2.1 Stator-winding losses and temperature correction

The uncorrected stator-winding losses at rated load are:

$$P_{\text{s}} = 1{,}5 \times I^2 \times R \tag{8}$$

where I and R are determined in 5.7.1.

Determine the stator-winding losses, using the stator winding resistance R_{N} from the rated load test, corrected to a reference coolant temperature of 25 °C:

$$P_{\text{s},\theta} = P_{\text{s}} \times k_{\theta} \tag{9}$$

where k_{θ} is the correction according to 5.7.3 for the stator winding.

6.1.3.2.2.2 Rotor winding losses and temperature correction

For the uncorrected rotor winding losses use the formula:

$$P_{\text{r}} = \left(P_1 - P_{\text{s}} - P_{\text{fe}}\right) \times s \tag{10}$$

where

$$s = 1 - \frac{p \times n}{f} \tag{11}$$

P_1, n and f are according to the rated load test;

P_{s} according to the load test as stated above;

P_{fe} is according to 6.1.3.2.5.

The corrected rotor winding losses are determined using the corrected value of the stator winding losses:

$$P_{\text{r},\theta} = \left(P_1 - P_{\text{s},\theta} - P_{\text{fe}}\right) \times s_{\theta}$$

where

P_{fe} is according to 6.1.3.2.5 for a reference coolant temperature of 25 °C;

$s_{\theta} = s \times k_{\theta}$ is the slip corrected to a reference coolant temperature of 25 °C (see 5.7.3);

k_θ is the correction according to 5.7.3.

6.1.3.2.2.3 Temperature correction of input power (for a motor)

With the corrected stator and rotor winding losses, the corrected input power is:

$$P_{1,\theta} = P_1 - (P_s - P_{s,\theta} + P_r - P_{r,\theta})$$ (12)

6.1.3.2.3 Load curve test

This test shall be carried out immediately after the rated load test with the motor at operating temperature.

If that is not possible, prior to the start of recording data for this test, the temperature rise of the windings shall be within 5 K of the initial temperature rise θ_N, obtained from a rated load temperature test.

Apply the load (shaft power) to the machine at the following six load points: approximately 125 %, 115 %, 100 %, 75 %, 50 % and 25 % of rated load. These tests shall be performed as quickly as possible to minimize temperature changes in the machine during testing.

NOTE 1   As an indication, the applied load may vary by ± 5 % from the figures given above. The impact on the further evaluation of the residual losses is limited.

Supply frequency variation between all points shall be less than 0,1 %.

Measure R before the highest and after the lowest load reading. The resistance for 100 % load and higher loads shall be the value determined before the highest load reading. The resistance used for loads less than 100 % shall then be determined as varying linearly with load, using the reading before the test for the highest load and after the lowest reading for 25 % load.

NOTE 2   Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each load point may then be determined from measured resistance before load curve test multiplied with the ratio of the temperature of the winding at that load point to the temperature of the winding measured before the start of the test.

Record for each load point: U, I, P_1, n, f, T.

The stator-winding losses at each of the load points are:

$$P_s = 1{,}5 \times I^2 \times R$$ (13)

where I and R are determined according to 6.1.3.2.2 for each load point.

For the rotor winding losses for each of the load points use the formula:

$$P_r = (P_1 - P_s - P_{fe}) \times s$$ (14)

where

$$s = 1 - \frac{p \times n}{f} \quad\quad\quad (15)$$

P_1, n and f are according to the load curve test;

P_s is according to the load curve test as stated above;

P_{fe} is according to 6.1.3.2.5.

6.1.3.2.4   No-load test

The no-load test shall be carried out on a hot machine immediately after the load curve test.

Alternatively, the test may also be carried out with stabilized no-load losses. The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at the following eight values of voltage, including rated voltage, so that:

- the values at approximately 110 %, 100 %, 95 % and 90 % of rated voltage are used for the determination of iron losses;
- the values at approximately 60 %, 50 %, 40 % and 30 % of rated voltage are used for the determination of windage and friction losses.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linearly with the electrical power P_0.

For induction machines R_0 is $R_{ll,0}$. Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

NOTE   Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each voltage point may then be determined from measured resistance before no-load test multiplied with the ratio of the temperature of the winding at that load point to the temperature of the winding measured before the start of the test.

For a coupled machine, P_0 is determined from T and n.

6.1.3.2.5   Constant losses

6.1.3.2.5.1   General

Subtracting the no-load winding losses from the no-load input power gives the constant losses that are the sum of the friction, windage and iron losses. Determine the constant losses for each value of voltage recorded.

$$P_c = P_0 - P_s = P_{fw} + P_{fe} \quad\quad\quad (16)$$

where

$$P_s = 1{,}5 \times I_0^2 \times R_{ll,0} \tag{17}$$

with $R_{ll,0}$ being the interpolated winding resistance at each voltage point.

6.1.3.2.5.2   Friction and windage losses

From the four or more consecutive no-load loss points between approximately 60 % of voltage and 30 % of voltage develop a curve of constant losses (P_c) against the voltage squared ($U_0{}^2$).

Extrapolate a straight line to zero voltage. Determine the intercept at zero voltage, which is considered the friction and windage losses P_{fw0} at approximately synchronous speed.

6.1.3.2.5.3   Iron losses

From the values of voltage between approximately 90 % and 110 % of rated voltage, develop a curve of $P_{fe} = P_c - P_{fw}$ against voltage U_0.

To determine the iron losses at full load the inner voltage U_i that takes the resistive voltage drop in the primary winding into account shall be calculated:

$$U_i = \sqrt{\left(U - \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{for a motor} \tag{18}$$

$$U_i = \sqrt{\left(U + \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{for a generator} \tag{19}$$

Where

$$\cos\varphi = \frac{P_1}{\sqrt{3} \times U \times I}; \quad \sin\varphi = \sqrt{1 - \cos^2\varphi} \tag{20}$$

U, P_1, I and R are from the load test according to 6.1.3.2.1.

The iron losses at full load shall be interpolated from the iron losses over voltage U_0 curve at the voltage U_i.

NOTE   The iron losses at full load may be calculated by using the ratio $(U_i/U_N)^2$ applied to the iron losses at no-load.

Because the stator leakage inductance is unknown, the voltage is only considering the resistive voltage drop. Due to the low power factor at no-load, the resistive voltage drop is negligible during the measurement itself and shall only be taken into consideration for the load values.

6.1.3.2.6 Additional load losses P_{LL}

6.1.3.2.6.1 Residual losses P_{Lr}

The residual losses shall be determined for each load point by subtracting from the input power: the mechanical output power, the uncorrected stator winding losses at the resistance of the test, the adjusted iron losses, the corrected windage and friction losses, and the uncorrected rotor winding losses corresponding to the determined value of slip.

The iron losses at each load point shall be interpolated from the iron losses over voltage U_0 curve at the voltage U_i for the respective load point.

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fe} - P_{fw} \; ; \tag{21}$$

$$P_2 = 2\pi \cdot T \cdot n \text{ for a motor and } P_1 = 2\pi \cdot T \cdot n \text{ for a generator.} \tag{22}$$

where

$$P_{fw} = P_{fw0} \cdot (1-s)^{2,5} \text{ with } s = 1 - \frac{p \times n}{f} \tag{23}$$

are the corrected friction and windage losses.

6.1.3.2.6.2 Smoothing of the residual loss data

The residual loss data shall be smoothed by using the linear regression analysis (see Figure 5) based on expressing the losses as a function of the square of the load torque according to the relationship:

$$P_{Lr} = A \times T^2 + B \tag{24}$$

A and B are constants determined from the six load points using the following formulas:

A is the slope according to
$$A = \frac{i \cdot \sum \left(P_{Lr} \cdot T^2 \right) - \sum P_{Lr} \cdot \sum T^2}{i \cdot \sum \left(T^2 \right)^2 - \left(\sum T^2 \right)^2} \tag{25}$$

B is the intercept according to
$$B = \frac{\sum P_{Lr}}{i} - A \cdot \frac{\sum T^2}{i} \tag{26}$$

i is the number of load points summed.

The intercept B should be considerably smaller (< 50 %) than the additional load losses P_{LL} at rated torque. Otherwise the measurement may be erroneous and should be checked.

NOTE   The intercept B may be positive or negative. Figure 5 shows an example for positive intercept B.
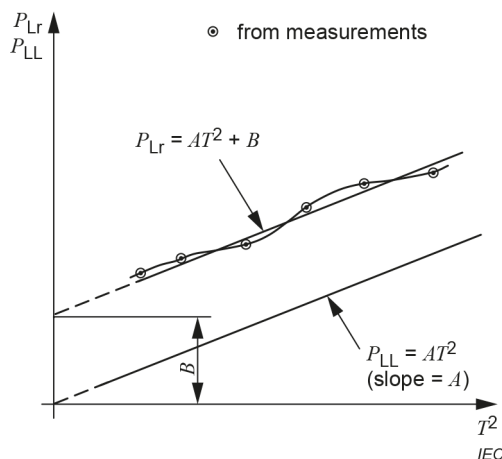
Figure 5 – Smoothing of the residual loss data

The correlation coefficient is calculated as

$$\gamma = \frac{i \cdot \Sigma\left(P_{Lr} \cdot T^2\right) - \left(\Sigma P_{Lr}\right) \cdot \left(\Sigma T^2\right)}{\sqrt{\left(i \cdot \Sigma\left(T^2\right)^2 - \left(\Sigma T^2\right)^2\right) \cdot \left(i \cdot \Sigma P_{Lr}^2 - \left(\Sigma P_{Lr}\right)^2\right)}} \tag{27}$$

If the correlation coefficient γ is less than 0,95, delete the worst point and repeat the regression. If γ increases to ≥ 0,95, use the second regression; if γ remains less than 0,95, the test is unsatisfactory and errors in the instrumentation or test readings, or both, are indicated. The source of the error should be investigated and corrected, and the test should be repeated. In case of sufficient test data, a correlation coefficient of 0,98 or better is likely.

If the slope constant A is established, a value of additional load losses for each load point shall be determined by using the formula:

$$P_{LL} = A \times T^2 \tag{28}$$

6.1.3.3   Efficiency determination

6.1.3.3.1   Total losses

The total losses shall be taken as the sum of the adjusted iron losses, the corrected friction and windage losses, the load losses and the additional load losses:

$$P_T = P_{fe} + P_{fw} + P_{s\,\theta} + P_{r\,\theta} + P_{LL}, \tag{29}$$

where

24

$$P_{fw} = P_{fw0} \cdot (1 - s_\theta)^{2,5} \qquad (30)$$

are the corrected friction and windage losses.

6.1.3.3.2 Efficiency

The efficiency is determined from

$$\eta = \frac{P_{1,\theta} - P_T}{P_{1,\theta}} = \frac{P_2}{P_2 + P_T} \qquad (31)$$

NOTE   Usually, the first expression is preferred for a motor, the second one for a generator.

where

$P_{1,\theta}$ is the temperature corrected input power from the rated load test;

P_2 is the output power from the rated load test.

6.1.4 Method 2-1-1C – Summation of losses with additional load losses from assigned allowance

6.1.4.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. For the reason that full load testing as required by method 2-1-1B is in general not practical for ratings above 2 MW, this method is based on a load test with reduced voltage and an assigned value for the additional load losses. Therefore the full load test and the load curve test are not required for method 2-1-1C.

Apart from this, method 2-1-1C is similar to method 2-1-1B.

