

BS EN 60034-4:2008



BSI Standards Publication

Rotating electrical machines —

Part 4: Methods for determining synchronous machine quantities from tests

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National foreword

This British Standard is the UK implementation of EN 60034-4:2008. It is identical to IEC 60034-4:2008. It supersedes BS EN 60034-4:1995, which will be withdrawn on 1 July 2011.

The UK participation in its preparation was entrusted to Technical Committee PEL/2, Rotating electrical machinery.

A list of organizations represented on this committee can be obtained on request to its secretary.

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English version

**Rotating electrical machines -
Part 4: Methods for determining synchronous machine quantities
from tests
(IEC 60034-4:2008)**

Machines électriques tournantes -
Partie 4: Méthodes pour la détermination,
à partir d'essais, des grandeurs
des machines synchrones
(CEI 60034-4:2008)

Drehende elektrische Maschinen -
Teil 4: Verfahren zur Ermittlung
der Kenngrößen von Synchronmaschinen
durch Messungen
(IEC 60034-4:2008)

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Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

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European Committee for Electrotechnical Standardization
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Foreword

The text of document 2/1488/FDIS, future edition 3 of IEC 60034-4, prepared by IEC TC 2, Rotating machinery, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60034-4 on 2008-07-01.

This European Standard supersedes EN 60034-4:1995.

The main changes with respect to EN 60034-4:1995 are listed below:

- tests described in supplement A of EN 60034-4:1995 were partly removed for lack of relevance in current practice;
- provisions were made for tests on machines with brushless excitation;
- a table of test methods indicates preferred tests, and a test cross-reference is provided;
- the conventional two-axes salient-pole machine model description was added in an annex.

The following dates were fixed:

- | | | |
|--|-------|------------|
| – latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement | (dop) | 2009-04-01 |
| – latest date by which the national standards conflicting with the EN have to be withdrawn | (dow) | 2011-07-01 |

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60034-4:2008 was approved by CENELEC as a European Standard without any modification.

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application 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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60034-1	2004	Rotating electrical machines - Part 1: Rating and performance	EN 60034-1	2004
IEC 60034-2-1	- ¹⁾	Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)	EN 60034-2-1	2007 ²⁾
IEC 60034-2A	- ¹⁾	Rotating electrical machines - Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles) – First supplement: Measurement of losses by the calorimetric method	-	-
IEC 60051	Series	Direct acting indicating analogue electrical measuring instruments and their accessories	EN 60051	Series

¹⁾ Undated reference.

²⁾ Valid edition at date of issue.

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ROTATING ELECTRICAL MACHINES ±

Part 4: Methods for determining synchronous machine quantities from tests

1 Scope

This part of IEC 60034 applies to three-phase synchronous machines of 1 kVA rating and larger with rated frequency of not greater than 500 Hz and not less than 10 Hz.

Most of the methods are intended to be used for machines having an excitation winding with slip-rings and brushes for their supply. Synchronous machines with brushless excitation require special effort for some of the tests. For machines with permanent magnet excitation, there is a limited applicability of the described tests, and special precautions have to be taken against irreversible demagnetization.

Excluded are axial-field machines and special synchronous machines such as inductor type machines and transversal flux machines.

It is not intended that this standard be interpreted as requiring any or all of the tests described therein on any given machine. The particular tests to be carried out shall be subject to agreement between manufacturer and customer.

2 Normative references

The following referenced documents are indispensable for the application 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 60034-1:2004, *Rotating electrical machines ± Part 1: Rating and performance*

IEC 60034-2-1, *Rotating electrical machines ± Part 2-1: Standards methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*

IEC 60034-2A, *Rotating electrical machines ± Part 2: Methods for determining losses and efficiency from tests (excluding machines for traction vehicles) ± First supplement: Measurement of losses by the calorimetric method*

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

initial starting impedance, synchronous motors

quotient of the applied armature voltage and the sustained average armature current, the machine being at standstill

3.2

direct-axis synchronous reactance

the quotient of the sustained value of that fundamental a.c. component of armature voltage, which is produced by the total direct-axis primary flux due to direct-axis armature current, and the value of the fundamental a.c. component of this current, the machine running at rated speed

[IEV 411-50-07]