For an overview, Figure 6 provides a flowchart for efficiency determination by this test method.

```
                    ┌─────────────────────────┐
                    │  Indirect measurement   │
                    └─────────────────────────┘
                                 │
                                 ▼
                       ┌──────────────────┐
                       │ Separate losses  │
                       └──────────────────┘
                                 │
                                 ▼
              ┌──────────────────────────────────────┐
              │ Winding resistance at ambient temperature │
              └──────────────────────────────────────┘
                                 │
                                 ▼
              ┌──────────────────────────────────────┐
              │ 6.1.4.2.1 Load test at reduced voltage │
              └──────────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────────┐
            │        6.1.4.2.2 Load losses          │
            │  Stator and rotor winding losses      │
            │  including temperature correction     │
            └──────────────────────────────────────┘
                                 │
                                 ▼
              ┌──────────────────────────────┐
              │    6.1.4.2.3 No-load test     │
              └──────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────────┐
            │      6.1.4.2.4 Constant losses        │
            │    Friction and windage losses        │
            │            Iron losses                │
            └──────────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────────┐
            │   6.1.4.2.5 Additional load losses    │
            │        from assigned value            │
            └──────────────────────────────────────┘
                                 │
                                 ▼
              ┌──────────────────────────────┐
              │    6.1.4.3.1 Total losses     │
              └──────────────────────────────┘
                                 │
                                 ▼
              ┌──────────────────────────────┐
              │     6.1.4.3.2 Efficiency      │
              └──────────────────────────────┘
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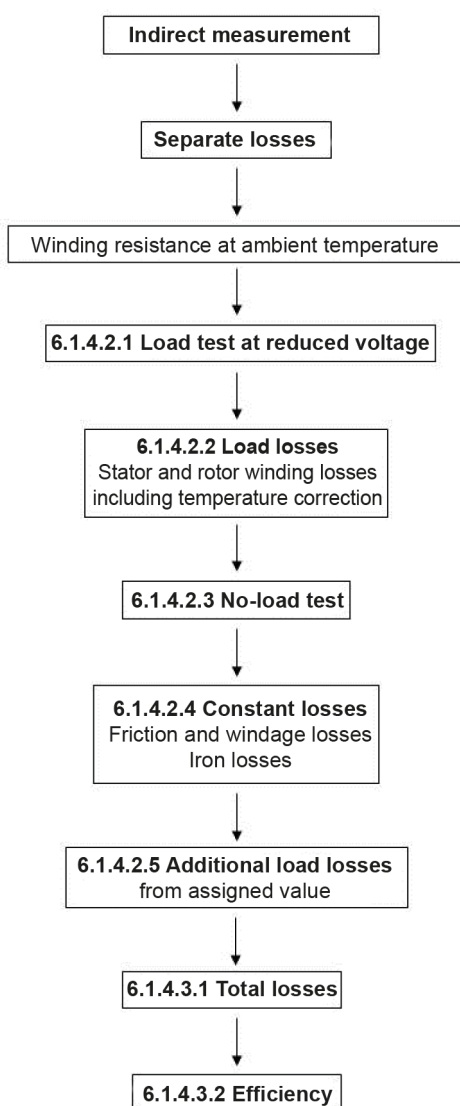
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Figure 6 – Efficiency determination according to method 2-1-1C

6.1.4.2   Test procedure

6.1.4.2.1   Load test at reduced voltage

For large machines which cannot be tested at full load, the load test at reduced voltage is an appropriate method. The following are required: a load test with the machine acting as a motor at reduced voltage U_{red} at rated speed, a no-load test at the same reduced voltage U_{red}, and a no-load test at rated voltage and rated frequency.

Using this method, it is assumed that at reduced voltage, while keeping the speed constant, currents diminish as the voltage and power diminishes as the square of the voltage.

Operate the machine using the maximum available load with a decrease in voltage to achieve rated speed. Operate to achieve thermal equilibrium.

At reduced voltage, record: U_{red}, I_{red}, P_{1red}, I_{0red}, $\cos(\varphi_{0red})$.

At rated voltage and no-load, record: U_N, I_0, $\cos(\varphi_0)$.

From the result of such a test calculate the current under load and the absorbed power at rated voltage:

$$\underline{I} = \underline{I}_{\text{red}} \frac{U_{\text{N}}}{U_{\text{red}}} + \Delta \underline{I}_0 \tag{32}$$

where

$$\Delta \underline{I}_0 = -j(\left|\underline{I}_0\right| \sin \varphi_0 - \left|\underline{I}_{0,\text{red}}\right| \frac{U_{\text{N}}}{U_{\text{red}}} \sin \varphi_{0,\text{red}}) \tag{33}$$

$$P_1 = P_{1,\text{red}} \times \left(\frac{U_{\text{N}}}{U_{\text{red}}}\right)^2 \tag{34}$$

NOTE   Underlined current symbols indicate vectors (see Figure 7).

By means of the values I and P_1 thus determined, and with the slip measured at reduced voltage, it is possible to calculate the load losses, similar to a load test at rated voltage.
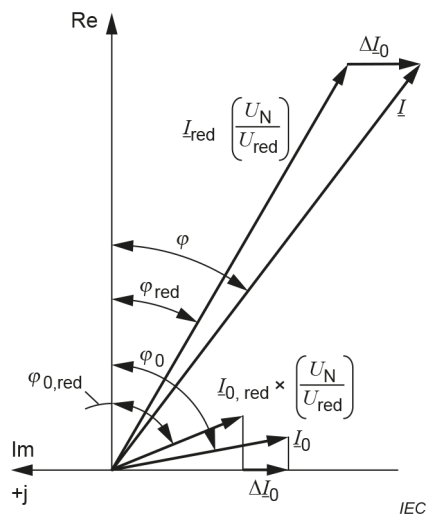
Figure 7 – Vector diagram for obtaining current vector from reduced voltage test

6.1.4.2.2   Load losses

The determination of load losses is similar to 6.1.3.2.2.

6.1.4.2.3   No-load test

The no-load test shall be carried out on a hot machine immediately after the load test.

The no-load test is similar to 6.1.3.2.4.

6.1.4.2.4 Constant losses

The determination of the constant losses is similar to 6.1.3.2.5.

6.1.4.2.5 Additional load losses P_{LL}

The value of additional load losses P_{LL} at rated load shall be determined as a percentage of input power P_1 using the curve in Figure 8.
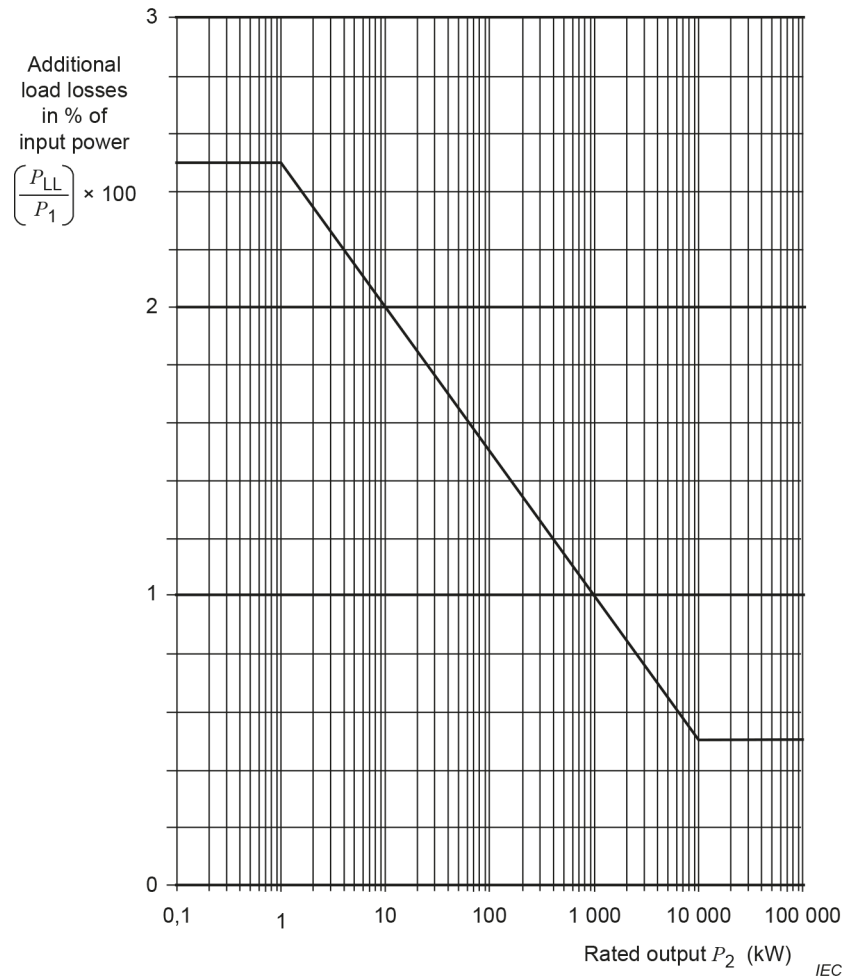
Figure 8 – Assigned allowance for additional load losses P_{LL}

The values of the curve may be described by the following formulas:

for $P_2 \leq 1$ kW $\qquad\qquad\qquad\qquad P_{LL} = P_1 \times 0{,}025$

for 1 kW $< P_2 <$ 10 000 kW $\qquad P_{LL} = P_1 \times \left[0{,}025 - 0{,}005 \log_{10}\left(\dfrac{P_2}{1\,\text{kW}} \right) \right]$

for $P_2 \geq 10\,000$ kW $\qquad\qquad\qquad P_{LL} = P_1 \times 0{,}005$

For other than rated loads, it shall be assumed that the additional load losses vary as the square of the primary current minus the square of the no-load current:

$$P_{\text{LL}}(I) = P_{\text{LL}}(I_{\text{N}}) \times \frac{I^2 - I_0^2}{I_{\text{N}}^2 - I_{0\text{N}}^2}$$

NOTE   The curve does not represent an average but an upper envelope of a large number of measured values, and may in most cases yield greater additional load losses than 6.1.3.

6.1.4.3   Efficiency determination

6.1.4.3.1   Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_{\text{T}} = P_{\text{c}} + P_{\text{s}} + P_{\text{r}} + P_{\text{LL}} \tag{35}$$

6.1.4.3.2   Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_{\text{T}}}{P_1} = \frac{P_2}{P_2 + P_{\text{T}}} \tag{36}$$

NOTE   Usually, the first expression is preferred for a motor, the second one for a generator.

6.2   Testing methods for field or routine-testing

6.2.1   General

These test methods may be used for any test, i.e. field-tests, customer-specific acceptance tests or routine-tests.

In addition, preferred methods of Table 2 may also be used outside the power range identified in Table 2.

Methods defined by this document are given in Table 3.

Table 3 – Induction machines: other methods

Reference	Method	Description	Subclause	Required facility
2-1-1D	Dual-supply-back-to-back	Dual-supply, back-to-back test	6.2.2	Machine set for full-load; two identical units
2-1-1E	Single-supply-back-to-back	Single-supply, back-to-back test	6.2.3	Two identical units (wound rotor)
2-1-1F	Reverse rotation	P_{LL} from removed rotor and reverse rotation test	6.2.4	Auxiliary motor with rated power up to 5 × total losses
2-1-1G	Eh-star	P_{LL} from Eh-star test	6.2.5	Winding shall be connected in star connection.
2-1-1H	Equivalent circuit	Currents, powers and slip from the equivalent circuit method, P_{LL} from assigned value	6.2.6	If test equipment for other tests is not available (no possibility of applying rated load, no duplicate machine)

6.2.2   Method 2-1-1D – Dual supply back-to-back-test

6.2.2.1   General

For an overview, Figure 9 provides a flowchart for efficiency determination by this test method.

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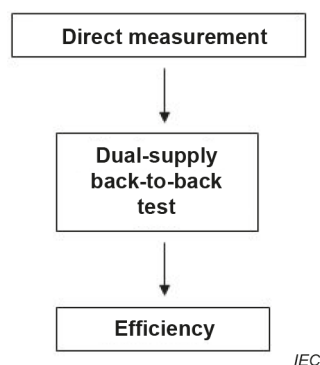
Figure 9 – Efficiency determination according to method 2-1-1D

6.2.2.2   Test procedure

Mechanically, couple two identical machines together (see Figure 10).

Tests are made with the power supplies exchanged but with the instruments and instrument transformers remaining with the same machine.

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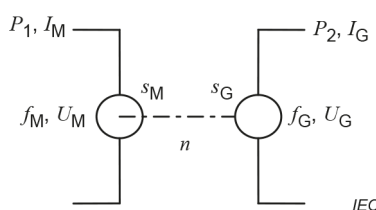
Figure 10 – Sketch for dual supply back-to-back test

Connect the driven machine (induction generator) terminals to either a machine set or a converter, supplying reactive power and absorbing active power. Supply one machine (the motor for motor rating, the generator for generator rating) with rated voltage and frequency; the second one shall be supplied with a frequency lower than that of the first machine for generator operation or higher for motor operation. The voltage of the second machine shall be that required to result in the rated voltage-to-frequency ratio.

Reverse the motor and generator connections and repeat the test.

For each test, record:

- U_M, I_M, P_1, f_M, s_M for the motor;

- U_G, I_G, P_2, f_G, s_G for the generator;

- θ_c.

6.2.2.3 Efficiency determination

If identical machines are run at essentially the same rated conditions, the efficiency shall be calculated from half the total losses and the average of motor input power and generator output power as follows:

$$\eta = 1 - \frac{P_T}{\dfrac{P_1 + P_2}{2}} \tag{37}$$

where

$$P_T = \frac{1}{2}(P_1 - P_2) \tag{38}$$

6.2.3 Method 2-1-1E – Single supply back-to-back-test

6.2.3.1 General

For an overview, Figure 11 provides a flowchart for efficiency determination by this test method.
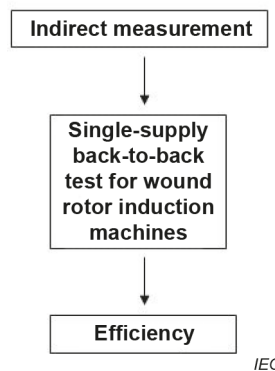
Figure 11 – Efficiency determination according to method 2-1-1E

6.2.3.2 Test procedure

This test is applicable to wound-rotor induction machines. Mechanically couple two identical machines together and connect them both electrically to the same power supply so as to operate at rated speed and rated voltage, one as a motor and the other as a generator.

The rotor winding of the motor shall be short-circuited and the rotor winding of the generator shall be connected to a polyphase supply suitable to deliver rated rotor current at slip-frequency. The desired motor-power will be achieved by adjusting frequency and current of the lower frequency power supply.

For each test, record:

- U_1, P_1, I_1 of the power-frequency supply;
- U_r, I_r, P_r of the low-frequency supply;
- P_M absorbed at the motor terminals;
- P_G delivered at the generator terminals;
- θ_c.

6.2.3.3 Efficiency determination

If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M} \tag{39}$$

where

P_M is the power absorbed at the terminals of the machine acting as motor;

P_T is the total losses, defined as half the total absorbed, for wound-rotor induction machines

as follows: $P_T = \frac{1}{2}\left(P_1 + P_r\right)$

6.2.4 Method 2-1-1F – Summation of losses with additional load losses determined by test with rotor removed and reverse rotation test

6.2.4.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. But in this case the additional load losses are determined by a combination of two individual tests: the test with rotor removed and the reverse rotation test. Apart from that, method 2-1-1F is similar to method 2-1-1B.

For an overview, Figure 12 provides a flowchart for efficiency determination by this test method.

```
┌─────────────────────────┐
│  Indirect measurement   │
└─────────────────────────┘
             │
             ▼
   ┌───────────────────┐
   │  Separate losses  │
   └───────────────────┘
             │
             ▼
┌───────────────────────────────────────┐
│ Winding resistance at ambient temperature │
└───────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────────┐
│     6.1.3.2.1 Rated load test            │
│  Winding resistance at rated load test   │
└─────────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────────┐
│     6.1.3.2.2 Load losses                │
│   Stator and rotor winding losses        │
└─────────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────────┐
│     6.1.3.2.4 No-load test               │
│  Winding resistances at no-load test     │
└─────────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────────┐
│     6.1.3.2.5 Constant losses            │
│  Friction and windage losses             │
│  Iron losses                             │
└─────────────────────────────────────────┘
             │
             ▼
┌─────────────────────────────────────────┐
│   6.2.4.2 Additional load losses         │
│  from test with rotor removed and        │
│  reverse rotation test                   │
└─────────────────────────────────────────┘
             │
             ▼
   ┌───────────────────────┐
   │ 6.2.4.3.2 Total losses │
   └───────────────────────┘
             │
             ▼
   ┌─────────────────────────┐
   │  6.2.4.3.3 Efficiency   │
   └─────────────────────────┘
```

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Figure 12 – Efficiency determination according to method 2-1-1F

6.2.4.2   Test procedure

Apart from the determination of the additional load losses, the same procedures as in 6.1.3.2 shall be applied, except that the torque does not need to be measured.

The required combination of tests for the determination of the additional load losses is as follows:

a) with the rotor removed (for the fundamental frequency additional losses);

b) with the machine rotating at synchronous speed opposite to the magnetic field, driven by external means (for the higher frequencies losses).

During both tests, the stator shall be supplied by a balanced polyphase current of rated frequency for four currents between 25 % and 100 % rated current, and two currents above and of not more than 150 % rated current. Calculate the (rotor) load current I_L:

$$I_L = \sqrt{I^2 - I_0^2} \qquad (40)$$

where

I is the value of stator current during the test giving a desired load current;

I_0 is the no-load current at rated voltage.

NOTE   Due to lack of cooling, the current is usually limited to 125 % or 115 % for 2-pole machines to reduce the risk of overheating.

6.2.4.2.1   Test with the rotor removed

For this test, all parts in which eddy currents might be induced, for example end shields and bearing parts, shall be in place. Apply load current.

For each load current, record (symbols indexed "rm"): $P_{1,rm}$, $I_{L,rm}$, R_{rm}, $\theta_{w,rm.}$.

6.2.4.2.2   Reverse-rotation test

For this test, couple a completely assembled machine to a driving motor with an output capability of not less than rated total loss and not more than five times the rated losses of the machine to be tested. For wound-rotor machines, the rotor terminals shall be short-circuited.

Drive the machine under test at synchronous speed in the direction reverse to the rotation when fed in normal phase sequence:

a) without voltage applied to the stator until friction losses are stabilized. Record: $P_{0,rr}$ supplied by the driving machine at $I = 0$;

b) with voltage applied to the stator to obtain stator current values equal to those for the test with rotor removed. For all test currents, record (symbols indexed "rr"): $I_{L,rr}$, R_{rr}, $P_{1,rr}$; $\theta_{w,rr}$ for the test motor; $P_{D,rr}$ of the drive motor.

The low power factor of the tests may require a phase error correction to all wattmeter readings.

6.2.4.3   Efficiency determination

6.2.4.3.1   Additional load losses

Smooth the test values of the stator powers $P_{1,rm}$ and $P_{1,rr}$, and the shaft power $\left(P_{D,rr} - P_{0,rr}\right)$ by applying a regression analysis to the log of powers and currents, resulting in the relationships below:

$$P_{1,rm} = A_{rm} \times I^{N1} + B_{L,rm}; \quad P_{1,rr} = A_{rr} \times I^{N2} + B_{L,rr}; \quad \left(P_{D,rr} - P_{0,rr}\right) = A_{D,rr} \times I^{N3} + B_{D,rr} \qquad (41)$$

The smoothed powers will then be as follows:

$$P_{1,rm} = A_{rm} \times I^{N1}; \quad P_{1,rr} = A_{rr} \times I^{N2}; \quad \left(P_{D,rr} - P_{0,rr}\right) = A_{D,rr} \times I^{N3} \qquad (42)$$

If the data are accurate, each curve will show a close square-law relationship between power and current.

The additional load losses are: $P_{LL} = P_{LL,rm} + P_{LL,rr}$ where for each test current:

$$P_{LL,rm} = P_{1,rm} - \left(3 \times I^2 \times R_{s,rm}\right) \quad \text{is the fundamental frequency loss} \tag{43}$$

where

$R_{s,rm}$ is the stator phase resistance referred to the average of the temperatures $\theta_{W,rm}$;

$P_{LL,rr} = \left(P_{D,rr} - P_{0,rr}\right) - \left(P_{1,rr} - P_{LL,rm} - \left(3 \times I^2 \times R_{s,rr}\right)\right)$ is the higher frequencies loss

where

$R_{s,rr}$ is the stator phase resistance referred to the average of the temperatures $\theta_{W,rr}$.

The additional load loss at a specified operating point can be determined in the following steps.

a) Calculate an approximate value for the rated load current I_{NL} corresponding to the rated value of stator line current:

$$I_{NL} = \sqrt{I_N^2 - I_0^2} \tag{44}$$

where

I_N is the rated value of stator line current;

I_0 is the value of no-load stator current.

For the value of load current I_{NL}, calculate a rated value of stray load loss P_{NLL} as follows:

$$P_{NLL} = A_{Drr} \times I_{NL}^{N3} + 2A_{rm} \times I_{NL}^{N1} - A_{rr} \times I_{NL}^{N2} - 6I_{NL}^2 \times \left(R_{srm} - 0{,}5R_{srr}\right) \tag{45}$$

b) Calculate the value of load current I_L at any operating point:

$$I_L = \sqrt{I^2 - I_0^2} \tag{46}$$

where

I is the stator line current at the operating point.

c) Calculate the stray load loss P_{LL} at the operating point:

$$P_{LL} = P_{NLL} \times \left(\frac{I_L}{I_{NL}}\right)^2 \tag{47}$$

6.2.4.3.2 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_T = P_c + P_s + P_r + P_{LL} \qquad (48)$$

6.2.4.3.3 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_T}{P_1} = \frac{P_2}{P_2 + P_T} \qquad (49)$$

where

P_1 is the input power from a rated load test;

P_2 is the output power.

6.2.5 Method 2-1-1G – Summation of losses with additional load losses determined by Eh-star method

6.2.5.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. But in this case the additional load losses are determined by the Eh-star test. Apart from that, method 2-1-1G is similar to method 2-1-1B.

For an overview, Figure 13 provides a flowchart for efficiency determination by this test method.

```
                    Indirect measurement
                            │
                            ▼
                      Separate losses
                            │
                            ▼
          Winding resistance at ambient temperature
                            │
                            ▼
              6.1.3.2.1 Rated load test
           Winding resistance at rated load test
                            │
                            ▼
                 6.1.3.2.2 Load losses
              Stator and rotor winding losses
                            │
                            ▼
                6.1.3.2.4 No-load test
            Winding resistances at no-load test
                            │
                            ▼
              6.1.3.2.5 Constant losses
             Friction and windage losses
                    Iron losses
                            │
                            ▼
            6.2.5.2 Additional load losses
                 from Eh-star test
                            │
                            ▼
               6.2.5.3.3 Total losses
                            │
                            ▼
               6.2.5.3.4 Efficiency
```

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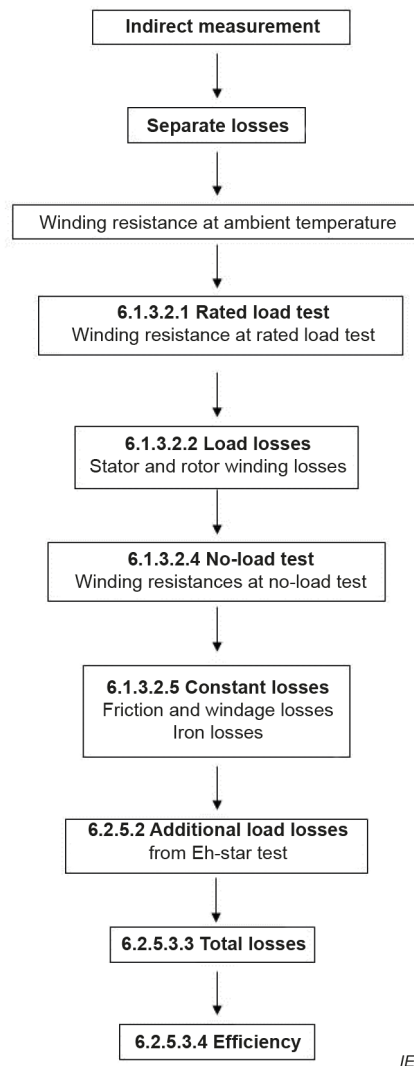
Figure 13 – Efficiency determination according to method 2-1-1G

6.2.5.2   Test procedure

Apart from the determination of the additional load losses, the same procedures as in 6.1.3.2 shall be applied.

The procedure for the determination of the additional load losses requires operating the uncoupled motor with unbalanced voltage supply. The test circuit is according to Figure 14.

Motors rated for and connected in delta-connection shall be reconnected to star-connection during this test. The star-point shall not be connected to system neutral or earth, to avoid zero-sequence currents.

The third motor-phase shall be connected to the power-line by means of a resistor R_{eh} (see Figure 14) having approximately the following typical value:

for motors rated for star-connection: $R'_{eh} = \dfrac{U_N}{\sqrt{3} \cdot I_N} \cdot 0,2$ (50)

for motors rated for delta-connection:
$$R'_{eh} = \frac{\sqrt{3} \cdot U_N}{I_N} \cdot 0,2 \qquad (51)$$

The resistor R_{eh} used during the test shall be adjusted so that the positive sequence current $I_{(1)}$ stays below 30 % of negative sequence current $I_{(2)}$ and the speed stays in the range of typical motor speeds near rated speed (see below). It is recommended to begin the test with an actual resistor R_{eh} that differs no more than 20 % from the typical value R'_{eh}.
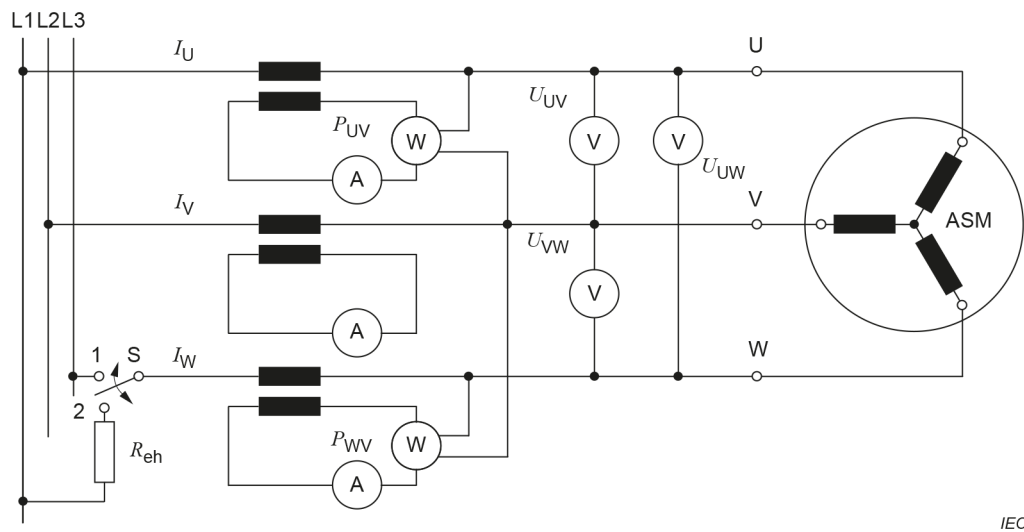
Figure 14 – Eh-star test circuit

Test current I_t is given by

for motors rated for star-connection:
$$I_t = \sqrt{I_N^2 - I_0^2} \qquad (52)$$

for motors rated for delta-connection:
$$I_t = \frac{\sqrt{I_N^2 - I_0^2}}{\sqrt{3}} \qquad (53)$$

Test voltage U_t is given by

for motors rated for star-connection:
$$U_t = U_N \qquad (54)$$

for motors rated for delta-connection:
$$U_t = U_N \cdot \sqrt{3} \qquad (55)$$

Prior to the test the no-load losses have to be stabilised according to 6.1.3.2.4.

Measure and record the resistance between the terminals V and W (R_{VW}) before and after the complete test.

In order to avoid excessive unequal heating of the three phases, the test shall be conducted on a cold machine and carried out as quickly as possible.

Large motors can only be started without the R_{eh} resistor (switch S to position 1, see Figure 14) at reduced voltage (25 % − 40 % U_N). After run-up connect R_{eh} by switching to position 2.

Small motors should start-up with resistor R_{eh} already connected. In this case, the switch is not needed.

Vary the supply voltage for six test points. The test points shall be chosen to be approximately equally spaced between 150 % and 75 % of rated phase current measured in phase V (I_V). When starting the test, begin with the highest current and proceed in descending order to the lowest current.

The line-to-line resistance R_{VW} for 100 % test current and lower currents shall be the value determined after the lowest reading (at the end of the test). The resistance used for currents higher than 100 % shall be determined as being a linear function of current, using the readings before and after the complete test. The test resistance is determined using the extrapolation according to 5.7.1.

Record for each test point: I_U, I_V, I_W, U_{UV}, U_{VW}, U_{WU}, P_{UV}, P_{WV}, n .

It is understood that in this test no averaging of phase resistances is permissible.

NOTE   Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each load point may then be determined from the temperature of the winding at that point in relation to the resistance and temperature measured before the start of the test.

Some commonly used integrated wattmeters symmetrize the three phases by an internal virtual star connection. However, in this test the power supply is intentionally unsymmetrical. Therefore, it is essential to ensure that neither earthing of the star point nor a virtual star point is established. The provided test circuit (see Figure 14) should be strictly applied.

In order to achieve accurate results the slip shall be not greater than twice the rated slip for all currents, in other words: $n > n_{syn} − 2·(n_{syn} − n_N)$. If this condition cannot be met the test shall be repeated with an increased value of R_{eh}. If the motor still runs unstable at currents below 100 % of rated phase current these test points should be omitted.

6.2.5.3   Efficiency determination

6.2.5.3.1   Additional load losses

For each test point calculate the values using the formulas in Annex A.

6.2.5.3.2   Smoothing of the additional-load loss data

The additional-load loss data shall be smoothed by using the linear regression analysis (see Figure 5).

The losses shall be expressed as a function of the square of the negative sequence current $I_{i(2)}$ related to test current I_t:

$$P_{\mathrm{Lr}} = A \cdot \left(\frac{I_{\mathrm{i}(2)}}{I_{\mathrm{t}}} \right)^2 + B \qquad (56)$$

A and B shall be computed similar to the procedure described in 6.1.3.2.6.

When the slope constant A is established, the value of additional load losses for rated load shall be determined by using the formula $P_{\mathrm{LL}} = A \times T^2$.

6.2.5.3.3 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_{\mathrm{T}} = P_{\mathrm{c}} + P_{\mathrm{s}} + P_{\mathrm{r}} + P_{\mathrm{LL}} \qquad (57)$$

6.2.5.3.4 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_{\mathrm{T}}}{P_1} = \frac{P_2}{P_2 + P_{\mathrm{T}}} \qquad (58)$$

NOTE   Usually, the first expression is preferred for a motor, the second one for a generator.

where

P_1 is the input power from a rated load test;

P_2 is the output power.

6.2.6 Method 2-1-1H – Determination of efficiency by use of the equivalent circuit parameters

6.2.6.1 General

This method may be applied if a load test is not possible. It is based on the conventional T-model per-phase circuit of an induction machine, including an equivalent iron-loss resistor parallel to the main field reactance (see Figure 15). The rotor side parameters and quantities are referred to the stator side; this is indicated by the presence of an apostrophe ' at the symbols for example $X'_{\sigma\mathrm{r}}$.
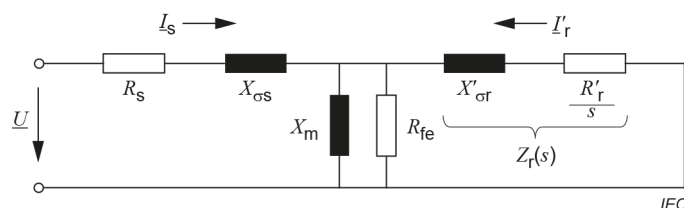

Figure 15 – Induction machine, T-model with equivalent iron loss resistor

Application of the method to cage induction machines requires the following designed values to be available.

- $\dfrac{X_{\sigma s}}{X'_{\sigma r}}$ ratio of stator leakage reactance to rotor leakage reactance.

- α_r temperature coefficient of the rotor windings (conductivity referred to 0 °C).

- $X_{\sigma s}, X_m$ stator leakage and magnetizing reactances.

NOTE 1   When using the equivalent circuit method, all voltages, currents and impedances are per phase values for a three-phase machine in Y-connection; active and reactive powers are per complete machine.

NOTE 2   For copper α_r = 1/235 and for aluminium α_r = 1/225.

For an overview, Figure 16 provides a flowchart for efficiency determination by this test method.
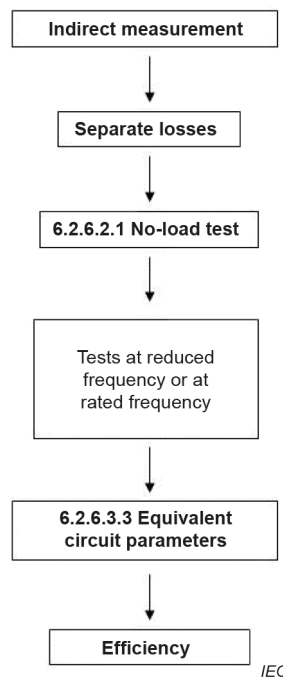
Figure 16 – Efficiency determination according to method 2-1-1H

6.2.6.2   Test procedure

6.2.6.2.1   No-load test

The no-load losses shall be stabilized at rated frequency and voltage.

The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

6.2.6.2.2   Tests at reduced frequency

With the rotor of the machine locked, supply power from a three-phase, adjustable-frequency converter capable of furnishing up to 25 % of the rated frequency at rated current. An average value of impedance shall be obtained from the position of the rotor relative to the stator.

During the tests the frequency converter, either a machine set or a static converter, should supply practically sinusoidal current at the output.

The rotor windings of wound-rotor machines should be short-circuited for the test.

Supply rated current and take readings for at least three frequencies, including one at less than 25 % and the others between 25 % and 50 % rated frequency. During this quick test the stator winding temperature increase should not exceed 5 K.

For at least three frequencies, record: U, I, f, P_1, R_s, θ_c, θ_w.

6.2.6.2.3   Tests at rated frequency

Impedance values can also be determined from the following tests.

a) Reactance from a rated frequency, reduced voltage, rated current locked rotor test: record voltage, current, power, frequency and temperatures.

b) Rotor running resistance:

1) from a stabilized rated frequency, rated voltage reduced load test. Record voltage, power, current, slip and temperatures for the load point; or

2) from an open-circuit test, following a stabilized rated frequency, rated voltage no-load operation. Record the open-circuit voltage and winding temperature as a function of time after the motor is tripped from a no-load test.

NOTE   This test assumes relatively low current displacement in the rotor.

6.2.6.3   Efficiency determination

6.2.6.3.1   Values from measurements

The method is based on the T-model circuit (see Figure 15).