3.3

direct-axis transient reactance

the quotient of the initial value of a sudden change in that fundamental a.c. component of armature voltage, which is produced by the total direct-axis primary flux, and the value of the simultaneous change in fundamental a.c. component of direct-axis armature current, the machine running at rated speed and the high decrement components during the first cycles being excluded

[IEV 411-50-09]

3.4

direct-axis sub-transient reactance

the quotient of the initial value of a sudden change in that fundamental a.c. component of armature voltage, which is produced by the total direct-axis armature flux, and the value of the simultaneous change in fundamental a.c. component of direct-axis armature current, the machine running at rated speed

[IEV 411-50-11]

3.5

quadrature-axis synchronous reactance

the quotient of the sustained value of that fundamental a.c. component of armature voltage, which is produced by the total quadrature-axis primary flux due to quadrature-axis armature current, and the value of the fundamental a.c. component of this current, the machine running at rated speed

[IEV 411-50-08]

3.6

quadrature-axis transient reactance

the quotient of the initial value of a sudden change in that fundamental a.c. component of armature voltage, which is produced by the total quadrature-axis armature winding flux, and the value of the simultaneous change in fundamental a.c. component of quadrature-axis armature current, the machine running at rated speed and the high decrement components during the first cycles being excluded

[IEV 411-50-10]

3.7

quadrature-axis sub-transient reactance

the quotient of the initial value of a sudden change in that fundamental a.c. component of armature voltage, which is produced by the total quadrature-axis primary flux and the value of the simultaneous change in fundamental a.c. component of quadrature-axis armature current, the machine running at rated speed

[IEV 411-50-12]

3.8

positive sequence reactance

the quotient of the reactive fundamental component of the positive sequence armature voltage, due to the sinusoidal positive sequence armature current at rated frequency, by the value of that component of current, the machine running at rated speed

[IEV 411-50-14]

3.9**negative sequence reactance**

the quotient of the reactive fundamental component of negative sequence armature voltage, due to the sinusoidal negative sequence armature current at rated frequency, by the value of that component of current, the machine running at rated speed

[IEV 411-50-15]

3.10**zero sequence reactance**

the quotient of the reactive fundamental component of zero sequence armature voltage, due to the presence of fundamental zero sequence armature current at rated frequency, by the value of that component of current, the machine running at rated speed

[IEV 411-50-16]

3.11**Potier reactance**

a reactance taking into account the leakage of the field winding, on load and in the over-excited region, which is used in place of the armature leakage reactance to calculate the excitation on load by means of the Potier method

[IEV 411-50-13]

3.12**armature-leakage reactance**

quotient of the reactive fundamental component of armature voltage due to the leakage flux of armature winding and the fundamental component of armature current, the machine running at rated speed

3.13**armature resistance**

resistance measured by direct current between terminals of the armature winding, assigned to a certain winding temperature, expressed as per phase value

3.14**excitation winding resistance**

resistance measured by direct current between terminals of the excitation winding, assigned to a certain winding temperature

3.15**positive sequence resistance**

the quotient of the in-phase component of positive sequence armature voltage corresponding to losses in the armature winding and stray load losses due to the sinusoidal positive sequence armature current, by the value of that component of current, the machine running at rated speed

[IEV 411-50-18]

3.16**negative sequence resistance**

the quotient of the in-phase fundamental component of negative sequence armature voltage, due to the sinusoidal negative sequence armature current at rated frequency, by the value of that component of current, the machine running at rated speed

[IEV 411-50-19]

3.17**zero sequence resistance**

the quotient of the in-phase fundamental component of zero sequence armature voltage, due to the fundamental zero sequence armature current of rated frequency, by the value of that component of current, the machine running at rated speed

[IEV 411-50-20]

3.18

short-circuit ratio

the ratio of the field current for rated armature voltage on open-circuit to the field current for rated armature current on sustained symmetrical short-circuit, both with the machine running at rated speed

[IEV 411-50-21]

3.19

direct-axis transient open-circuit time constant

the time required, following a sudden change in operating conditions, for the slowly changing component of the open-circuit armature voltage, which is due to direct-axis flux, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-27]

3.20

direct-axis transient short-circuit time constant

the time required, following a sudden change in operating conditions, for the slowly changing component of direct-axis short-circuit armature current to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-28]

3.21

direct-axis sub-transient open-circuit time constant

the time required, following a sudden change in operating conditions, for the rapidly changing component present during the first few cycles of the open-circuit armature winding voltage which is due to direct-axis flux, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-29]

3.22

direct-axis sub-transient short-circuit time constant

the time required, following a sudden change in operating conditions, for the rapidly changing component, present during the first few cycles in the direct-axis short-circuit armature current, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-30]

3.23

quadrature-axis transient open-circuit time constant

the time required, following a sudden change in operating conditions, for the slowly changing component of the open-circuit armature winding voltage which is due to quadrature-axis flux, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-32]

3.24

quadrature-axis transient short-circuit time constant

the time required, following a sudden change in operating conditions, for the slowly changing component of quadrature-axis short-circuit armature winding current, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-33]

3.25**quadrature-axis sub-transient open-circuit time constant**

the time required, following a sudden change in operating conditions, for the rapidly changing component of the open-circuit armature winding voltage which is due to quadrature-axis flux, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-34]

3.26**direct-axis open-circuit equivalent damper circuit time constant**

time required for the induced current component in the equivalent damper circuit to decrease to $1/e \approx 0,368$ of its initial value following a sudden change in operating conditions with open-circuited armature winding and the excitation winding being also open, the machine running at rated speed

3.27**direct-axis short-circuit equivalent damper winding time constant**

time required for the induced current component of the equivalent damper winding to decrease to $1/e \approx 0,368$ of its initial value following a sudden change in operating conditions with short-circuited armature winding the excitation winding being open, and the machine running at rated speed

3.28**quadrature-axis sub-transient short-circuit time constant**

the time required, following a sudden change in operating conditions, for the rapidly changing component present during the first few cycles in the quadrature-axis short-circuit armature winding current, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-35]

3.29**short-circuit time constant of armature windings**

the time required, following a sudden change in operating conditions, for the d.c. component present in the short-circuit armature winding current, to decrease to $1/e$, that is 0,368 of its initial value, the machine running at rated speed

[IEV 411-48-31]

3.30**unit acceleration time**

the time which would be required to bring the rotating parts of a machine from rest to rated speed if the accelerating torque were constant and equal to the quotient of rated active power by rated angular velocity

[IEV 411-48-15]

3.31**stored energy constant**

quotient of the kinetic energy stored in the rotor when running at rated speed and of the rated apparent power

3.32**rated excitation current**

current in the excitation winding when the machine operates at rated voltage, current, power-factor and speed

3.33**excitation current, corresponding to the rated armature short-circuit current**

current in the excitation winding when the machine operates at rated speed and sustained rated armature current, the armature (primary) winding being short-circuited

3.34**rated voltage regulation**

change in the terminal voltage when rated operation is replaced by no-load operation with open-circuit armature and with unchanged speed and excitation current

3.35**frequency response characteristics**

a set of characteristic curves or analytical expressions relating complex admittance or its reciprocal complex impedance (or components thereof) to slip at rated supplied frequency unless otherwise stated

3.36**frequency response characteristic of direct-axis reactance**

complex quotient expressed as a slip function of the sustained complex value (vector) of that fundamental component of armature voltage which is produced by the d-axis armature current, and the vector of the fundamental component of this current, the machine running at a given slip, with the excitation winding short-circuited

NOTE The term for the complex representation of a sinusoidal quantity of one single frequency is phasor or, alternatively, vector which is the term used in this standard.

3.37**frequency response characteristic of quadrature-axis reactance**

complex quotient expressed as a slip function of the sustained vector of that fundamental component of armature voltage which is produced by the q-axis armature flux due to q-axis armature current and the vector of the fundamental component of this current, the machine running at a given slip, with the excitation winding short-circuited

3.38**frequency response characteristic of excitation factor**

complex quotient of the sustained vector of the armature voltage, produced by the current in the excitation winding at frequency $s \cdot f$, and the complex value of the voltage applied to the excitation winding, the machine running at a rated speed

NOTE There are several methods of deriving the frequency response characteristics (3.36 to 3.38) (or in the case of 3.36 and 3.37 their reciprocal values), see for instance 7.28.2 to 7.28.4. Characteristics may be obtained with the excitation winding closed through a specified impedance.