NOTE   When using the equivalent circuit method, all voltages, currents and impedances are per phase values for a three-phase machine in Y-connection; active powers and reactive powers are per complete machine.

The procedure described in this subclause is based on the test with reduced frequency. When using the test with rated frequency notice the following deviations:

a) the reactances are calculated in the same manner as in the following;

b) the rotor running resistance is determined:

– using the test at rated frequency described in b) by reverse calculation using the equivalent circuit in Figure 15, assuming a value for R_r'. Adjust the value of R_r' until the calculated power is within 0,1 % of the measured power, or the calculated current is within 0,1 % of the measured current;

– using the test at rated frequency described in b) by determining the time constant from the slope of the plot of the decaying voltage and the time on the open-circuit test. Determine R_r' from the formula:

$$R_r' = \frac{\left(X_m + X_{\sigma r}'\right)}{2\pi f \tau_0}$$

(59)

where

X_m is the magnetizing reactance;

$X'_{\sigma r}$ is the rotor leakage reactance;

f is the line frequency;

τ_0 is the open-circuit time constant.

Correct the value of R_r' to the operating temperature from the test temperature.

6.2.6.3.2 Determine the reactive powers

– from the no-load test at rated voltage $U_0 = U_N$ and rated frequency

$$P_{Q,0} = \sqrt{(3U_0 I_0)^2 - P_0^2} \tag{60}$$

– from the locked rotor test at reduced frequency

$$P_{Q,lr} = \sqrt{(3U\,I)^2 - P_1^2} \tag{61}$$

where

U_0, I_0 and P_0 are phase voltage, phase current and supplied power from the no-load test at rated terminal voltage;

U, I and P_1 are phase voltage, phase current and supplied power from the locked rotor impedance test at the frequencies f of this test.

6.2.6.3.3 Equivalent circuit parameters

6.2.6.3.3.1 General

The equivalent circuit parameters are determined in the following steps.

6.2.6.3.3.2 Reactances

Calculate the reactances X_m from the no-load test and $X_{\sigma s,lr}$ from the locked-rotor test at 25 % rated frequency:

$$X_m = \frac{3U_0^2}{P_{Q,0} - 3I_0^2 X_{\sigma s}} \times \frac{1}{\left(1 + \dfrac{X_{\sigma s}}{X_m}\right)^2} \qquad X_{\sigma s,lr} = \frac{P_{Q,lr}}{3I^2 \left(1 + \dfrac{X_{\sigma s}}{X'_{\sigma r}} + \dfrac{X_{\sigma s}}{X_m}\right)} \times \left(\frac{X_{\sigma s}}{X'_{\sigma r}} + \frac{X_{\sigma s}}{X_m}\right) \tag{62}$$

$$X_{\sigma s} = \frac{f_N}{f_{lr}} X_{\sigma s,lr} \qquad X'_{\sigma r} = \frac{X_{\sigma s}}{X_{\sigma s} / X'_{\sigma r}} \tag{63}$$

Calculate using designed values as start values.

$$X_{\sigma s}, X_m \text{ and } \frac{X_{\sigma s}}{X'_{\sigma r}} \tag{64}$$

Recalculate until X_m and $X_{\sigma s}$ deviate less than 0,1 % from the values of the preceding step.

6.2.6.3.3.3 Iron loss resistance

Determine the resistance per phase equivalent to the iron losses at rated voltage from

$$R_{fe} = \frac{3U_{N,ph}^2}{P_{fe}} \times \frac{1}{\left(1 + \dfrac{X_{\sigma s}}{X_m}\right)^2}$$

(65)

where

P_{fe} is the iron losses according to the procedure given in 6.1.3.2.5 from P_0 at rated voltage.

6.2.6.3.3.4 Rotor resistance

Determine the uncorrected rotor resistance for each locked rotor impedance test point:

$$R_{r,lr}^{'} = \left(\frac{P_1}{3I^2} - R_s\right) \times \left(1 + \frac{X_{\sigma r}^{'}}{X_m}\right)^2 - \left(\frac{X_{\sigma r}^{'}}{X_{\sigma s}}\right)^2 \times \frac{X_{\sigma s.lr}^2}{R_{fe}}$$

(66)

where

R_s is the stator winding resistance per phase at the corresponding temperature θ_W.

NOTE   If the rotor winding temperature deviates much from the stator winding temperature the method will become inaccurate.

The rotor resistance corrected to reference temperature (see 5.7.2, and Table 1) is, for each locked rotor impedance test frequency, given by

$$R_{r,lr}^{''} = R_{r,lr}^{'} \times \frac{1 + \alpha_r \theta_{ref}}{1 + \alpha_r \theta_W}$$

(67)

Plot a curve of $R_{r,lr}^{''}$ values against frequency f_{lr}. The intercept with $f_{lr} = 0$ results in the stator referred rotor resistance $R_r^{'}$.
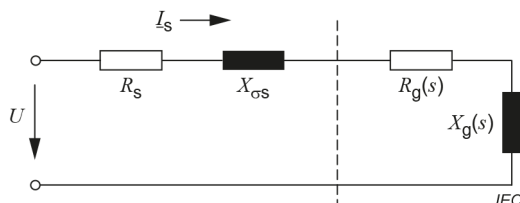
Figure 17 – Induction machines, reduced model for calculation

6.2.6.3.3.5 Load dependent impedances

For each desired load point intermediate, calculate slip dependent impedance and admittance values (see Figure 17):

$$Z_r = \sqrt{\left(\frac{R_r'}{s}\right)^2 + X_{\sigma r}'^2} \qquad Y_g = \sqrt{\left(\frac{R_r'/s}{Z_r^2} + \frac{1}{R_{fe}}\right)^2 + \left(\frac{X_{\sigma r}'}{Z_r^2} + \frac{1}{X_m}\right)^2}$$

$$R_g = \frac{\dfrac{R_r'/s}{Z_r^2} + \dfrac{1}{R_{fe}}}{Y_g^2} \qquad X_g = \frac{\dfrac{X_{\sigma r}'}{Z_r^2} + \dfrac{1}{X_m}}{Y_g^2} \tag{68}$$

Calculate the resulting impedance seen from the terminals:

$$R = R_s + R_g \qquad X = X_{\sigma s} + X_g \qquad Z = \sqrt{R^2 + X^2} \tag{69}$$

where

s is the estimated slip;

R_s is the stator winding resistance per phase at reference temperature θ_{ref}.

6.2.6.3.4   Currents and losses

The performance values are determined in the following steps. Determine:

$I_s = \dfrac{U_N}{Z}$ stator phase current; $I_r' = I_s \dfrac{1}{Y_g Z_r}$ rotor phase current;

$P_\delta = 3 I_r'^2 \dfrac{R_r'}{s}$ air gap power transferred to the rotor; $P_{fe} = 3 I_s^2 \dfrac{1}{Y_g^2 R_{fe}}$ iron loss;

$P_s = 3 I_s^2 R_s$; $P_r = 3 I_r'^2 R_r'$ stator and rotor winding loss;

$P_{LL} = P_{LL,N} \left(\dfrac{I_r'}{I_{r,N}'}\right)^2$ additional load losses,

from a value $P_{LL,N}$ at rated load, either by assigned value (method C) or measured by the reverse rotation test (method F) or by Eh-star test (method G).

The total losses are:

$$P_T = P_s + P_{fe} + P_r + P_{LL} + P_{fw} \tag{70}$$

Since input and shaft power are $P_1 = 3 I_s^2 R$ and $P_2 = P_1 - P_T$, the slip shall be corrected, and the current and loss calculations shall be repeated until P_2 for motor operation, or P_1 for generator operation, is near enough to the desired value.

The efficiency (motor operation) results from:

$$\eta = \frac{P_2}{P_1} \qquad (71)$$

7 Test methods for the determination of the efficiency of synchronous machines

7.1 Preferred testing methods

7.1.1 General

This document defines three different preferred methods with low uncertainty within the given range of application, Table 4 and Table 5. The method to be used depends on the frame size or the rating of the machine under test:

Method 2-1-2A: Direct measurement of input and output power by using a torque measuring device. To be applied for all machines with a frame size below or equal 180 mm and for permanent-magnet-excited machines of any rating.

Method 2-1-2B: Summation of separate losses with a full load test and short circuit test for the determination of the additional load losses. To be applied for all machines with a frame size above 180 mm and a rated output power up to 2 MW.

Method 2-1-2C: Summation of separate losses without a full load test. Short circuit test for the determination of the additional load losses. To be applied for all machines with a rated output power greater than 2 MW.

Table 4 – Synchronous machines with electrical excitation: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-2A	Direct measurement: Input-output	Torque measurement	7.1.2	Machine size: $H \leq$ 180	Torque measuring device for full-load
2-1-2B	Summation of losses with rated load test and short circuit test	P_{LL} from short circuit test	7.1.3	Machine size: $H >$ 180 and rated output power up to 2 MW	Machine set for full-load
2-1-2C	Summation of separate losses without rated load test and P_{LL} from short circuit test	Excitation current from Potier / ASA / Swedish diagram; P_{LL} from short-circuit test	7.1.4	Rated output power greater than 2 MW	
NOTE In the table, H is the shaft height (distance from the centre line of the shaft to the bottom of the feet), in millimetres (see frame numbers in IEC 60072-1).					

Table 5 – Synchronous machines with permanent magnets: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-2A	Direct measurement: Input-output	Torque measurement	7.1.2	All ratings	Torque measuring device for full-load

7.1.2 Method 2-1-2A – Direct measurement of input and output

7.1.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the stator is measured in the same test.

This procedure is also applicable for synchronous machines with excitation by permanent magnets.

Input and output power are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 18);

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

$$P_{el}, I$$
$$U \quad P_{mech}, T, n$$

IEC
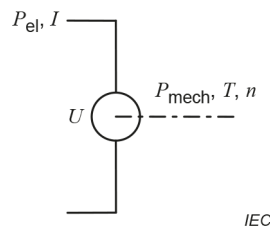
Figure 18 – Sketch for torque measurement test

For an overview, Figure 19 provides a flowchart for efficiency determination by this test method.

Direct measurement

↓

Output power by torque measurement device

↓

Efficiency

IEC
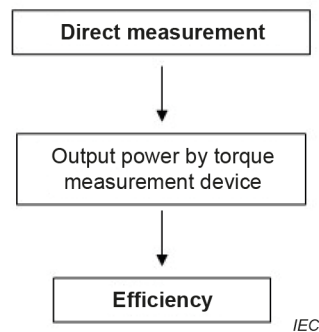
Figure 19 – Efficiency determination according to method 2-1-2A

7.1.2.2 Test procedure

Couple either the motor under test to a load machine or the generator under test to a motor with a torque meter. Operate the machine under test at the required load.

Record U, I, P_{el}, n, T, cos φ, θ_c.

If excitation is required, proceed according to 5.9.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of permanent magnet motors, physically uncouple the motor under test, to avoid residual torque in unexcited condition induced by permanent magnets. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

7.1.2.3   Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1 + P_{1E}}$$

(72)

Input power P_1 and output power P_2 are:

−   in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;

−   in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

where

P_{mech} $= 2\pi \times T \times n$.

P_{1E} is according to 5.9.

NOTE   Excitation circuit losses not supplied by P_{1E} are mechanically covered from the shaft.

7.1.3   Method 2-1-2B – Summation of separate losses with a rated load temperature test and a short circuit test

7.1.3.1   General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

−   iron losses;

−   windage and friction losses;

−   stator and rotor copper losses;

−   excitation circuit losses;

−   additional load losses.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

For an overview, Figure 20 provides a flowchart for efficiency determination by this test method.