4 Symbols and units

f	Frequency
f_N	Rated frequency
$G(js)$	Complex frequency response characteristic of excitation factor
H	Stored energy constant
I, i	Current
I_N	Rated current
I_{fk}	Excitation current, for rated armature short-circuit current
I_{fN}	Rated excitation current
K_c	Short-circuit ratio
$R_{(0)}$	Zero-sequence resistance
$R_{(1)}$	Positive-sequence armature winding resistance
$R_{(2)}$	Negative-sequence resistance
R_a	Armature direct-current resistance
R_f	Excitation winding direct-current resistance
s	Slip
S_N	Rated apparent power

U, u	Voltage
U_N	Rated voltage
$X_{(0)}$	Zero-sequence reactance
$X_{(1)}$	Positive-sequence reactance
$X_{(2)}$	Negative-sequence reactance
X_d	Direct-axis synchronous reactance
X'_d	Direct-axis transient reactance
X''_d	Direct-axis sub-transient reactance
X_p	Potier reactance
X_q	Quadrature-axis synchronous reactance
X'_q	Quadrature-axis transient reactance
X''_q	Quadrature-axis sub-transient reactance
X_σ	Armature-leakage reactance
$X_d(j\omega)$	Complex frequency response characteristic of direct-axis reactance
$X_q(j\omega)$	Complex frequency response characteristic of quadrature-axis reactance
Z	Impedance
Z_N	Rated impedance
ΔU_N	Rated voltage regulation
δ	Load angle
τ_a	Armature short-circuit time constant
τ_{kd}	Direct-axis short-circuit equivalent damper winding time constant
τ_{kdo}	Direct-axis open-circuit equivalent damper circuit time constant
τ'_d	Direct-axis transient short-circuit time constant
τ'_{do}	Direct-axis transient open-circuit time constant
τ'_q	Quadrature-axis transient short-circuit time constant
τ'_{qo}	Quadrature-axis transient open-circuit time constant
τ''_d	Direct-axis sub-transient short-circuit time constant
τ''_{do}	Direct-axis sub-transient open-circuit time constant
τ''_q	Quadrature-axis sub-transient short-circuit time constant
τ''_{qo}	Quadrature-axis sub-transient open-circuit time constant
τ_J	Unit acceleration time

5 Overview of tests

Table 1 gives a cross-reference table of the tests to determine synchronous machine quantities and indicates preferred methods.

Table 1 ± Test methods and cross-reference table

Quantity	Clause	Test description	Test	Preference/ uncertainty
Reactances				
Direct-axis synchronous reactance X_d	7.2.1	No-load saturation, sustained three-phase short-circuit	6.4 and 6.5	Preferred (unsaturated)
	7.2.2	Motor no-load	6.6	Preferred (saturated)
	7.2.3	Phase shifting	6.7	
	7.2.4	On-load measuring the load angle	6.10	
Direct-axis transient reactance X'_d	7.3.1	Sudden three-phase short-circuit	6.12	Preferred
	7.3.2	Voltage recovery	6.13	
	7.3.3	DC decay in the armature winding at standstill	6.15	
	7.3.4	Calculation from test values	-	
Direct-axis sub-transient reactance X''_d	7.4.1	Sudden three-phase short-circuit	6.12	Preferred
	7.4.2	Voltage recovery	6.13	
	7.4.3	Applied voltage test with rotor in direct and quadrature axis	6.17	
	7.4.4	Applied voltage with the rotor in arbitrary position	6.18	
Quadrature axis synchronous reactance X_q	7.5.1	Negative excitation	6.9	Preferred (unsaturated)
	7.5.2	Low slip	6.11	
	7.5.3	Phase shifting	6.7	
	7.5.4	On-load measuring the load angle	6.10	
Quadrature-axis transient reactance X'_q	7.6.1	DC decay test at standstill	6.15	
	7.6.2	Calculation from test values	-	
Quadrature-axis sub-transient reactance X''_q	7.7.1	Applied voltage test with rotor in direct and quadrature axis	6.17	Preferred
	7.7.2	Applied voltage with the rotor in arbitrary position	6.18	
Zero-sequence reactance $X_{(0)}$	7.8.1	Single-phase voltage application to the three phases	6.19	Preferred
	7.8.2	Line-to-line and to neutral sustained short-circuit	6.22	
Negative-sequence reactance $X_{(2)}$	7.9.1	Line-to-line sustained short-circuit	6.20	Preferred
	7.9.2	Negative-phase sequence	6.23	
	7.9.3	Calculation from test values	-	
	7.9.4	Sudden line-to-line short-circuit	6.21	
	7.9.5	DC decay in the armature winding at standstill	6.15	
Armature leakage reactance X_σ	7.10	Rotor removed	6.28	
Potier reactance X_p	7.11	No-load saturation, sustained three-phase short-circuit	6.4 and 6.5	
Resistances				
Zero-sequence resistance $R_{(0)}$	7.12.1	Single-phase voltage application to the three phases	6.19	Preferred
	7.12.2	Line-to-line and to neutral sustained short-circuit	6.22	
Positive-sequence armature winding resistance $R_{(1)}$	7.13	Calculation from test values	-	
Negative-sequence resistance $R_{(2)}$	7.14.1	Line-to-line sustained short-circuit	6.20	Preferred
	7.14.2	Negative-phase sequence	6.23	
Armature resistance R_a	7.15	Ammeter-voltmeter or bridge	6.3	
Excitation winding resistance R_f	7.15	Ammeter-voltmeter or bridge	6.3	