```
┌─────────────────────────────┐
│    Indirect measurement     │
└─────────────────────────────┘
              │
              ▼
     ┌──────────────────┐
     │  Separate losses │
     └──────────────────┘
              │
              ▼
┌────────────────────────────────────────┐
│ Winding resistances at ambient temperature │
└────────────────────────────────────────┘
              │
              ▼
┌────────────────────────────────────────┐
│  7.1.3.2.1 Rated load temperature test  │
└────────────────────────────────────────┘
              │
              ▼
   ┌──────────────────────────────┐
   │         Load losses          │
   │ Stator and rotor winding losses │
   │ including temperature correction │
   └──────────────────────────────┘
              │
              ▼
   ┌──────────────────────────┐
   │  Excitation circuit losses │
   └──────────────────────────┘
              │
              ▼
   ┌──────────────────────────┐
   │  7.1.3.2.2 No-load test   │
   └──────────────────────────┘
              │
              ▼
   ┌──────────────────────────┐
   │       Constant losses     │
   │ Friction and windage losses │
   │        Iron losses        │
   └──────────────────────────┘
              │
              ▼
   ┌──────────────────────────┐
   │ 7.1.3.2.3 Short-circuit test │
   └──────────────────────────┘
              │
              ▼
   ┌──────────────────────────┐
   │   Additional load losses  │
   └──────────────────────────┘
              │
              ▼
   ┌──────────────────────────┐
   │   7.1.3.3 Total losses    │
   └──────────────────────────┘
              │
              ▼
      ┌──────────────┐
      │   Efficiency  │
      └──────────────┘
```
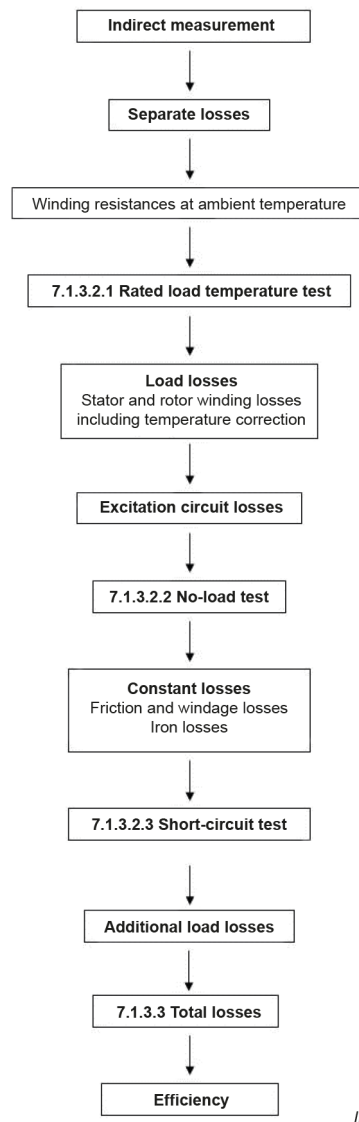
IEC

Figure 20 – Efficiency determination according to method 2-1-2B

7.1.3.2   Test procedure

7.1.3.2.1   Rated load temperature test

7.1.3.2.1.1   General

Before this load test, determine the temperature and the winding resistance of the machine with the machine at ambient temperature.

The machine shall be loaded by suitable means, with supply power according to the machine rating and operated until thermal equilibrium is achieved (rate of change of 1 K or less per half hour).

At the end of the rated-load test, record the average of at least 3 sets of test results:

– P_N, I_N, U_N, f, θ_c, θ_N;

– $R_N = R$ (the test resistance for rated load according to 5.7.1);

– θ_N (the winding temperature at rated load according to 5.7.2);

–   Excitation system values according to 5.9.

7.1.3.2.1.2   Stator winding losses

Determine the stator-winding losses:

$$P_s = 1,5 \times I^2 \times R_{||} \tag{73}$$

where

$R_{||}$ is according to 5.7.1, corrected to 25 °C primary coolant reference temperature.

7.1.3.2.1.3   Field winding loss

The field winding loss is

$$P_f = I_f \cdot U_f \tag{74}$$

7.1.3.2.1.4   Electrical losses in brushes

In case of brushes determine brush losses from an assigned voltage drop per brush of each of the two polarities:

$$P_b = 2 \times U_b \times I_e \tag{75}$$

where

I_e is according to the load test;

U_b is the voltage drop per brush of each of the two polarities depending on brush type:

   1,0 V for carbon, electrographitic or graphite;

   0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

7.1.3.2.1.5   Exciter loss

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input according to the input-output method; or

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter (in the case of a synchronous machine excited via slip-rings) to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for rated load.

Record:

− U_e, I_e, P_{1E}, n, T_E for rated load;

− $T_{E,0}$ (the torque with the exciter unexcited).

The exciter loss is:

$$P_{Ed} = 2\pi n \left(T_E - T_{E,0} \right) + P_{1E} - P_f \qquad (76)$$

When the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The total excitation loss is:

$$P_e = P_f + P_{Ed} + P_b \qquad (77)$$

7.1.3.2.2   No-load test

7.1.3.2.2.1   General

machine can be tested running as an uncoupled motor or coupled with a driving machine and operating as a generator (supplied power from shaft, measured according input-output method).

The no-load test shall be carried out on a hot machine immediately after the rated load test.

When this is not possible the test may also be carried out starting with a cold machine but the no-load losses shall be stabilized at rated frequency and voltage (by adjusting the excitation current), and unity power factor (minimum current) when running as an uncoupled motor.

In the case of a synchronous machine with shaft driven exciter (see 3.13.3.3a)), the machine should be separately excited and the exciter disconnected from its supply and from the excitation winding.

The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at a minimum number of eight values of voltage, including rated voltage, so that:

– four or more values are read approximately equally spaced between approximately 110 % and 80 % of rated voltage;
– four or more values are read approximately equally spaced between approximately 70 % and approximately 30 % of rated voltage, or (for an uncoupled running machine) to a point where the current no longer decreases.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linear with the electrical power P_0.

R_0 is $R_{ll,0}$. Where resistance measurement is impracticable due to very low resistances, calculated values are permissible. The calculated values have to be based on the average value of the measured winding temperatures.

For a coupled machine, P_0 is determined from T and n.

Record excitation system values according to 5.9.

For large synchronous machines, it is recommended to record other values influencing efficiency, for example coolant temperature, gas purity, gas pressure, sliding bearings oil temperature, bearing oil viscosity.

7.1.3.2.2.2   Constant losses

For each value of voltage determine the constant losses:

$$P_c = P_0 - P_{s0} \tag{78}$$

where

$$P_{s0} = 1{,}5 \cdot I_0^2 \cdot R_{\|0} \tag{79}$$

For machines with brushless exciters, excitation losses shall also be subtracted as follows:

$$P_c = P_0 - P_{s0} - P_{f,0} - P_{Ed,0} + P_{1E,0} \tag{80}$$

where

$P_{f,0}$ is the excitation winding losses at no-load;

$P_{Ed,0}$ is the exciter loss (see above) corresponding to U_e and I_e of the test point;

$P_{1E,0}$ is the power according to 5.9 corresponding to U_e and I_e of the test point.

7.1.3.2.2.3   Friction and windage losses

From the no-load test points, use all that show no significant saturation effect and develop a curve of constant losses (P_c), against the voltage squared ($U_0{}^2$). Extrapolate a straight line to zero voltage. The intercept with the zero voltage axis is the friction and windage losses P_{fw}.

Windage and friction losses are considered to be independent of load and the same windage and friction loss values may be used for each of the load points.

7.1.3.2.2.4   Iron losses

For each of the values of voltage develop a curve of constant losses against voltage. Subtract from this value the windage and friction losses to determine the iron losses.

$$P_{fe} = P_c - P_{fw} \tag{81}$$

7.1.3.2.3 Short-circuit test

7.1.3.2.3.1 Short-circuit test with coupled machine

Couple the machine under test with its armature winding short-circuited to a drive machine, with provisions to record the torque using a torque meter (see method 2-1-2A). Operate at rated speed and excited so that the current in the short-circuited primary winding is equal to the rated current.

In the case of a machine with a shaft driven exciter (see 3.13.3.3a)), the machine should be separately excited and the exciter disconnected from its supply and from the excitation winding.

The sum of the load losses and the additional load losses is assumed to be temperature independent, and no correction to a reference temperature is made. It is assumed that the additional load losses vary as the square of the stator current.

Record: T, n, I.

Excitation system values are according to 5.9.

7.1.3.2.3.2 Short-circuit test with uncoupled machine

7.1.3.2.3.2.1 General

The machine is operated as a synchronous motor at a fixed voltage, preferably about 1/3 normal or at the lowest value for which stable operation can be obtained. The armature current is varied by control of the field current. The armature current should be varied in about six steps between 125 % and 25 % of rated current and should include one or two points at very low current. The maximum test current value, traditionally set at 125 %, should be obtained from the manufacturer since sometimes stator cooling will not permit operation in excess of 100 % rated current without damage. The highest readings should be taken first to secure more uniform stator winding temperatures during the test.

Record: P_1, I, U.

Excitation system values are according to 5.9.

NOTE   For large machines, the maximum step may be limited to 60 % to 70 % of rated armature current.

7.1.3.2.3.2.2 Additional load losses

7.1.3.2.3.2.2.1 From test with coupled machine

The additional load losses at rated current result from the absorbed power of the short-circuit test with coupled machine diminished by the friction and windage losses P_{fw} and the load loss at rated current.

$$R_{LL,N} = 2\pi n T - P_{fw} - P_s \tag{82}$$

In the case of a machine with brushless excitation, the excitation winding and the exciter loss part supplied by the driving machine shall additionally be subtracted:

$$R_{LL,N} = 2\pi n T + P_{1E} - P_{fw} - P_s - P_f - P_{Ed} \tag{83}$$

For other load points the additional load losses result from

$$R_{LL} = R_{LL,N} \times \left(\frac{I}{I_N}\right)^2 \qquad (84)$$

7.1.3.2.3.2.2.2 From test with uncoupled machine

In order to determine additional load losses at any armature current, the constant losses P_c and the armature winding loss P_s at any armature current shall be subtracted from the power input at each armature current taken in the test.

7.1.3.3   Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \qquad (85)$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1   Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses P_T including excitation circuit losses are:

$$P_T = P_c + P_S + R_{LL} + P_e \qquad (86)$$

7.1.4   Method 2-1-2C – Summation of separate losses without a full load test

Method 2-1-2C shall be applied to machines with ratings above 2 MW. The test procedure is in principle similar to method 2-1-2B. The only difference is that the rated load temperature test is replaced by the determination of the field current by the ASA-, Swedish- or Potier-Diagram (see IEC 60034-4-1).

Apart from that the procedures for loss and efficiency determination are equivalent to method 2-1-2B.

For an overview, Figure 21 provides a flowchart for efficiency determination by this test method.

```
                    ┌──────────────────────────┐
                    │   Indirect measurement   │
                    └──────────────────────────┘
                                 │
                                 ▼
                    ┌──────────────────────────┐
                    │      Separate losses     │
                    └──────────────────────────┘
                                 │
                                 ▼
        ┌──────────────────────────────────────────────┐
        │   Winding resistance at ambient temperature   │
        └──────────────────────────────────────────────┘
                                 │
                                 ▼
        ┌──────────────────────────────────────────────┐
        │       IEC 60034-4-1:2018 6.4, 6.5, 6.8:       │
        │      Rated field current according to ASA-,   │
        │         Swedish- or Potier-diagram            │
        └──────────────────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │            Load losses           │
            │   Stator and rotor winding losses│
            │    including temperature correction│
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │      Excitation circuit losses   │
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │      7.1.3.2.2 No-load test       │
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │          Constant losses         │
            │    Friction and windage losses   │
            │            Iron losses           │
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │    7.1.3.2.3 Short-circuit test   │
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │      Additional load losses      │
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │       7.1.3.3 Total losses       │
            └──────────────────────────────────┘
                                 │
                                 ▼
            ┌──────────────────────────────────┐
            │            Efficiency            │
            └──────────────────────────────────┘
```

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Figure 21 – Efficiency determination according to method 2-1-2C

Prior to this test, the results of a no-load saturation test, a sustained polyphase short-circuit test and an over-excitation test at zero power factor, in accordance with 6.4, 6.5 and 6.8 of IEC 60034-4-1:2018, shall be available.

For the procedures to determine efficiency see 7.1.3, method 2-1-2B.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

7.2   Testing methods for field or routine testing

7.2.1   General

These test methods may be used for any test, i.e. field tests, customer-specific acceptance tests or routine tests.

In addition, preferred methods of Table 4 and Table 5 may also be used outside the power range identified in Table 4 and Table 5

Methods defined by this document are given in Table 6.

Table 6 – Synchronous machines: other methods

Reference	Method	Description	Subclause	Required facility
2-1-2D	Dual-supply-back-to-back	Dual-supply, back-to-back test	7.2.2	Two identical units
2-1-2E	Single-supply-back-to-back test	Single supply, back-to-back test	7.2.3	Two identical units
2-1-2F	Zero power factor with excitation current from Potier / ASA / Swedish diagram	Excitation current from Potier / ASA / Swedish diagram;	7.2.4	Supply for full voltage and current
2-1-2G	Summation of losses with load test except P_{LL}	Without consideration of P_{LL}	7.2.5	Machine set for full load

7.2.2   Method 2-1-2D – Dual supply back-to-back-test

7.2.2.1   General

For an overview, Figure 22 provides a flowchart for efficiency determination by this test method.
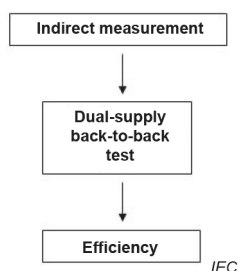
Figure 22 – Efficiency determination according to method 2-1-2D

This procedure is not applicable for synchronous machines with excitation by permanent magnets.
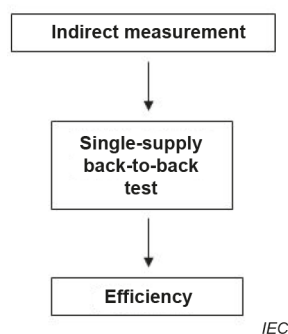
7.2.2.2   Test procedure

Mechanically, couple two identical machines together (see Figure 23). Tests are made with the power supplies exchanged but with the instruments and instrument transformers remaining with the same machine.
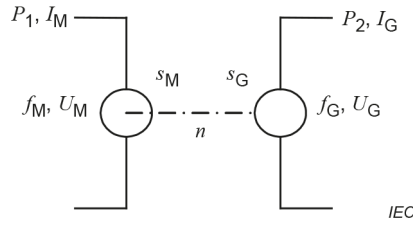
Figure 23 – Sketch for dual supply back-to-back test
$$(I_\mathrm{M} = I_\mathrm{G}, f_\mathrm{M} = f_\mathrm{G})$$

The voltage and current of the two machines shall be identical, and one machine (the motor for motor rating, the generator for generator rating) shall have the rated power factor. This can be achieved by a set of synchronous and DC machines feeding the generator output back to the line.

NOTE Power factor and excitation current of the other machine will deviate from rated values because of the losses absorbed by the two machines.

Reverse the motor and generator connections and repeat the test.

For each test, record: U, I, f, P_1, P_2, $\cos \varphi_\mathrm{M}$, $\cos \varphi_\mathrm{G}$, θ_c.

For excitation systems proceed according to 5.9.

7.2.2.3   Efficiency determination

If identical machines are run at essentially the same rated conditions, the efficiency shall be calculated from half the total losses and the average of motor input power and generator output power as follows:

$$\eta = 1 - \frac{P_\mathrm{T}}{\dfrac{P_1 + P_2}{2} + P_\mathrm{1E}} \tag{87}$$

where

$$P_\mathrm{T} = \frac{1}{2}(P_1 - P_2) + P_\mathrm{1E} \; ; \; P_\mathrm{1E} = \frac{1}{2}\left(P_\mathrm{1E,M} + P_\mathrm{1E,G}\right) \tag{88}$$

P_1E is according to 5.9.

7.2.3   Method 2-1-2E – Single supply back-to-back-test

7.2.3.1   General

For an overview, Figure 24 provides a flowchart for efficiency determination by this test method.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

Figure 24 – Efficiency determination according to method 2-1-2E

7.2.3.2   Test procedure

Mechanically couple two identical machines together and connect them both electrically to the same power supply to operate at rated speed and rated voltage, one as a motor and the other as a generator.

NOTE   Alternatively, the losses can be supplied by a calibrated driving motor.

Mechanically couple the machines with an angular displacement of their rotors enabling one machine to operate at the load conditions for which the efficiency is required, and the other machine to operate at the same absolute value of stator current (see Figure 25).
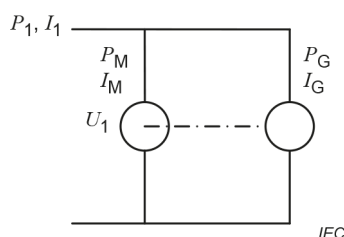
Figure 25 – Single supply back-to-back test for synchronous machines

The displacement expressed as electrical angle α for this condition is approximately the double internal electrical angle at the required load condition. In general, for a given voltage the circulating power depends on the angle α and on the excitation currents of the motor and generator. Adjust the current and power factor to rated values at one machine; the deviation in excitation current from the rated value at the other machine can be used for accuracy considerations.

For each test, record:

– U_1, I_1, P_1 of the power-frequency supply;

– I_M, P_M of the motor;

– I_G, P_G of the generator;

– excitation system values according to 5.9.

7.2.3.3   Efficiency determination

If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M + P_{1E}}$$ (89)

where

P_M is the power absorbed at the terminals of the machine acting as a motor (excluding excitation power);

P_T is the total losses, defined as half the total absorbed;

P_{1E} is the excitation power supplied by a separate source.

$$P_T = \frac{1}{2}P_1 + P_{1E}; \quad P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right)$$

7.2.4 Method 2-1-2F – Zero power factor test with excitation current from Potier-, ASA- or Swedish-diagram

7.2.4.1 General

For an overview, Figure 26 provides a flowchart for efficiency determination by this test method.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.
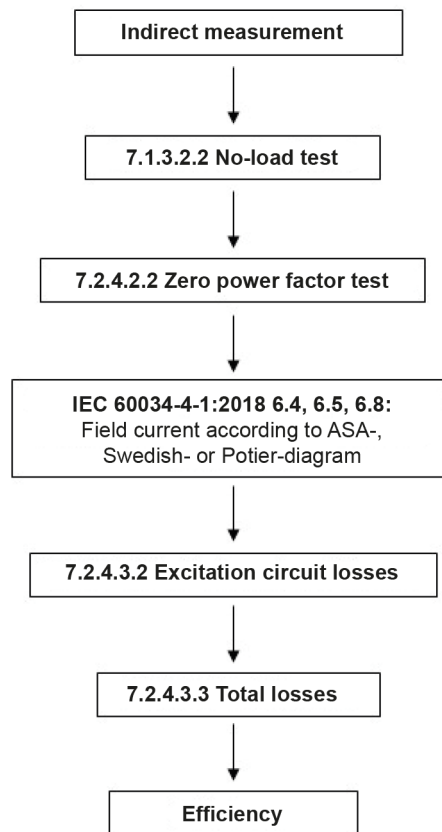
Figure 26 – Efficiency determination according to method 2-1-2F

7.2.4.2 Test procedure

7.2.4.2.1 General

Prior to this test, the results of a no-load saturation test, a sustained polyphase short-circuit test and an over-excitation test at zero power factor, in accordance with 6.4, 6.5 and 6.7 of IEC 60034-4-1:2018, shall be available.

The evaluation of the results of the no-load test shall be in accordance with 7.1.3.2.2.

7.2.4.2.2 Zero power factor test

Operate the machine uncoupled as a motor, at rated speed and over-excited. Adjust the supply voltage to the same electromotive force E and armature current I (at a power factor near zero) as at the desired load.

NOTE 1 E is the vectorial sum of terminal voltage and Potier reactance voltage drop according to 7.26.2 of IEC 60034-4-1:2018.

The test shall be made as near as possible to the stabilized operating temperature attained in operation at rated load. No winding temperature correction shall be made.

For the above test, it is necessary that the supply voltage is adjustable so that the iron losses have the same value during this test as at a rated power factor under load at rated voltage. If the supply voltage is not adjustable but is equal to the rated voltage, this could give an active iron loss appreciably different from that at full-load. In principle, reactive power should be delivered (i.e. machine over-excited), but when this is impossible due to limited exciter voltage, the test may be made with reactive power absorbed (i.e. machine under-excited) as far as stable running is possible.

The excitation winding losses at the desired load will be obtained from the excitation current estimated according to 7.26.2 of IEC 60034-4-1:2018 (Potier diagram), or 7.26.3 (ASA diagram), or 7.26.4 (Swedish diagram).

NOTE 2   The accuracy of this method depends on the accuracy of the wattmeters and the instrument transformers at low power factor.

Record at zero power factor:

– $U, f, I, P_{1,\text{zpf}}$;

– excitation system values according to 5.9;

– θ_c and θ_w.

7.2.4.3 Efficiency determination

7.2.4.3.1 General

For each desired load point, determine the efficiency with the measured values as follows:

$$\eta = 1 - \frac{P_T}{P_1 + P_{1E}} \tag{90}$$

where

$P_1 = \sqrt{3} \times U_N \times I \cos\varphi_N$ is the power absorbed at the armature winding terminals in rated operation;

P_T is the total losses, including excitation losses;

P_{1E} is the excitation power supplied by a separate source.

7.2.4.3.2 Excitation losses

7.2.4.3.2.1 Field winding loss

The field winding loss is

$$P_f = I_e \cdot U_f = I_e^2 \cdot R_e \tag{91}$$

applying the following temperature correction for the excitation winding resistance:

$$R_e = R_{e,0} \times \frac{235 + \theta_e}{235 + \theta_0}; \quad \theta_e = 25 + \left(\theta_w - \theta_c\right)\left(\frac{I_e}{I_{e,zpf}}\right)^2 \tag{92}$$

where

I_e is the excitation winding current determined as described in IEC 60034-4-1;

R_e is the excitation winding resistance, temperature corrected for the desired load;

$R_{e,0}$ is the cold winding resistance at temperature θ_0;

$I_{e,zpf}$ is the excitation winding current from the zero power factor test;

θ_w is the excitation winding temperature of the zpf-test;

θ_c is the reference coolant temperature of the zpf-test;

θ_e is the excitation winding temperature corrected to I_e.

7.2.4.3.2.2 Electrical losses in brushes

In case of brushes determine brush losses from an assigned voltage drop per brush of each of the two polarities:

$$P_b = 2 \times U_b \times I_e \tag{93}$$

where

I_e is the excitation winding current determined as described in IEC 60034-4-1;

U_b is the voltage drop per brush of each of the two polarities depending on brush type:

    1,0 V for carbon, electrographitic or graphite;

    0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

7.2.4.3.2.3 Exciter loss

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input according to the input-output method; or

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter (in the case of a synchronous machine excited via slip-rings) to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for rated load.

Record:

- U_e, I_e, P_{1E}, n, T_E for rated load;
- $T_{E,0}$ (the torque with the exciter unexcited).

The exciter loss is:

$$P_{Ed} = 2\pi n \left(T_E - T_{E,0} \right) + P_{1E} - P_f \tag{94}$$

If the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The total excitation loss is:

$$P_e = P_f + P_{Ed} + P_b \tag{95}$$

7.2.4.3.3 Total losses

For machines with exciter types c) and d) (see 3.13.3.3) the total losses are:

$$P_T = P_{1,zpf} + \Delta P_{fe} + P_e \tag{96}$$

where

$P_{1,zpf}$ is the absorbed power at zero power factor test;

Δp_{fe} is determined from the iron loss-voltage curve (see 7.1.3.2.2), and is the difference of the values at voltages equal to the e.m.f. for the desired load and the e.m.f. of the zero power factor test;

P_e determined as stated above.

For machines with exciters type a) and b) (see 3.13.3.3) the total losses are:

P_e, P_{ed} and P_{1E} are as defined above for the excitation winding current of the desired load, determined according to IEC 60034-4-1:

$$P_T = P_{1,zpf} + P_{1E,zpf} + \Delta P_{fe} + P_e \tag{97}$$

$$P_e = P_f + P_{Ed} - P_{f,zpf} - P_{Ed,zpf} \tag{98}$$

where

$P_{1,zpf}$, $P_{f,zpf}$ and $P_{1E,zpf}$ are measured values from the zero power factor test;

P_f is determined as for separately excited machines;

P_{Ed}, $P_{Ed,zpf}$ are determined from a test as stated above for I_e, R_e and $I_{e,zpf}$, $R_{e,zpf}$;

ΔP_{fe} is determined from the iron loss-voltage curve (see 7.1.3.2.2), and is the difference of the values at voltages equal to the e.m.f. for the desired load and the e.m.f. of the zero power factor test.

NOTE   The formulas are expressed for motor operation.

7.2.5   Method 2-1-2G – Summation of separate losses with a load test without consideration of additional load losses

The test procedure is in principle similar to method 2-1-2B. The only difference is that the additional load losses are not considered by this method, i.e. the short circuit test for their determination is skipped. This results in a significantly lower accuracy.

Apart from that, the procedures for loss and efficiency determination are equivalent to method 2-1-2B.

For an overview, Figure 27 provides a flowchart for efficiency determination by this test method.

For the procedures to determine efficiency see 7.1.3, method 2-1-2B, without consideration of the additional load loss.

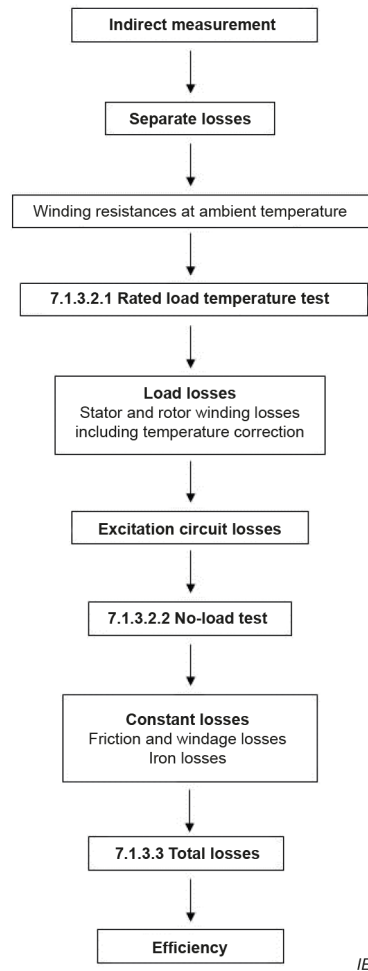This procedure is not applicable for synchronous machines with excitation by permanent magnets.

Figure 27 – Efficiency determination according to method 2-1-2G

8 Test methods for the determination of the efficiency of DC machines

8.1 Testing methods for field or routine testing

The methods shall be used for field tests, customer specific acceptance tests or routine tests.