Table 1 (continued)

Quantity	Clause	Test description	Test	Preference/ uncertainty
Time Constants				
Direct-axis transient short-circuit time constant τ'_d	7.16.1 7.16.2 7.16.3 7.16.4 7.16.5	Sudden three-phase short-circuit Field current decay at rated speed with armature winding short-circuited DC decay in the armature winding at standstill Suddenly applied excitation with short-circuited armature Field current decay at standstill with two phases of armature winding short-circuited	6.12 6.25 6.15 6.26 6.27	Preferred
Direct-axis transient open-circuit time constant τ'_{do}	7.17.1 7.17.2 7.17.3 7.17.4 7.17.5	Field current decay, with the armature winding open-circuited, at rated speed Field current decay, with the armature winding open-circuited, at standstill Voltage recovery DC decay in the armature winding at standstill Suddenly applied excitation with open-circuited armature	6.24.1 6.24.2 6.13 6.15 6.16	Preferred
Direct-axis sub-transient short-circuit time constant τ''_d	7.18	Sudden three-phase short-circuit	6.12	
Direct-axis sub-transient open-circuit time constant τ''_{do}	7.19.1 7.19.2	Voltage recovery DC decay in the armature winding at standstill	6.13 6.15	Preferred
Quadrature-axis transient short-circuit time constant τ'_q	7.20.1 7.20.2	Calculation from test values DC decay in the armature winding at standstill	- 6.15	Preferred
Quadrature-axis transient open-circuit time constant τ'_{qo}	7.21.1	DC decay in the armature winding at standstill	6.15	
Quadrature-axis sub-transient short-circuit time constant τ''_q	7.22.1 7.22.2	Calculation from test values DC decay in the armature winding at standstill	- 6.15	Preferred
Quadrature-axis sub-transient open-circuit time constant τ''_{qo}	7.23.1	DC decay in the armature winding at standstill	6.15	
Armature short-circuit time constant τ_a	7.24.1 7.24.2	Sudden three-phase short-circuit Calculation from test values	6.12 -	Preferred
Other quantities				
Unit acceleration time τ_J , stored energy constant H	7.25.1 7.25.2	Suspended rotor oscillation No-load retardation	6.30 6.29	- Preferred
Rated excitation current i_{fN}	7.26.1 7.26.2 7.26.3 7.26.4	Direct measurement Potier diagram ASA diagram Swedish diagram	6.2 - - -	Preferred
Excitation current, re: rated armature short-circuit current i_{fk}	7.27.1 7.27.2	Over-excitation at zero power-factor and variable armature (primary) winding voltage Sustained three-phase short-circuit test	6.32 6.5	Preferred
Frequency response characteristics	7.28.2 7.28.3 7.28.4	Asynchronous operation at reduced voltage Applied variable frequency voltage at standstill DC decay in the armature winding at standstill	6.33 6.34 6.15	Preferred
Short-circuit ratio K_c	7.29	No-load saturation, Sustained three-phase short-circuit	6.4 6.5	
Rated voltage regulation ΔU_N	7.30.1 7.30.2	Direct measurement By diagram from no-load saturation characteristic and known i_{fN}	6.2 6.4.2	Preferred
Initial starting impedance of synchronous motors Z_{st}	7.31	Locked rotor	6.31	

6 Test procedures

6.1 General

6.1.1 Instrumentation requirements

Indicating measuring instruments and their accessories, such as measuring transformers, shunts and bridges used during tests, unless otherwise stated, shall have an accuracy class of at least 0,5 according to IEC 60051. The instruments used for determining d.c. resistances shall have an accuracy class of at least 0,2.

The accuracy class for the oscillographic measuring and other recording equipment should be chosen with due regard to the rating of the machine to be tested.

The speed of rotation may be determined either by means of a stroboscopic method or by using tachometers (mechanical or electrical) or by means of a frequency meter when the machine is running synchronously with any other machine or running on its own.

6.1.2 Excitation system requirements

In case of a synchronous machine provided with a brushless exciter, the excitation winding is connected via a rotating converter, mostly a diode rectifier, to the exciter armature winding without slip-rings. As a result some tests either requiring measurement of excitation current, feeding the field winding from a separate source or its short-circuiting may not be conducted without special arrangements (for example, mounting temporary slip-rings on the shaft).

6.1.3 Test conditions

Tests for determining synchronous machine quantities shall be conducted on a complete machine with all devices for automatic regulation being switched off unless specifically required by the test procedure. Devices which have no impact on the values of the parameters need not be installed.

Unless otherwise stated, the tests shall be conducted at the rated speed of rotation.

NOTE Test methods with the rotor at standstill may give results different from those received on a rotating machine, for example when damper winding quantities are dependent upon centrifugal forces.

Winding temperatures are measured when

- the quantities to be determined by the test depend on temperature, or
- safety considerations require monitoring the temperature during tests.

In cases where transient temperatures might exceed the safe values, it is recommended that the tests be started only after the machine has been run at no-load with normal cooling or has been at rest for a period to ensure low starting temperature, and the temperatures should be carefully monitored or pre-determined so that the test may be discontinued before the temperature becomes excessive.

During the test, the machine winding connection, as a rule, should be as for normal working.

The determination of all quantities is made with star connection of the armature winding (unless special connections such as open delta are specified). When the armature winding is actually delta connected, the values of the quantities, obtained in accordance with this standard, shall correspond to an equivalent star-connected winding.

6.1.4 Per unit base quantities

All equations are given either in physical values using SI units, or in per unit referred to specified basic values. Generally, these basic values are rated voltage (U_N), and rated apparent power (S_N), with derived basic current

$$I_N = \frac{S_N}{\sqrt{3} U_N}$$

and basic impedance

$$Z_N = \frac{U_N^2}{S_N} = \frac{S_N}{3I_N^2}$$

Intermediate calculations may be performed in physical values with subsequent conversion to the quantity in per unit value. It is recommended to express time in seconds. In the calculations of characteristics, and when drawing diagrams, excitation current corresponding to the rated voltage on the no-load curve is taken as the basic value of the excitation current. When the diagrams and characteristics are drawn, the currents and voltages may be designated in physical values.

If a machine has several rated values, those taken for the basic values shall be stated.

Unless otherwise stated, the above-mentioned system is accepted in this standard. Small letters designate the quantities in per unit values, and capital letters designate physical quantities.

In the formulae given in this standard for determining synchronous reactances, the positive sequence armature resistance, unless otherwise stated, is considered to be negligible. When the positive sequence armature resistance constitutes more than 0,2 of the measured reactance, the formulae shall be considered as approximate.

6.1.5 Conventions and assumptions

The definitions of the majority of quantities and their experimental methods of determination, as given in this standard, correspond to the widely accepted two-axis theory of synchronous machines with approximate representation of all circuits additional to the field-winding, and stationary circuits relative to it, by two equivalent circuits, one along the direct axis and the other along the quadrature axis, neglecting armature resistance or taking it into consideration only approximately.

As a consequence of this approximate machine representation, three reactances (synchronous, transient and sub-transient) and two time constants (transient and sub-transient) are considered in this standard for transient phenomena studies along the direct axis, two reactances (synchronous and sub-transient) and one time constant (sub-transient) along the quadrature axis, and the armature short-circuit time constant.

These time constants are based on the assumption of an exponential decrease of the particular components of quantities involved (currents, voltages, etc.). If the plot of the measured component under consideration does not decrease as a pure exponential, as in the case, for example, of a solid rotor machine, the time constant should normally be interpreted as the time required for the component to decrease to $1/e \approx 0,368$ of its initial value. Exponential decay curves corresponding to these time constants shall be considered as equivalent curves replacing the actual measured ones.

NOTE 1 Frequently the conventional representation by means of three reactances and two time-constants is not satisfactory to describe the machine sufficiently, and higher order parameters should be added to the model. This

is the case with turbo type machines, where the model may be amended by parameters X_d''', τ_d''' . Their determination may be performed as outlined in this document (see Annex B).

NOTE 2 This document provides methods to determine the quadrature axis transient parameters $X_q', \tau_q', \tau_{qo}'$ (see 6.15), though they are frequently not considered in conventional calculations when $X_q' = X_q$ is assumed.

6.1.6 Consideration of magnetic saturation

Synchronous machine quantities vary with saturation of the magnetic circuits. In practical calculations, both saturated and unsaturated values are used.

In this standard, unless otherwise stated, the “saturated value” of reactances and resistances will be taken as the rated (armature) voltage value of the quantity, and their “unsaturated value” will be taken as the rated (armature) current value, except synchronous reactances, the unsaturated values of which will be taken as the low voltage values of the quantities, the saturated as the rated voltage values of the machine on load. The saturated values of the quantities will depend on the mode of operation.

The rated (armature) voltage value of a quantity (except synchronous reactance) corresponds to the magnetic condition of the machine during sudden short-circuit of the armature winding from no-load rated voltage operation, the machine running at rated speed.

The rated (armature) current value of a quantity corresponds to the condition in which the fundamental a.c. component of armature current which determines this particular quantity is equal to the rated current.

The no-load saturation and sustained three-phase short-circuit tests are usually used for unsaturated values of X_d . The motor at no-load and the phase-shifting tests permit the unsaturated and saturated values of X_d to be determined. The saturated quantities determined by these tests can however not be referred to the specific mode of operation of the machine and may be used only for comparison of the values obtained for different machines by the same tests.

The negative excitation and low slip tests are used for unsaturated values. The phase shifting test permits the unsaturated and saturated values of X_q to be determined.

The method of sudden three-phase short-circuit is preferred. It permits saturated and unsaturated values of X_d' to be determined.

If the calculation method is used, the values of τ_{do}' and τ_d' obtained from the field current decay tests at rated speed (see 6.24 and 6.25) are preferred.

The sudden three-phase short-circuit test as well as the field current decay tests at rated speed (for determining τ_{do}' and τ_d') may be performed on a brushless machine if the machine is excited from its own or a separate exciter via temporary slip-rings mounted on the rotor, the exciter being separately excited. The voltage recovery test may be performed without slip-rings if the machine is excited from its own exciter, the latter being separately excited. Otherwise, the value of X_d' in a brushless machine is determined by calculation from the test values of τ_{do}' and τ_d' obtained from the field current decay tests at standstill with the armature winding open-circuited (time constant τ_{do}' , see 6.24) and with two phases of armature winding short-circuited (time constant τ_d' , see 6.27).

The sudden three-phase short-circuit method is preferred. It permits saturated and unsaturated values of X_d'' to be determined.

The applied-voltage methods are practically equivalent and may be used for the unsaturated values of X''_d and X''_q , but are usually not practicable for the saturated value because of the large current required and possible overheating of the windings and solid parts.

If a sudden short-circuit test is performed for determining X'_d , then τ'_d should be determined from the same test. In all other cases, preference is given to the field current decay method at rated speed with the armature winding short-circuited.

If the time constant τ_a is less than one fundamental period, its value is determined from the decrease of the aperiodic (d.c.) component of the current in the armature winding; if τ_a exceeds one period, the method of measurement of the decrease of the periodic component in the excitation winding current is preferred.

NOTE For synchronous compensators, the rated active power (output) is replaced by the rated apparent power.

All the above-mentioned methods are practically equivalent. The application of one or another method depends on the design and the apparent power of the machine under test.

6.2 Direct measurements of excitation current at rated load

I_{fN} is the excitation winding current when the machine operates at rated values of voltage, current, power-factor and speed.

The graphical methods are used when the zero-power factor loading of the tested machine is performed. When determining the rated excitation current by the direct measurement during operation under rated conditions, the machine under test should be excited from its own automatic regulation system because the excitation current when the machine is excited from automatic system may differ from that when the machine is separately excited (especially in machines with static excitation system).

NOTE In brushless machines direct measurement of the excitation current may be performed using temporary slip-rings.

6.3 Direct-current winding resistance measurements

Any d.c. supply (battery, generator, etc.) of required output rating with stable voltage may be used for measuring d.c. resistance by the voltmeter and ammeter method (recommended) or by the bridge method.

The resistance shall be measured directly at the winding terminals with the rotor at rest.

The single bridge method is not permissible for measuring resistances less than 1 Ω .

Armature winding resistance shall be measured for each phase separately. If, for some reason, phase resistance cannot be measured directly, the measurements are to be made between each pair of the line terminals of the armature winding.

In measuring the d.c. resistance of the armature or of the excitation winding by

- the bridge method, it is necessary to take at least three readings, each time disturbing the bridge balance. The resistance should be measured on the slip-rings or winding terminals so that the resistance of the brushes and their contacts are not included;
- the voltmeter and ammeter method, it is recommended to take three to five readings at various steady values of the current.

The current value during the d.c. resistance measurements should be such that the winding temperature rise during the test is not more than 1 K, assuming adiabatic heating. To calculate adiabatic heating use formula:

$$\Delta\theta = \frac{j^2}{c} \quad \text{K/s}$$

where

j is the current density during test, in amperes per mm²;

c is a constant, equal to 200 for copper and 86 for aluminium.

If the winding heating is unknown, the current should be not more than 0,1 of the rated winding current and should be supplied for not longer than 1 min.

The time of the measurements should be such that, at the instant of taking the measurements, the instrument readings are steady, i.e. transients have disappeared both in the instruments themselves and in the circuits the resistances of which are being measured.

The winding temperature during the measurements should be determined by means of built-in or embedded temperature detectors where fitted.

Thermometers and thermocouples used for contact measuring the winding temperature should have been in place for not less than 15 min and should be protected from any outside influence.

The identification numbers of the instruments should be recorded, in order to use the same instruments when performing the heat test.

6.4 No-load saturation test

6.4.1 Test procedure

The no-load saturation test is conducted:

- a) driving the test machine as a generator by some prime-mover; or
- b) running the machine under test as a motor without shaft load from a source of alternating symmetrical three-phase voltage (for symmetry of voltage, see 7.2 of IEC 60034-1:2004);
or
- c) during retardation of the machine under test.

When making the no-load test, excitation changes should be made in gradual steps from high to low voltage using evenly distributed points; if possible, from the voltage value corresponding to the excitation at rated load, but not below 1,3 of the rated voltage of the machine under test, down to 0,2 of its rated voltage, unless the residual voltage is higher.

Measure the residual voltage of the generator when the excitation current is decreased to zero.

It is preferred to conduct test a) with a d.c. calibrated prime-mover, as it also permits the no-load losses to be determined during the test.

When using test b), it is also necessary to measure armature current. At each voltage step, readings shall be recorded for minimum armature current that corresponds to unity power-factor.

When using test c), the rate of deceleration should not exceed 0,04 of the rated speed per second. However, when the machine under test has a rate of deceleration above 0,02 rated speed per second, excitation from a separate source is required in order to have more stable excitation during the test. Before disconnecting from the line, the machine is excited to the highest required value, but not below 1,3 of the rated voltage of the machine. The excitation is lowered in steps and at each step, readings of speed (frequency) are taken simultaneously