Methods defined by this document are given in Table 7.

Table 7 – DC machines: test methods

Reference	Method	Description	Subclause	Required facility
2-1-3A	Direct measurement: Input-output	Torque measurement	8.2	Torque measuring device for full-load
2-1-3B	Summation of losses with load test and DC component of additional load losses from test	P_{LL} DC component from single supply back-to-back test	8.3	Two identical units, booster generator, specified rectifier
2-1-3C	Summation of losses with load test and DC component of additional load losses from assigned value	P_{LL} DC component from assigned value	8.4	Specified rectifier
2-1-3D	Summation of losses without a load test	Excitation loss from an assigned ratio of load to no-load excitation current P_{LL} from assigned value	8.5	
2-1-3E	Single-supply-back-to-back test	Single supply, back-to-back test	8.6	Two identical units Booster generator

8.2 Method 2-1-3A – Direct measurement of input and output

8.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the armature is measured in the same test.

Input and output power are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 28);
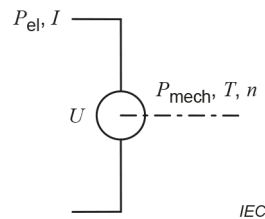– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

Figure 28 – Sketch for torque measurement test

For an overview, Figure 29 provides a flowchart for efficiency determination by this test method.
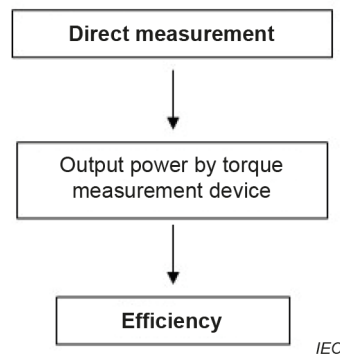
Figure 29 – Efficiency determination according to method 2-1-3A

8.2.2 Test procedure

Couple either the motor under test to a load machine or the generator under test to a motor with a torque meter. Operate the machine under test at the required load.

Record U, I, P_{el}, n, T, θ_c.

If excitation is required, proceed according to 5.9.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

8.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1 + P_{1E}} \tag{99}$$

Input power P_1 and output power P_2 are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$;

    where

    P_{mech} = $2\pi \times T \times n$;

    P_{1E} is according to 5.9.

NOTE   Excitation circuit losses not supplied by P_{1E} are mechanically covered from the shaft.

8.3 Method 2-1-3B – Summation of losses with a load test and DC component of additional load losses from test

8.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

– iron losses;

– windage and friction losses;

– armature winding and brush losses;

– excitation circuit and exciter losses;

– additional load losses.

For an overview, Figure 30 provides a flowchart for efficiency determination by this test method.
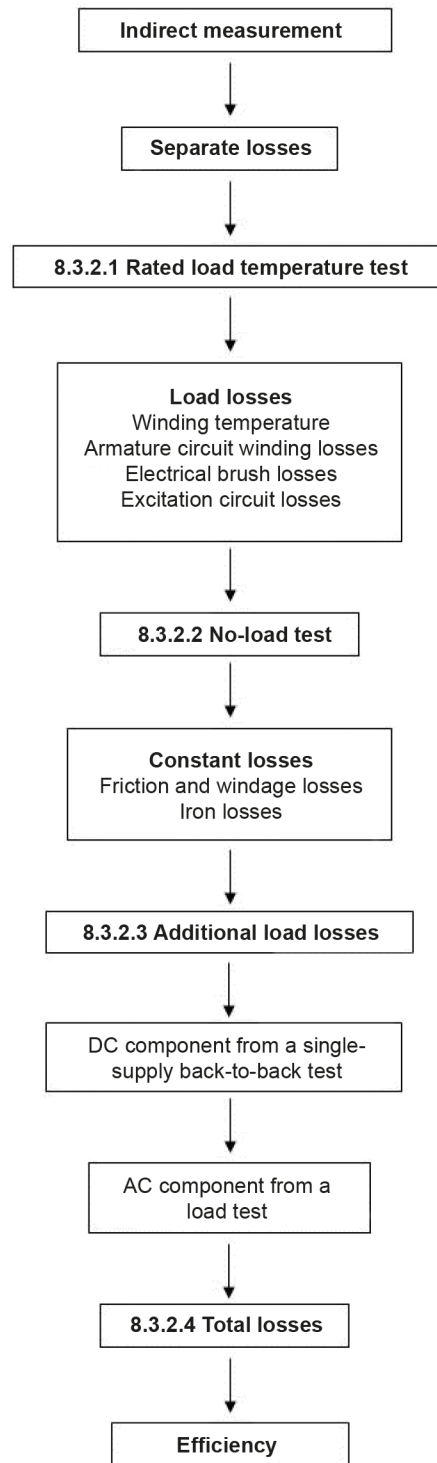
Figure 30 – Efficiency determination according to method 2-1-3B

8.3.2 Test procedure

8.3.2.1 Rated load temperature test

8.3.2.1.1 General

Before this load test, determine the ambient temperature and the winding resistance of the motor.

The machine shall be loaded by suitable means, with supply power according to the machine rating and operated until thermal equilibrium is achieved (rate of change of 1 K or less per half hour).

At the end of the rated-load test, record the average of at least 3 sets of test results:

- P_N, I_N, U_N, θ_c, θ_N;
- $R_N = R$ (the test resistance for rated load according to 5.7.1);
- θ_N (the winding temperature at rated load according to 5.7.2);
- excitation system values according to 5.9.

In the case of DC machines on rectified power, the mean value I_{av} and the RMS value I shall be measured.

For DC machines, R is the total resistance of all windings carrying armature current (armature, commutating, compensating winding, compound winding). Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

8.3.2.1.2 Armature circuit winding losses

For each load recorded determine the armature-circuit-windings losses:

$$P_a = I^2 \times R \tag{100}$$

R according to 5.7.2 with R taking all windings in the armature circuit into account.

8.3.2.1.3 Electrical brush losses

Determine brush losses using an assigned voltage drop per brush:

$$P_b = 2 \times U_b \times I \tag{101}$$

where

I is the armature current at the rating considered;

U_b is the assumed voltage drop per brush depending on brush type:

    1,0 V for carbon, electrographitic or graphite;

    0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

8.3.2.1.4 Excitation circuit losses

The excitation winding losses result from the measured voltage and current as follows:

$$P_f = U_e \times I_e \tag{102}$$

8.3.2.1.5   Exciter losses

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input;

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for each of the load points.

Record:

– U_e, I_e, P_{Ed}, n, T_E for each load point (P_{Ed} according to 3.13.3.3);

– $T_{E,0}$ (the torque with the exciter unexcited).

If the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The exciter losses P_{Ed} are

$$P_{Ed} = \left(T_E - T_{E,0}\right) \times 2\pi n + P_{1E} - U_e \times I_e \tag{103}$$

where $T_{E,0}$ is the torque with the exciter unexcited.

If testing is not practical, calculated losses shall be used.

8.3.2.2   No-load test

8.3.2.2.1   General

The machine can be tested running as an uncoupled motor or coupled with a driving machine and operating as a generator (supplied power from torque, measured according input-output method).

The no-load test shall be carried out on a hot machine immediately after the rated load test.

If this is not possible the test may also be carried out starting with a cold machine but the no-load losses shall be stabilized. The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at a minimum number of eight values of voltage, including rated voltage, so that:

–   four or more values are read approximately equally spaced between 110 % and 80 % of rated voltage;

–   four or more values are read approximately equally spaced between 70 % and approximately 30 % of rated voltage, or (for an uncoupled running machine) to a point where the current no longer decreases.

For uncoupled DC machines, the speed shall be maintained constant by adjusting the field current.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linear with the electrical power P_0.

Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

For a coupled machine, P_0 is determined from T and n.

8.3.2.2.2 Constant losses

Determine the constant losses from the following formula:

$$P_c = P_0 - P_a \tag{104}$$

where

$$P_a = I_0{}^2 \times R_0 \tag{105}$$

I_0 and R_0 are recorded for each value of voltage.

If resistance measurement is impracticable due to very low resistances, calculated values are permissible, corrected to the expected winding temperature.

NOTE   In the armature losses P_a, the following are included: compensating windings, commutating pole windings and shunt resistors (diverters). In the case of diverters in parallel with a series winding, the electrical winding losses may be determined using the total current and the resulting resistance.

8.3.2.2.3 Friction and windage losses (optional)

For each of the values of voltage 70 % or less develop a curve of constant losses (P_c) against voltage $U_0{}^2$. Extrapolate a straight line to zero voltage. The intercept with the zero voltage axis is the windage and friction losses P_{fw}.

8.3.2.2.4 Iron losses (optional)

For each of the values of voltage between 80 % and 110 % develop a curve of constant losses (P_c) against voltage U_0. The iron loss shall be taken for the inner voltage U_i, at:

$$U_i = U_N - (IR)_a - 2U_b \text{ in the case of a motor} \tag{106}$$

$$U_i = U_N + (IR)_a + 2U_b \text{ in the case of a generator} \tag{107}$$

where

U_N is the rated voltage;

$2U_b$ is the brush voltage-drop as given at the load test;

I is the current of the desired load point;

R is the resistance of all windings of the armature circuit at full-load temperature.

Determine the iron loss from

$$P_{fe} = P_c - P_{fw} \qquad (108)$$

8.3.2.3 Additional load losses

8.3.2.3.1 DC losses from single supply back-to-back-test

This method allows the determination of the DC component of the additional load losses if two identical DC machines are available. They shall be coupled and electrically connected together and supplied by a DC source, the machine acting as a generator with a booster generator in series (see Figure 31).
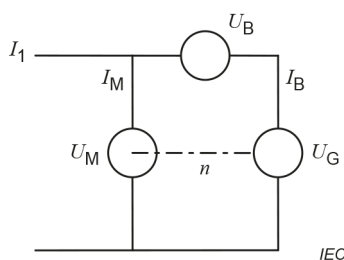

**Figure 31 – Sketch for single supply back-to-back test
for determination of DC component of additional load losses**

If the machines are designed for motor operation, the supply shall deliver rated voltage and rated current to the machine acting as motor. In the case of machines designed for generator operation, the supply voltage shall be adjusted to rated voltage and rated current at the machine acting as generator. The motor and the generator shall be operated with the flux required to produce the e.m.f. corresponding to the test load.

NOTE   The voltage supply mainly covers the no-load losses, the booster mainly covers the load losses.

In the case of machines with shaft driven exciters, the excitation windings shall be separately excited for this test, with the exciters disconnected from their supply and the excitation winding.

When temperatures have stabilized, record: $U, I, U_B, I_B, U_{e,M}, I_{e,M}, U_{e,G}, I_{e,G}, n, \theta_c$.

The DC component of the additional load loss is

$$P_{LL} = \frac{1}{2}\left(P_1 - \sum P_c - \sum P_a - P_{con} - 2U_b(I + I_B) - 2I_B U_b\right) \qquad (109)$$

where

$P_1 = U_M \times I_1 + U_B \times I_B$ is the power from supply and booster; see Figure 31;

ΣP_c is the sum of constant losses of both machines;

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ΣP_a is the sum of the resistance losses of both armature circuits;

P_{con} is the loss in cable connections.

For determination of losses for other load points, apply the factors as described in Table 8.

8.3.2.3.2 AC losses (converter-fed DC machines)

For motors supplied by static power converters, whenever the current ripple factor (see IEC 60034-1) of the armature current exceeds 0,1, the additional losses caused by the AC component of the armature current shall be considered in addition to the losses specified above.

The losses are obtained from a load test with the machine supplied by an appropriate rectifier. See also IEC 60034-19.

Record:

- P_1 the AC power supplied to the machine;
- I the AC r.m.s. current component; and
- θ_w the temperatures of the windings in galvanic contact with the armature circuit.

NOTE   For series-wound motors, a small amount of the AC power input contributes to the developed motor torque. This amount is usually so small that it can be neglected.

The additional losses due to the AC part of the supply voltage result from:

$$P_{LL} = P_1 - I^2 \times R \tag{110}$$

where R is the DC resistance of the armature circuit at rated load temperatures according to 5.7.2.

8.3.2.4 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{111}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1   Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \tag{112}$$

$$P_e = P_f + P_{Ed} \tag{113}$$

where

P_a is the armature-winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional load losses;

P_f is the excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.4 Method 2-1-3C – Summation of losses with a load test and DC component of additional load losses from assigned value

8.4.1 General

As method 2-1-3B, this test method determines efficiency by the summation of separate losses. But in this case the DC component of the additional load losses is derived from an assigned value.

For an overview, Figure 32 provides a flowchart for efficiency determination by this test method.
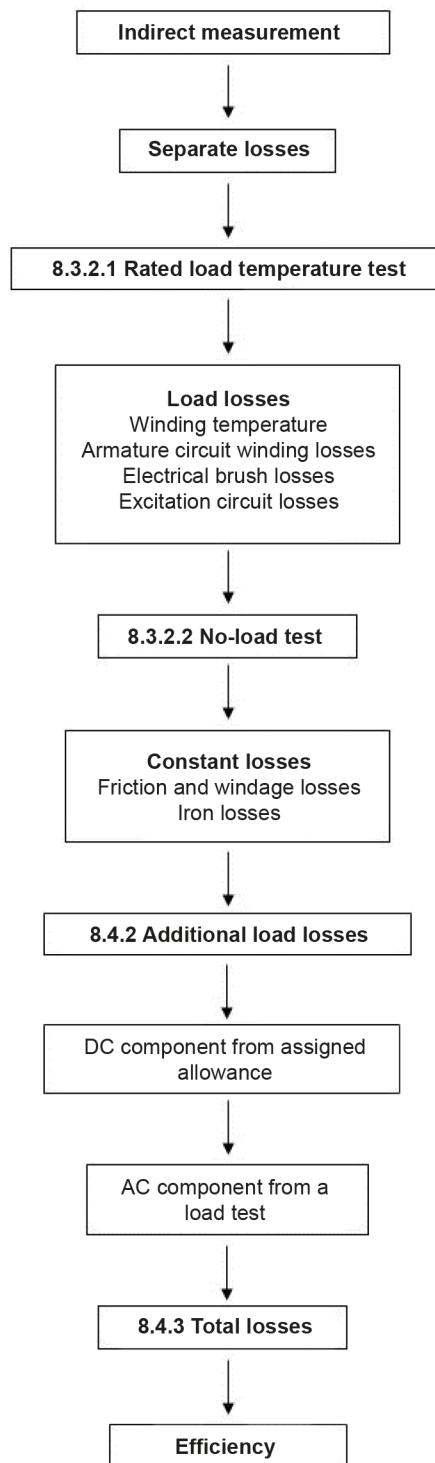
Figure 32 – Efficiency determination according to method 2-1-3C

8.4.2 Test procedure

8.4.2.1 General

Apart from the determination of the DC component of the additional load losses, the same procedures as in 8.3.2 shall be applied.

8.4.2.2   DC component of the additional load losses from assigned allowance

It is assumed that the DC losses vary as the square of the current, and that their total value at maximum rated current is:

a) for uncompensated machines:
   –   1 % of the rated input power for motors;
   –   1 % of the rated output power for generators;

b) for compensated machines:
   –   0,5 % of the rated input power for motors;
   –   0,5 % of the rated output power for generators.

For constant speed machines, the rated power is the power with maximum rated current and maximum rated voltage.

For variable speed motors where the speed change is obtained by applied voltage, the rated input power is defined at each speed as being the input power when the maximum rated current is associated with the applied voltage of the particular speed considered.

For variable speed motors where the increase in speed is obtained by weakening the field, the rated input power is defined as being the input power when the rated voltage is associated with the maximum rated current. For variable speed generators where the voltage is maintained constant by varying the field, the rated output power is defined as being the output power, which is available at the terminals at rated voltage and maximum rated current. The allowances for additional losses at the speed corresponding to the full field shall be as specified above under a) and b). The allowances for additional losses at other speeds shall be calculated using the appropriate multiplying factors given in Table 8.

Table 8 – Multiplying factors for different speed ratios

Speed ratio	Factor
1,5:1	1,4
2:1	1,7
3:1	2,5
4:1	3,2

The speed ratio in the first column of Table 8 shall be taken as the ratio of actual speed under consideration to the minimum rated speed for continuous running.

For speed ratios other than those given in Table 8, the appropriate multiplying factors may be obtained by interpolation.

8.4.3   Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{114}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1   Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \qquad (115)$$

$$P_e = P_f + P_{Ed} \qquad (116)$$

where

P_a is the armature winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional losses;

P_f is the excitation (field winding) loss;
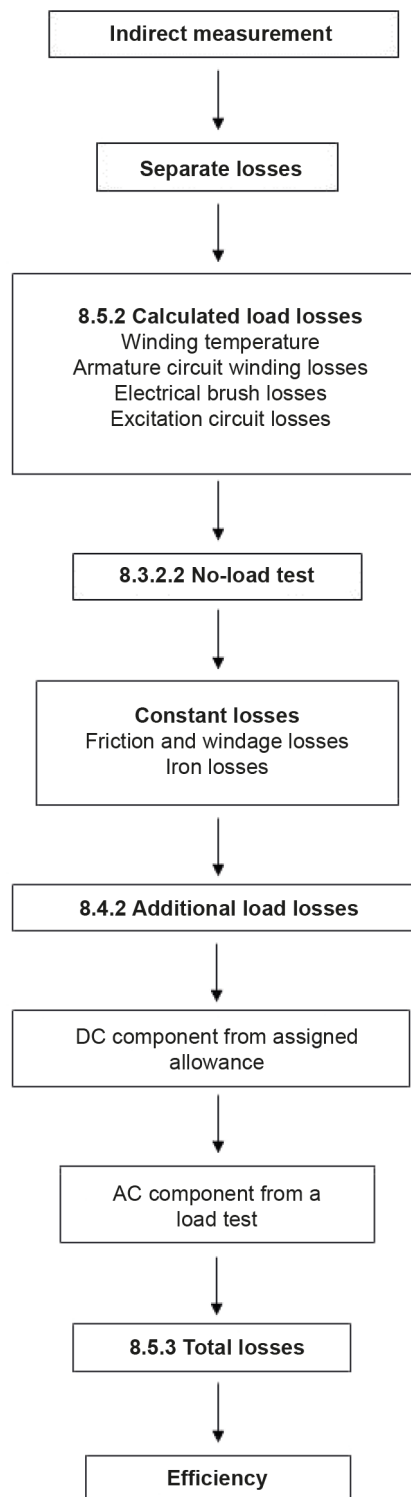
P_{Ed} is the exciter loss.

8.5   Method 2-1-3D – Summation of losses without a load test

8.5.1   General

As method 2-1-3C, this test method determines efficiency by the summation of separate losses. But in this case, the armature circuit winding losses and the excitation circuit losses are not determined by a load test, but by calculation.

For an overview, Figure 33 provides a flowchart for efficiency determination by this test method.

```
                    ┌─────────────────────────────┐
                    │    Indirect measurement     │
                    └─────────────────────────────┘
                                  │
                                  ▼
                    ┌─────────────────────────────┐
                    │       Separate losses        │
                    └─────────────────────────────┘
                                  │
                                  ▼
              ┌───────────────────────────────────────┐
              │      8.5.2 Calculated load losses      │
              │          Winding temperature           │
              │     Armature circuit winding losses    │
              │         Electrical brush losses        │
              │        Excitation circuit losses       │
              └───────────────────────────────────────┘
                                  │
                                  ▼
                   ┌────────────────────────────┐
                   │    8.3.2.2 No-load test     │
                   └────────────────────────────┘
                                  │
                                  ▼
                ┌──────────────────────────────────┐
                │          Constant losses          │
                │    Friction and windage losses    │
                │            Iron losses            │
                └──────────────────────────────────┘
                                  │
                                  ▼
                ┌──────────────────────────────────┐
                │    8.4.2 Additional load losses   │
                └──────────────────────────────────┘
                                  │
                                  ▼
                ┌──────────────────────────────────┐
                │    DC component from assigned     │
                │            allowance             │
                └──────────────────────────────────┘
                                  │
                                  ▼
                ┌──────────────────────────────────┐
                │       AC component from a         │
                │           load test              │
                └──────────────────────────────────┘
                                  │
                                  ▼
                   ┌────────────────────────────┐
                   │      8.5.3 Total losses     │
                   └────────────────────────────┘
                                  │
                                  ▼
                   ┌────────────────────────────┐
                   │          Efficiency         │
                   └────────────────────────────┘
                                                    IEC
```

Figure 33 – Efficiency determination according to method 2-1-3D

8.5.2 Test procedure

8.5.2.1 General

Apart from the determination of the excitation circuit losses, the same procedures as in 8.4.2 shall be applied.

8.5.2.2 Excitation circuit losses

Without a load test, the excitation winding losses P_e shall be calculated from $I_e^2 \times R_f$, where R_f is the resistance of the shunt excitation winding (or separately excited winding), corrected to the reference temperature specified in 5.7.3 and I_e is the excitation current according to the following list.

a) For shunt connected or separately excited generators with or without commutating poles, I_e is 110 % of the excitation current corresponding to no-load at a voltage equal to the rated voltage plus ohmic drop in the armature circuit (armature, brushes and commutating windings if any) at the current of the specific load point.

b) For compensated shunt or separately excited generators, I_e is the excitation current corresponding to no-load at a voltage equal to the rated voltage plus ohmic drop in the armature circuit at the current of the specific load point.

c) For level-compounded generators, I_e is the excitation current for the rated no-load voltage.

d) For over-compounded and under-compounded generators, and special types of generator not covered by items a) to c), I_e is subject to agreement.

e) For shunt wound motors, I_e is equal to no-load excitation current corresponding to the rated voltage.

8.5.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{117}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1   Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \tag{118}$$

$$P_e = P_f + P_{Ed} \tag{119}$$

where

P_a is the armature winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional losses;

P_e is the excitation circuit losses;

P_f is the calculated excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.6   Method 2-1-3E – Single supply back-to-back test

8.6.1   General

For an overview, Figure 34 provides a flowchart for efficiency determination by this test method.
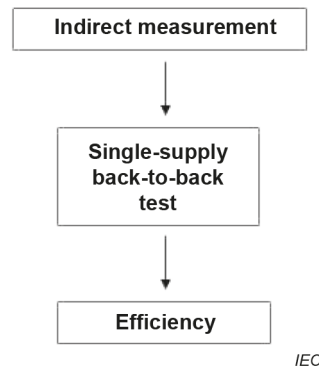
Figure 34 – Efficiency determination according to method 2-1-3E

8.6.2   Test procedure

Mechanically couple two identical machines together and connect them both electrically to the same power supply so as to operate at rated speed and rated voltage, one as a motor and the other as a generator.

NOTE   Alternatively, the losses can be supplied either by a calibrated driving motor, a booster, or otherwise by a combination of these various means.

Connect the driven machine to the supply with a booster generator in series (see Figure 35). Operate both machines at approximately the current and the internal voltage corresponding to the load point for which the efficiency is required. For motors, the supply shall deliver rated voltage and the required load to the motor. For generators, the voltage has to be adjusted by the booster for rated voltage and the required load at the generator. The voltage supply mainly covers the no-load losses, the booster covers the load losses.
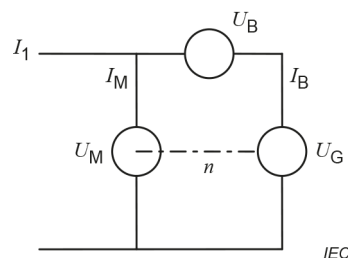
Figure 35 – Sketch for single supply back-to-back test

If no booster is available, the common terminal voltage should be adjusted so that the mean value of the currents of both machines is the rated current.

For each test, record:

- U_M, I_1 of the power supply;
- P_M absorbed at the motor terminals;
- U_B, I_B of the booster;
- n, θ_c.

For excitation systems, proceed according to 5.9.

8.6.3 Efficiency determination

If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M + P_{1E}} \qquad (120)$$

where

P_M is the power absorbed at the terminals of the machine acting as a motor (excluding excitation power);

P_T is the total losses, defined as half the total absorbed;

P_{1E} is the excitation power supplied by a separate source;

$$P_T = \frac{1}{2}\left(U_M \times I_1 + U_B \times I_B\right) + P_{1E} \; ; \qquad P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right) \qquad (121)$$

Annex A
(normative)

Calculation of values for the Eh-star method

Determine the following complex voltages and currents from the test results:

$$
\begin{aligned}
\underline{U}_{UV} &= U_{UV} \\
U'_{WU} &= \frac{U_{VW}^2 - U_{WU}^2 - U_{UV}^2}{2 \cdot U_{UV}} \\
U''_{WU} &= \sqrt{U_{WU}^2 - U_{WU}'^2} \\
U'_{VW} &= -U_{UV} - U'_{WU} \\
U''_{VW} &= -U''_{WU} \\
I'_V &= -\frac{(P_{UV} - P_{VW}) + U_{WU} \cdot I_W}{U_{UV}}
\end{aligned}
\tag{A.1}
$$

In the above formula, it is assumed that current I_W is in phase with voltage U_{WU}. In the case where the impedance of the resistor contains a noticeable reactive component, use the following formula

$$
I'_V = -\frac{(P_{UV} - P_{VW}) + R_{eh} \cdot I_W^2}{U_{UV}}
$$

where R_{eh} is the measured value of the resistive component.

$$
\begin{aligned}
I''_V &= \sqrt{I_V^2 - I_V'^2} \\
k_1 &= \frac{1}{2 \cdot I_V^2} \cdot \left(I_W^2 - I_U^2 - I_V^2 \right) \\
I'_U &= k_1 \cdot I'_V + \sqrt{\left(k_1^2 - \frac{I_U^2}{I_V^2}\right)(I_V'^2 - I_V^2)} \\
I''_U &= \frac{k_1 I_V^2 - I'_U \cdot I'_V}{I''_V} \\
I'_W &= -I'_U - I'_V \\
I''_W &= -I''_U - I''_V
\end{aligned}
\tag{A.2}
$$

Determine the inner line-to-line voltages from the complex line-to-line voltages and currents:

$$\underline{U}_{iUV} = \underline{U}_{UV} + \frac{R_{VW}}{2} \cdot \left(\underline{I}_V - \underline{I}_U \right)$$

$$\underline{U}_{iVW} = \underline{U}_{VW} + \frac{R_{VW}}{2} \cdot \left(\underline{I}_W - \underline{I}_V \right) \qquad (A.3)$$

$$\underline{U}_{iWU} = \underline{U}_{WU} + \frac{R_{VW}}{2} \cdot \left(\underline{I}_U - \underline{I}_W \right)$$

Separate into positive and negative sequence line-to-line components ($\underline{a} = e^{j2\pi/3}$):

$$\underline{U}_{iLL(1)} = \frac{1}{3} \cdot \left(\underline{U}_{iUV} + \underline{a} \cdot \underline{U}_{iVW} + \underline{a}^2 \cdot \underline{U}_{iWU} \right)$$

$$\underline{U}_{iLL(2)} = \frac{1}{3} \cdot \left(\underline{U}_{iUV} + \underline{a}^2 \cdot \underline{U}_{iVW} + \underline{a} \cdot \underline{U}_{iWU} \right) \qquad (A.4)$$

Determine the positive and negative sequence components of the inner phase voltage $\underline{U}_i$:

$$\underline{U}_{i(1)} = \frac{1}{\sqrt{3}} \cdot e^{-j\frac{\pi}{6}} \cdot \underline{U}_{iLL(1)}$$

$$\underline{U}_{i(2)} = \frac{1}{\sqrt{3}} \cdot e^{j\frac{\pi}{6}} \cdot \underline{U}_{iLL(2)} \qquad (A.5)$$

Determine the asymmetrical inner phase voltages:

$$\underline{U}_{iU} = \underline{U}_{i(1)} + \underline{U}_{i(2)}$$

$$\underline{U}_{iV} = \underline{a}^2 \cdot \underline{U}_{i(1)} + \underline{a} \cdot \underline{U}_{i(2)} \qquad (A.6)$$

$$\underline{U}_{iW} = \underline{a} \cdot \underline{U}_{i(1)} + \underline{a}^2 \cdot \underline{U}_{i(2)}$$

Determine the iron loss resistance:

$$R_{fe} = \frac{U_t^2}{P_{fe}} \qquad (A.7)$$

where

U_t is according to 6.2.5.2;

P_{fe} is according to 6.1.3.2.5.

$$\underline{I}_{feU} = \frac{U_{iU}}{R_{fe}}$$

$$\underline{I}_{feV} = \frac{U_{iV}}{R_{fe}}$$

$$\underline{I}_{feW} = \frac{U_{iW}}{R_{fe}}$$

(A.8)

Determine the inner phase currents:

$$\underline{I}_{iU} = \underline{I}_U - \underline{I}_{feU}$$
$$\underline{I}_{iV} = \underline{I}_V - \underline{I}_{feV}$$
$$\underline{I}_{iW} = \underline{I}_W - \underline{I}_{feW}$$

(A.9)

Determine the positive and negative sequence components of the inner phase currents:

$$\underline{I}_{i(1)} = \frac{1}{3} \cdot \left(\underline{I}_{iU} + \underline{a} \cdot \underline{I}_{iV} + \underline{a}^2 \cdot \underline{I}_{iW} \right)$$

$$\underline{I}_{i(2)} = \frac{1}{3} \cdot \left(\underline{I}_{iU} + \underline{a}^2 \cdot \underline{I}_{iV} + \underline{a} \cdot \underline{I}_{iW} \right)$$

(A.10)

The absolute values of the positive sequence current $I_{i(1)}$ shall be less than 30 % of the absolute value of the negative sequence current $I_{i(2)}$ in order to achieve accurate results. If this condition is not met, the test shall be repeated using a different value of R_{eh}.

Determine the air-gap power:

$$P_{\delta(1)} = 3 \cdot \left(U'_{i(1)} \cdot I'_{i(1)} + U''_{i(1)} \cdot I''_{i(1)} \right)$$

$$P_{\delta(2)} = 3 \cdot \left(U'_{i(2)} \cdot I'_{i(2)} + U''_{i(2)} \cdot I''_{i(2)} \right)$$

(A.11)

Determine the additional load losses:

$$P_{Lr} = k \cdot \left[(1-s) \cdot \left(P_{\delta(1)} - P_{\delta(2)} \right) - P_{fw} \right]$$

$$\text{where} \quad k = \frac{1}{1 + \left(I_{i(1)} / I_{i(2)} \right)^2}$$

(A.12)

Annex B
(informative)

Types of excitation systems

The types of excitation systems considered for determination of the exciter losses are:

a) shaft driven exciter

A DC or AC exciter machine is driven by the shaft of the main unit, directly or through a gear. If the main unit is a synchronous machine the excitation power is supplied to the excitation winding via slip-ring and brushes.

b) brushless exciter

An AC exciter coupled to a synchronous main unit supplies the field winding directly via rotating rectifiers, avoiding slip-rings and brushes. The exciter can be a synchronous generator or an induction machine.

Excitation power of a synchronous exciter is derived either from a directly coupled AC pilot exciter with permanent magnet excitation, or from an auxiliary (secondary) winding in the main unit stator slots (same as in e)), or from a static supply.

An induction exciter is connected to a variable AC voltage supply.

c) separate rotating exciter

A DC or AC generator as part of a separate motor generator set supplies the excitation current to the field winding of the main unit.

d) static excitation system (static exciter)

The excitation power is supplied to the field winding of the main unit by a static source such as batteries or a static power converter-fed from a separate source.

e) excitation from auxiliary winding (auxiliary winding exciter)

The excitation power for an AC generator is provided by an auxiliary (secondary) winding in the main unit stator slots, utilizing fundamental or harmonic flux, and supplied to the field winding via rectifiers, slip-rings and brushes.

Annex C
(informative)

Induction machine slip measurement

Rotor losses in induction machines are directly proportional to slip, with slip defined as the fractional departure of shaft speed from the synchronous speed corresponding to the supply frequency and the number of motor poles.

Slip measurements should be ratio-metric, i.e. concurrently account for both motor shaft speed and the frequency of the supply to the motor during the time interval over which those measurements are made. An example is the stroboscopic method, which uses supply-frequency-derived pulsed illumination of an induction motor shaft, and counts the number of slip revolutions over a known time period.

The following method is based on that principle, and provides very high accuracy slip measurements which can be automatically transferred to a data acquisition system.

Figure C.1 shows the principle of the measurement system, in which two pulse trains are generated: one derived directly from the shaft of an induction machine under test, and a second directly related to the frequency of the power supply. The diagram shows two sequential shaft encoders, each of which produce the same number of output pulses per revolution, connected to the shafts of an induction machine under test and a small synchronous motor connected to the same power supply, respectively.

The reference synchronous machine may be regarded as having zero slip.

The two pulse trains are fed to the inputs of a two-channel digital counter which has the facility to calculate and display the ratio of the two input frequencies.

If a motor-alternator set is used as the power supply for induction machine testing and measurements, then the second (reference) shaft encoder may be connected directly to the alternator shaft. A further possibility is that the reference frequency be generated electronically, using a phase-locked loop system.

If the ratio produced by the dual-channel counter, as above, is multiplied by the nominal synchronous speed of the reference (synchronous) motor in Figure C.1 (e.g. 1 500 min^{-1} for a 4 pole synchronous motor with a nominal supply frequency of 50 Hz), then the counter, configured as above, displays the shaft speed of the induction machine under test corrected for supply frequency, regardless of the induction machine pole number.

Slip may then be calculated directly from that indicated shaft speed.

If the two counters are started and stopped synchronously (i.e. at exactly the same times), the actual counting time is not critical. Slip measurement should be made over the same averaging time as the other measurements of motor voltage, current, electrical power and torque.
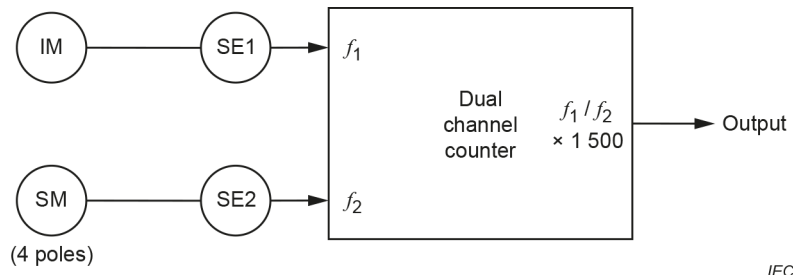
Key

IM	Induction machine under test (any number of poles)
SM	Small synchronous motor (e.g. 4 poles) or main laboratory M-G set
SE1	Sequential shaft encoder, with e.g. 600 pulses per revolution (p.p.r.)
SE2	Sequential shaft encoder, with same no. of p.p.r. as SE1
f_1	Frequency of pulse train from SE1
f_2	Frequency of pulse train from SE2
Output	ratio f_1/f_2 × synchronous speed of SM

Figure C.1 – Slip measurement system block diagram

Annex D
(informative)

Test report template for method 2-1-1B

Manufacturer Logo	

Date of test:		Report number:		Date of issue:	

Motor description							
Rated output power	kW			Manufacturer			
Rated voltage	V			Model Nr.			
Rated current	A			Serial Nr.			
Rated speed	min⁻¹			Duty type acc. to IEC 60034-1			
Supply frequency	Hz			Design			
Number of phases	-			Insulation class acc. to IEC 60085			
IEC 60034-30-1 (rated)	IE-Code			Max. ambient temperature		°C	

Initial motor conditions				**6.1.3.2.1 Rated load test**			
Test resistance	R_i	Ω		Test resistance	R_N	Ω	
Winding temperature	θi	°C		Winding temperature	θ_N	°C	
Ambient temperature	θ_a	°C		Ambient temperature	θ_a	°C	

6.1.3.2.3 Load curve test			Test resistance before load test			R	Ω	
Rated output power		%	125%	115%	100%	75%	50%	25%
Torque	T	N.m						
Input power	P_1	W						
Line current	I	A						
Operating speed	n	min⁻¹						
Teminal voltage	U	V						
Frequency	f	Hz						
Winding temperature	θ_L	°C						
			Test resistance after load test			R	Ω	

6.1.3.2.4 No-load test			Test resistance before no-load test			R	Ω	
Rated voltage		%	110%	100%	95%	90%	60%	50%	40%	30%
Input power	P_0	W								
Line current	I_0	A								
Terminal voltage	U_0	V								
Frequency	f_0	Hz								
W. temperature	θ_0	°C								
			Test resistance after no-load test			R	Ω	

6.1.3.3 Efficiency determination								
Rated output power corr.	$P_{2,\theta}$	%	125%	115%	100%	75%	50%	25%
Output power corrected	$P_{2,\theta}$	W						
Slip corrected	s_θ	p.u.						
Input power corrected	$P_{1,\theta}$	W						
Iron losses	P_{fe}	W						
Frict. and wind. losses corr.	$P_{fw,\theta}$	W						
Additional-load losses	P_{LL}	W						
Stator losses corrected	$P_{s,\theta}$	W						
Rotor losses corrected	$P_{r,\theta}$	W						
Power factor	cos φ	%						
Efficiency	η	%						

Tested by: _____   Approved _____

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Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected