

INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Rotating electrical machines –
Part 4: Methods for determining synchronous machine quantities from tests**

**Machines électriques tournantes –
Partie 4: Méthodes pour la détermination, à partir d'essais, des grandeurs des
machines synchrones**

Withdawn



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Withdrawn

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ROTATING ELECTRICAL MACHINES –

Part 4: Methods for determining synchronous machine quantities from tests

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- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60034-4 has been prepared by IEC technical committee 2: Rotating machinery.

This third edition cancels and replaces the second edition published in 1985 and its amendment 1 (1995). This edition constitutes a technical revision. The main changes with respect to the previous edition are listed below:

- Tests described in Supplement A of the previous edition were partly removed for lack of relevance in current practise.
- 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 text of this standard is based on the following documents:

FDIS	Report on voting
2/1488/FDIS	2/1495/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of IEC 60034 series, under the general title *Rotating electrical machines*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

Withdrawn

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
$G(j\omega)$	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	Sudden three-phase short-circuit	6.12	Preferred
	7.16.2	Field current decay at rated speed with armature winding short-circuited	6.25	
	7.16.3	DC decay in the armature winding at standstill	6.15	
	7.16.4	Suddenly applied excitation with short-circuited armature	6.26	
	7.16.5	Field current decay at standstill with two phases of armature winding short-circuited	6.27	
Direct-axis transient open-circuit time constant τ_{do}'	7.17.1	Field current decay, with the armature winding open-circuited, at rated speed	6.24.1	Preferred
	7.17.2	Field current decay, with the armature winding open-circuited, at standstill	6.24.2	
	7.17.3	Voltage recovery	6.13	
	7.17.4	DC decay in the armature winding at standstill	6.15	
	7.17.5	Suddenly applied excitation with open-circuited armature	6.16	
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	Voltage recovery	6.13	Preferred
	7.19.2	DC decay in the armature winding at standstill	6.15	
Quadrature-axis transient short-circuit time constant τ_q'	7.20.1	Calculation from test values	-	Preferred
	7.20.2	DC decay in the armature winding at standstill	6.15	
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	Calculation from test values	-	Preferred
	7.22.2	DC decay in the armature winding at standstill	6.15	
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	Sudden three-phase short-circuit	6.12	Preferred
	7.24.2	Calculation from test values	-	
Other quantities				
Unit acceleration time τ_J , stored energy constant H	7.25.1	Suspended rotor oscillation	6.30	-
	7.25.2	No-load retardation	6.29	Preferred
Rated excitation current i_{fN}	7.26.1	Direct measurement	6.2	Preferred
	7.26.2	Potier diagram	-	
	7.26.3	ASA diagram	-	
	7.26.4	Swedish diagram	-	
Excitation current, re: rated armature short-circuit current i_{fk}	7.27.1	Over-excitation at zero power-factor and variable armature (primary) winding voltage	6.32	Preferred
	7.27.2	Sustained three-phase short-circuit test	6.5	
Frequency response characteristics	7.28.2	Asynchronous operation at reduced voltage	6.33	Preferred
	7.28.3	Applied variable frequency voltage at standstill	6.34	
	7.28.4	DC decay in the armature winding at standstill	6.15	
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	Direct measurement	6.2	Preferred
	7.30.2	By diagram from no-load saturation characteristic and known i_{fN}	6.4.2	
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

with constant excitation current. The retardation test shall be repeated to obtain all the steps required.

Record simultaneously:

- excitation current;
- line voltage;
- frequency (or speed);
- for test b), minimum armature current that corresponds to unity power-factor;
- for test c), armature voltage.

6.4.2 No-load saturation characteristic determination

Plot the armature open-circuit winding voltage at the terminals (ordinate) versus the excitation current (abscissa) at rated speed (frequency) as shown in Figure 8. If, due to high residual voltage, the no-load characteristic intersects the axis above the origin, a correction shall be made. To this end, the straight portion of the no-load curve, which is usually called the air-gap line, is projected to the point of intersection with the abscissa axis. The length on the abscissa axis cut by this projected curve represents the correction value that shall be added to all the measured values of the excitation current.

When the test frequency differs from the rated value, all the measured voltage values shall be referred to the rated frequency.

6.5 Sustained three-phase short-circuit test

6.5.1 Test procedure

The sustained three-phase short-circuit test is conducted by

- a) driving the test machine as a generator by some prime-mover; or
- b) a retardation of the test machine; or
- c) driving the test machine as a motor.

When using tests a) or b), the short-circuit should be made as close to the machine terminals as possible, applying the excitation current after closing the short-circuit. Take one of the readings at a current close to the rated armature current.

It is preferred to conduct test a) with a d.c. calibrated prime-mover, as it also permits the short-circuit losses to be determined during the test.

Record simultaneously excitation current and armature line current.

NOTE 1 The speed of rotation (or frequency) may differ from the rated value but should not fall below 0,2 of rated value.

When using test b), the rate of deceleration should not exceed 0,10 of rated speed per second. If the machine under test has a rate of deceleration exceeding 0,04 of rated speed per second, excitation from a separate source is required.

When using test c), the machine is operated as a synchronous motor at a fixed voltage, preferably about 1/3 normal voltage, but 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.

NOTE 2 The maximum test current value, traditionally set at 125 %, should be obtained from the manufacturer as stator cooling may not permit operation in excess of 100 % rated current without damage.

For each point taken in descending order (for more uniform stator coil temperatures), record armature current, armature voltage and field current.

6.5.2 Three-phase sustained short-circuit characteristic

The relationship between the armature short-circuited winding current and the excitation current is drawn from the data of the three-phase sustained short-circuit test (6.5.1).

Plot the armature line current measured at the terminals (ordinate) versus the excitation current (abscissa) at rated speed (frequency) as shown in Figure 8.

6.6 Motor no-load test

The test is conducted as in 6.4.1 b), i.e. with the machine under test operating as a motor, with no-load on the shaft, but with zero excitation-winding current.

To obtain the unsaturated value of the reactance X_d , the value of the terminal voltage of the machine should not exceed 50 % to 70 % of the rated value.

Record simultaneously:

- armature current;
- line voltage;
- frequency (or speed);

6.7 Phase shifting test

This test is conducted in accordance with either one of the following methods:

- a) by driving the test machine with an ordinary synchronous motor and connecting the armature winding of the machine under test to a low-voltage supply of the same frequency as used for the synchronous motor by means of a phase shifter;
- b) by driving the machine under test with a synchronous motor provided with excitation windings both in the direct and the quadrature axis, the armature winding of the driven machine being connected to a symmetrical low-voltage supply of the same frequency as used for the synchronous motor.

The current in the test machine varies depending on the position of the pole axis between a minimum value corresponding to X_d and a maximum value corresponding to X_q .

Changing from one position to another either by operating the phase shifter (method a)) or by varying excitation in both axes of the synchronous motor (method b)), the maximum and minimum values of the armature current and the corresponding values of the voltage applied to the terminals of the machine are measured.

During measurements the excitation winding shall be open-circuited. However, to avoid possible damage, the excitation winding should be short-circuited (or closed through a discharge resistance) when measurements are not taken.

When using method a), the phase shifter shall be able to shift the armature applied voltage by not less than 180 electrical degrees.

When using method b), the power of the driving motor depends upon the voltage applied to the armature winding of the machine under test which develops a torque when moving from one position to another.

To determine unsaturated values of reactances X_d and X_q , the value of the applied voltage should not exceed 0,5 p.u. of the rated value.

Record:

- $U_{\max}$ at $I_{\max}$
- $U_{\min}$ at $I_{\min}$

6.8 Over-excitation test at zero power-factor

The over-excitation test at zero power-factor is conducted with the machine operating as a generator or as a motor. The active power should be equal to zero when the machine operates as a generator. When the machine operates as a motor, the load on the shaft shall be zero.

During the test, the excitation current is determined corresponding to values of voltage and armature current preferably differing by not more than $\pm 0,15$ per unit from the rated values, at zero power-factor with over-excitation.

The over-excitation test at zero power-factor and rated values of voltage and armature current is preferred.

6.9 Negative excitation test

The test is conducted with the machine operating under no-load in parallel with the grid. The excitation current is steadily reduced to zero, its polarity reversed, and it is then increased up to the moment when the machine slips one pole pitch.

NOTE This test is not suitable for permanent magnet machines, as it requires readings with either excitation winding open-circuited or at zero excitation current.

Record: voltage, armature current and excitation current up to the moment when the machine begins to slip.

6.10 On-load test measuring the load angle

The test is conducted with the machine operating in parallel with the grid. The loading of the machine shall be not less than 0,5 of the rated active load at rated power-factor.

Record: armature current and voltage, active power or directly measured $\cos \varphi$, field current and load angle.

NOTE Load angle δ is the internal angle between the vectors of terminal voltage and e.m.f., the latter indicating the q-direction.

6.11 Low slip test

During the low slip test, subnormal symmetrical three-phase voltage ($0,01 U_N$ to $0,2 U_N$) is applied to the armature terminals of the machine under test. The voltage should be such that the machine does not pull in. The excitation winding shall be open-circuited, the rotor driven by a prime-mover at a slip less than 0,01 and for solid rotor machines much less than that value so that the currents induced in the damper circuits during synchronous operation will have negligible influence on the measurements.

During switching on and off of the supply, the excitation winding shall be closed (short-circuited or through a discharge resistance) to avoid possible damage. Armature current and voltage and the slip-ring voltage and slip are measured by indicating instruments or recorded by oscilloscope. If the residual voltage measured before the test is larger than 0,3 of the supply test voltage, the rotor should be demagnetised. Demagnetising might be done, for example, by connecting the field winding to a low-frequency source with current about 0,5 of the no-load rated voltage excitation current of the tested machine and gradually decreasing its amplitude and frequency (the latter if possible).

NOTE This test is not suitable for permanent magnet machines, as it requires readings with either excitation winding open-circuited or at zero excitation current.

6.12 Sudden three-phase short-circuit test

This test is conducted at rated speed. Apply a short-circuit to the armature winding when operating at the desired voltage at no-load. Excitation of the machine is generally, accomplished from its own separately-excited exciter.

NOTE 1 If its own exciter cannot be used, then a separate exciter and, in case of a brushless machine, temporary slip rings may be used, but its rated current value should be at least twice the no-load field current of the machine under test, and its armature resistance should be not greater than that of the main machine exciter. This exciter should be separately excited.

Short-circuit the three phases simultaneously. The phase contacts should close within 15 electrical degrees of each other. This value may be exceeded on test when the armature d.c. component is not of importance. Use either non-inductive shunts, air-cored transformers or suitable current transformers to measure the short-circuit current. The latter should be used in dealing with a.c. current components only, and should be chosen so that the initial value of the sub-transient component of the short-circuit current is on the straight portion of the transformer characteristic.

NOTE 2 For machines with rated frequencies less than 60 Hz, d.c. shunts may be used.

Recording should continue for a time interval not less than $3\tau_d$ after short-circuiting. The steady state values should also be recorded (by restarting the oscillogram) following the establishment of steady conditions. Shorter oscillographic records may be taken if it is known from tests on similar machines that the current value decays exponentially.

The air-cored transformer is connected to the oscilloscope through an integrating amplifier. When it is required to determine the maximum aperiodic and periodic values of short-circuit current components only, an integrating galvanometer may be used.

The total resistance of the measuring instruments and their leads connected into the secondary circuit of current transformers should not exceed the rated values accepted for the given type of transformers.

To obtain quantities corresponding to the unsaturated state of the machine, the test is performed at several armature voltages of (0,1 to 0,4) rated value. The quantities are obtained for each test and plotted against the initial values of a.c. transient or sub-transient armature currents. From this relationship, the required quantities are obtained at the rated armature current value.

To obtain quantities corresponding to the saturated state of the machine, the test is performed with rated voltage at the terminals of the machine before short-circuiting the armature winding.

When the sudden short-circuit test cannot be performed at rated armature voltage, it is recommended that the tests should be conducted at several armature voltages (e.g. 30 %, 50 % and 70 % of rated armature voltage), and the quantities determined for each test. They are then plotted against open-circuit voltage before short-circuiting and the approximate rated armature voltage quantity is found by the extrapolation method.

Record immediately before the short-circuiting:

- terminal voltage;
- excitation current;
- excitation winding temperature.

Record oscillograms of the armature current in each phase and excitation current during the short-circuiting period. Data from oscillograms are analysed according to 7.1.2.

6.13 Voltage recovery test

Operate the test machine at rated speed, the armature winding short-circuited by a circuit-breaker, and excitation current set at a value corresponding to the linear portion of the no-load saturation curve, which as a rule is not higher than 0,7 of rated open-circuit armature voltage.

The sustained short-circuit shall be switched off practically simultaneously in all three phases, with the currents being interrupted within angles $\theta \leq 0,5 \cdot \tau''_d$ (with τ''_d designated in electric degrees) but not later than 180 electrical degrees. Oscillographic records (initial part at high speed) of one line-to-line voltage recovery and one armature current are required.

NOTE This test may be performed in a brushless machine if it is equipped with temporary slip-rings (excitation from separate exciter) or if the machine may be excited from its own exciter, the latter being separately excited.

Record immediately before disconnecting short-circuit:

- terminal voltage;
- excitation current;
- excitation winding temperature.

Record oscillograms of the armature current in each phase and excitation current after switching off the short-circuit.

Data from oscillograms are analysed according to 7.1.3.

6.14 Suddenly applied short-circuit test following disconnection from line

The sudden three-phase short-circuit test may be conducted during retardation of the machine under test, provided its rate of deceleration is not more than 0,05 rated speed per second. Before disconnecting from the line, the machine running on no-load is excited up to the current value for which the power factor is unity, or to a lower value of current. The excitation current and voltage are measured and recorded.

As soon as possible after disconnection, but not later than 1 s, the machine is short-circuited practically simultaneously. General requirements for the equipment, measuring devices, excitation and determination of quantities are similar to those stated in 6.12.

For salient pole machines the current may be increased up to the rated value, if the vibration of the machine does not exceed permissible values. For non-salient pole machines the armature current is usually limited to 0,5 of the rated value.

6.15 Direct current decay test in the armature winding at standstill test

The d.c. decay in the armature winding test is performed at standstill. DC voltage is applied to the armature winding (two terminals with the third one open, or two phases in parallel with the third in series with them) through a resistance (see Figure 1). When contactor K is closed, the winding is short-circuited and the current in the armature winding decays. The whole process of current decay is recorded.

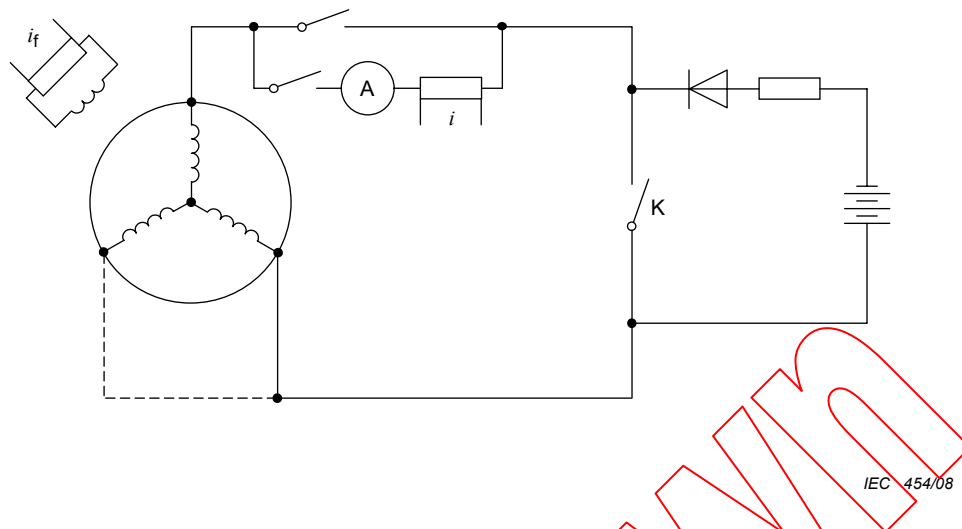


Figure 1 – Schematic for d.c. decay test at standstill

The resistance of contactor K shall be appreciably lower than the armature winding resistance. The resistance connected in series with the voltage source shall have its value so chosen that closing the contactor does not affect the source current value appreciably (the current value shall not change by more than a few per cent).

The test is performed with the rotor placed along the direct and then the quadrature axis after preliminary magnetization of the machine magnetic system by passing a d.c. current through the armature (primary) winding that will produce saturation. Following this, gradual demagnetization is carried out down to the test current value, and short-circuited or disconnected after closing contactor K.

Recording of the decay current should be carried out in such a way that the curves are available with different time-base, approximately in the ratio 10:1:0,1, for

- the initial portion of the decay;
- the initial portion and the middle portion of the curve;
- the whole decay curve.

NOTE The test may also be carried out once, using equipment with three oscilloscope channels.

In conducting the test with the rotor position along the d-axis, with the excitation winding short-circuited, the current in it is also recorded by the same oscilloscope. There should be no effective additional resistance in the excitation winding circuit.

In conducting the test with the rotor in the q-axis position, the excitation winding is open-circuited and the induced voltage in it is also recorded by the same oscilloscope. The same applies to the test with the rotor position along the d-axis, with the excitation winding open-circuited.

After the test, the d.c. resistance of the excitation winding circuit and the excitation winding itself are measured.

Data from oscillograms are analysed according to 7.1.4.

6.16 Suddenly applied excitation test with armature winding open-circuited

The suddenly applied excitation test with armature winding open-circuited is performed on a machine running at rated speed with the excitation winding initially open-circuited.

of the machine is provided, preferably, from its own exciter which shall be separately excited. If its own exciter cannot be used, then a separate exciter may be used but its rated current value shall be at least twice the no-load excitation current of the tested machine and its armature resistance not greater than that of the main machine exciter. This separate exciter shall also be separately excited.

The exciter voltage is set at a value corresponding to the linear portion of the no-load saturation curve, which as a rule is not higher than 0,7 times the rated open-circuit armature voltage. The excitation winding of the machine under test is suddenly connected to the exciter. Recorded are one line armature voltage, excitation current and, for control, exciter voltage.

The test is considered satisfactory if the exciter voltage remains substantially constant during the test.

Data from oscillograms are analysed according to 7.1.5.

6.17 Applied voltage test with the rotor in direct and quadrature axis positions

AC voltage, at rated frequency, is applied to any two line terminals of the armature winding.

The excitation winding is short-circuited with means to measure its current. The duration of the voltage application should be limited to avoid serious overheating.

NOTE In brushless machines, the excitation winding should be disconnected from the rotating rectifier and short-circuited.

The rotor is slowly rotated to find the angular positions corresponding to the maximum and practically zero values of the excitation winding current. The first position corresponds to the direct-axis, the second to the quadrature-axis. Supply voltage, armature-winding current and the power input are measured with the rotor stationary in these positions. Excitation winding current is needed for the purposes of evaluating the rotor position (direct-axis or quadrature-axis), therefore the measuring instruments need not necessarily be of high precision.

The quantities determined from this test may, depending upon the value of the armature current, include saturation of the damper winding leakage paths. The quantities determined at rated current with relative saturation of the damper winding paths are referred to the unsaturated ones.

As a rule, the saturated values cannot be determined from this test because of the large current required and possible overheating of the windings and solid parts.

If tests cannot be performed at rated armature current, the determination of quantities referred to the unsaturated state of the machine shall be done from several tests with different armature currents (0,2 to 0,7 I_N).

The quantities are plotted against the armature current, and the required values are found by extrapolation.

For machines with closed or semi-closed armature slots and closed damper winding slots, the supply voltage shall be not lower than 0,2 of the rated value.

6.18 Applied voltage test with the rotor in arbitrary position

To conduct the test, a.c. voltage is applied in turn to each pair of the armature winding line terminals of the stationary machine under test.

The excitation winding shall be short-circuited and its current measured. It is necessary that the rotor position remains the same for all three applications of test voltage.

NOTE In brushless machines, the excitation winding should be disconnected from the rectifier and short-circuited.

If necessary, the rotor should be braked. The duration of the voltage application should be limited so as to avoid serious overheating of solid parts.

The applied voltage, current and power input to the armature, and the excitation winding current are measured when applying a.c. supply voltage to each pair of the terminals. Requirements for obtaining quantities referred to the unsaturated or saturated state of the machine are similar to those in 6.17.

6.19 Single phase voltage test applied to the three phases

To conduct the test, a single-phase voltage is applied across the terminals of the three phases connected in series or in parallel, with the machine driven at or near rated speed. The connection shall be arranged so that the current flows in each phase in the same sense as defined by zero sequence. The excitation winding is short-circuited.

Record voltage U , current I and active power P .

6.20 Line-to-line sustained short-circuit test

To conduct the line-to-line sustained short-circuit test, any two line terminals are short-circuited (see Figure 2) and the machine is driven at rated speed by some prime-mover.

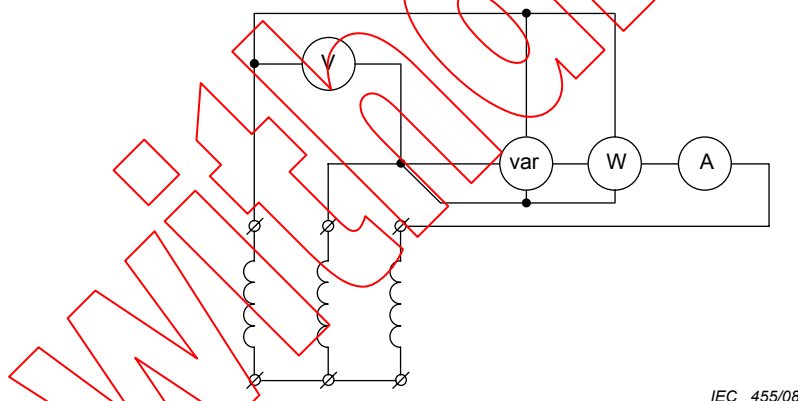


Figure 2 – Circuit diagram for line-to-line short-circuit test

The short-circuit current I_{k2} , excitation current and the voltage between the open line terminals and one of the short-circuited terminals are measured U_{k2} .

To increase the accuracy of the measurements in the presence of voltage or current harmonics, it is recommended to measure active power P and reactive power Q .

The measurements are taken at several values of the short-circuit current.

To avoid serious overheating of solid parts the duration of the line-to-line sustained short-circuit at current above $0,3 I_N$ should be limited to the time required for taking the readings of the instruments.

6.21 Sudden line-to-line short-circuit

The sudden line-to-line short-circuit test for determining negative phase-sequence reactance and negative phase-sequence resistance is conducted at rated speed. Before applying the short-circuit, the machine shall operate with open-circuited armature winding.

The requirements for the excitation system and choice of measuring instruments shall be in accordance with those stated in 6.12.

The terminal voltage of the machine, the excitation current and the rotor temperature are measured immediately before short-circuiting.

To determine negative-sequence reactance, oscillograms are taken of the armature winding voltage at the terminals to be short-circuited, armature current in the same phases and the current in the excitation circuit. Recording and method of analysis of the oscillograms shall be in accordance with 6.12.

To obtain $X_{(2)}$ corresponding to the unsaturated state of the machine, i.e. rated current conditions, the test is performed at several line-to-line voltages similar to the sudden three-phase short-circuit test described in 6.12, and the required value is obtained from the plotted results.

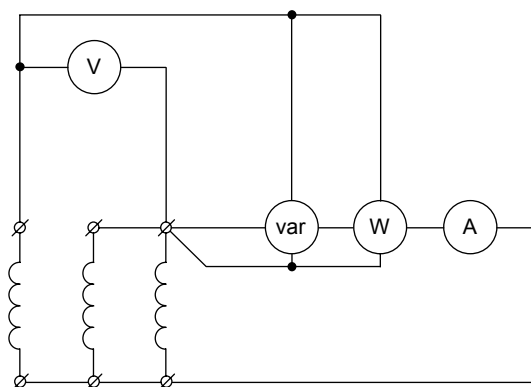
To obtain $X_{(2)}$ corresponding to the saturated state of the machine, the voltage at the terminals of the machine before line-to-line short-circuiting of the armature (primary) winding should be equal to the rated value.

If the test cannot be performed at rated voltage, it may be conducted at several decreased values of armature voltages as in 6.12, and $X_{(2)}$ determined for each test. These values are then plotted against open-circuit voltage before short-circuiting and an approximate value corresponding to the rated voltage shall be found by extrapolation.

The short-circuit test shall be performed in such a way that the aperiodic component is practically maximum, i.e. the actual short-circuit occurs within 30° of the time of voltage zero crossing.

6.22 Line-to-line and to neutral sustained short-circuit test

To conduct the line-to-line and to neutral sustained short-circuit test the armature winding is star connected, two line terminals are short-circuited to neutral, the machine is driven at rated speed and is excited (see Figure 3).



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Figure 3 – Circuit diagram for line-to-line and to neutral sustained short-circuit test

Measurements are taken of the voltage U_0 from the open terminal to neutral and the current I_0 in the connection from the short-circuited terminals to neutral.

To take into account the influence of harmonics, measurements are taken of active and reactive power.

The measurements are taken at several values of the neutral current. The current values and the duration of the test are limited by rotor overheating or vibration.

6.23 Negative-phase sequence test

The test is conducted with reduced symmetrical voltage of $0,02 U_N$ to $0,2 U_N$ applied to the machine driven at rated speed, connected to an external supply with negative-phase sequence, i.e. operating as an electromagnetic brake with the slip equal to 2.

The excitation winding shall be short-circuited.

If the residual voltage of the machine under test exceeds 30 % of the supply voltage, the rotor should be demagnetized before testing the machine. The voltage and current in all three phases and the supply power are measured during the test.

6.24 Field current decay test, with the armature winding open-circuited

6.24.1 Test at rated speed

Using a prime-mover drive the machine at rated speed, excited to rated voltage, and then suddenly short-circuit the excitation winding. Excitation winding supply source may require disconnecting within 0,02 s of its application.

NOTE When testing machines, a current limiting resistor may be connected in series with its excitation winding to limit the d.c. supply short-circuit current.

Take an oscillogram of the armature winding voltage, the excitation winding current and the slip-ring voltage. The latter serves for precise determination of the instant of the starting of field current decay (zero time) and the determination of the initial voltage value at this moment.

The difference between the transient voltage obtained from the oscillogram and the residual voltage of the machine is plotted against time on a semi-log scale.

6.24.2 Test at standstill

With the machine at standstill; the armature winding open-circuited; the excitation winding fed from a separate d.c. source; then suddenly short-circuit the excitation winding. The excitation winding supply source may require disconnecting within 0,02 s of its application.

NOTE When testing machines, a current limiting resistor may be connected in series with its excitation winding to limit the d.c. supply short-circuit current.

An oscillogram is taken of the excitation winding current, and plotted against time on a semi-log scale.

6.25 Field current decay test at rated speed with the armature winding short-circuited

To conduct the field winding decay test with the armature winding short-circuited, use a prime mover to drive the machine at rated speed and with rated armature current flowing, then suddenly short-circuit the excitation winding.

An oscillogram is taken of any line current and of the excitation current or slip-ring voltage.

The difference between the transient current obtained from the oscillogram and the current due to the residual voltage is plotted against time on a semi-log scale.

NOTE The short-circuit current should be sustained only temporarily to avoid damage due to heating.

6.26 Suddenly applied excitation with armature winding short-circuited

The suddenly applied excitation test with armature winding short-circuited is performed on a machine running at rated speed with the excitation winding initially open-circuited. The requirements for the excitation source are as stated in 6.16. Excitation of the machine is provided from its own exciter that shall be separately excited, or provided from another source.

The exciter voltage is set at a value corresponding to the rated short-circuit current of the machine under test. The excitation winding of the machine under test is suddenly connected to the exciter. An oscillographic recording of armature winding current, excitation current and exciter voltage is made. The test is considered satisfactory if the exciter voltage remains substantially constant during the test.

6.27 Field current decay test at standstill with two phases of armature winding short-circuited

The field current decay test with two phases of the armature winding short-circuited is conducted at standstill with the rotor in direct axis position with respect to the magnetic axis of short-circuited armature winding phases, and suddenly short-circuiting the excitation winding.

NOTE A current limiting resistor may be connected in series with the excitation winding to limit the d.c. supply short-circuit current.

This test will determine the time-constant τ'_d in the brushless machines when the test at rated speed may not be performed.

An oscillogram is taken of the excitation winding current, and plotted against time on a semi-log scale.

6.28 Applied voltage test with rotor removed

This test is performed applying three-phase rated frequency symmetrical voltage to the armature winding, the rotor being removed.

A search coil is placed over the teeth or at a diameter slightly less than the bore diameter in order to exclude cross-slot flux leakages. The length of the coil is equal to the full armature core length; the width of the coil is equal to the pole pitch. The end parts are stretched by bracing wires towards the machine axis along the radii in the planes of the end armature core teeth to remove them from the influence of the leakage fluxes around the armature end winding (see Figure 4).

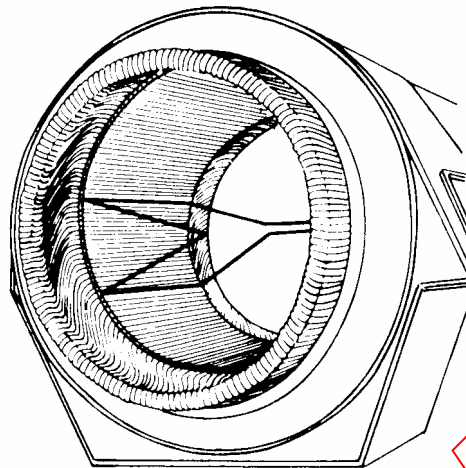


Figure 4 – Search coil installation with rotor removed

If the armature has a fractional number of slots per pole and phase, the width of the coil is made equal to the largest whole number of slots comprising the pole pitch.

The armature winding is connected to the voltage source and applied voltage U , armature winding magnetizing current I , input power P and voltage of the search coil U_c are measured. The search coil voltage measurement shall be done with a high internal resistance voltmeter.

6.29 No-load retardation test

The no-load retardation test is conducted when there is no additional flywheel mass on the shaft of the machine under test. The machine is excited from a separate source and the excitation remains unchanged during the test.

The machine under test is brought up to over-speed by increasing the supply frequency or by means of a prime-mover provided with a clutch; then the supply is disconnected.

This test consists of measuring the retardation time Δt when the machine is slowing down between two pre-determined speeds with difference $\Delta \omega$, say, from 1,10 to 0,90 per unit or from 1,05 to 0,95 per unit.

6.30 Suspended rotor oscillation test

To perform this test, the rotor is suspended on one filament or two parallel filaments in such a way as to have its shaft in a vertical position. Turning the rotor produces oscillations about the shaft axis. The time required to make several oscillations is recorded and an average time of one cycle of oscillation is calculated.

With one filament suspension, the test is performed twice, with the rotor itself and the rotor together with a flywheel or a pulley, acting as a flywheel of known inertia.

The unidirectional displacement angle for one-filament suspension should be not more than 45° , and for two-filament suspension not more than 10° .

6.31 Locked rotor test

The test is performed with the rotor locked and rated frequency three-phase voltage applied to the armature winding, the excitation winding being short-circuited or closed through a starting resistance as required.

The test shall be made with rated voltage applied to the armature winding unless excessive heating of damper winding and armature winding prevents such a test from being made.

In this case, a series of tests with reduced voltage may be performed so that rated voltage quantities may be determined by extrapolation. Due to the saturation effect, the value of reduced voltage applied should be high enough so that the point of rated voltage may be accurately extrapolated. Usually, the armature current during the test should be more than twice the rated current value.

The duration of the voltage application is limited by the time required to take the readings and by heating the rotor parts and should be kept below 10 s.

Record:

- armature voltage and current in all three phases;
- power input (desirable).

6.32 Over-excitation test at zero power factor and variable armature voltage

The test is conducted with the machine operating either generating or motoring. The active power when the machine operates as a generator should be equal to zero. The load on the shaft when the machine operates as a motor shall be zero.

During the test, armature winding current is kept constant and equal to the rated value, armature voltage is varied from at least rated value down to the lowest value at which the machine remains stable. For reasonable accuracy, it is recommended that armature voltage should be decreased below 0,5 times the rated value.

Care should be taken that no excessive heating of the excitation winding occurs.

6.33 Asynchronous operation during the low-voltage test

The test is performed with a reduced symmetrical voltage ($0,01 U_N$ to $0,2 U_N$) at rated frequency applied to the machine under test, from an external source.

The excitation winding is short-circuited. If the residual voltage of the machine exceeds 0,3 of the applied voltage, the rotor should be demagnetized before testing the machine. Line-to-line voltage, line current and the input power are measured and recorded during the test. In making calculations, average values of these quantities during the full swing period are considered.

The speed of rotation of the machine is changed by steps; at each speed step, voltage is applied to the armature winding for a time necessary to take instrument readings and make records. In the range of small slips (below 0,05) it becomes difficult to maintain constant speed of rotation within the required precision. In this case, the test with oscillographic recording may be performed with slow retardation (not more than 0,04 times the rated speed per second for small machines; for large machines it will be much smaller due to inherent characteristics of the set).

Average values for the power and current are plotted against slip (see Figure 5).

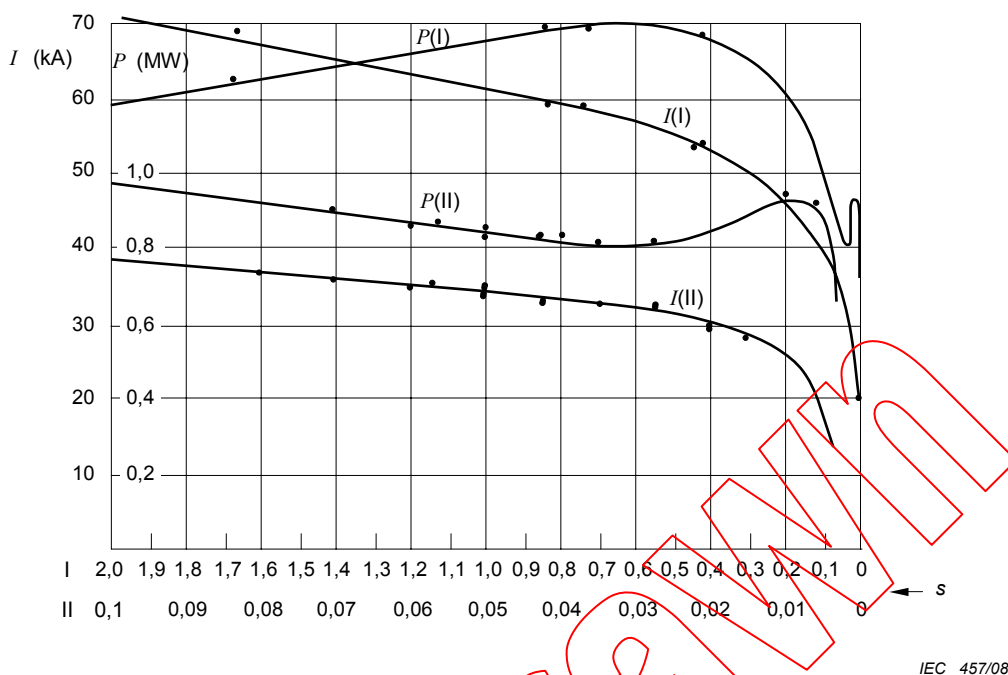
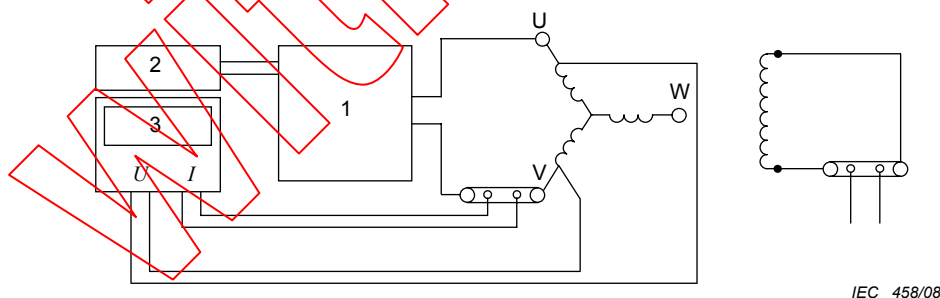


Figure 5 – Power and current versus slip (example)

6.34 Applied variable frequency voltage test at standstill

To perform this test, voltage at various frequencies is applied to a pair of line terminals of the armature winding. The machine is at standstill. The armature winding is supplied from a single-phase, variable frequency power amplifier. The connection is in star, with either feeding terminals U and V, the third terminal W open or short-circuited with terminal V. The excitation winding is short-circuited. Figure 6 shows a schematic of the principal connections.



Key

- 1 Power amplifier
- 2 Oscillator
- 3 Oscilloscope

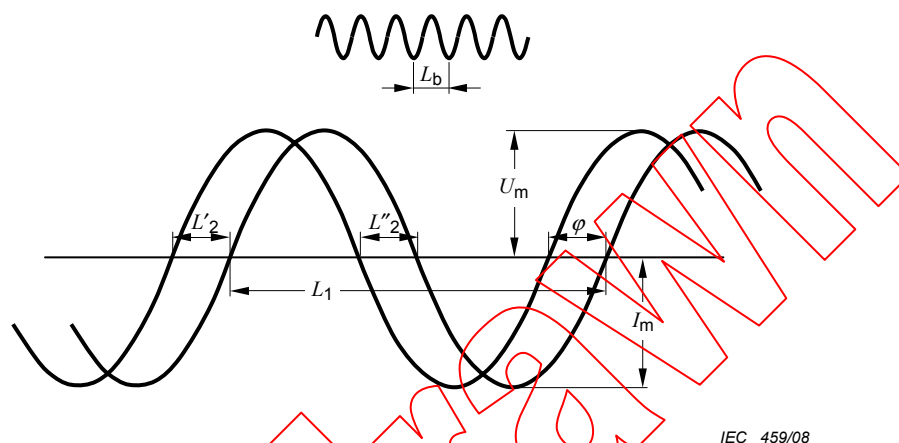
Figure 6 – Schematic for variable frequency test at standstill

During the test, the rotor is oriented once in such a position as to have maximum current induced in the excitation winding (direct axis), and once to have minimum (practically zero) induced current (quadrature axis).

Supply voltage, armature winding current and phase angle between them are measured and recorded; for determination from an oscilloscope, see Figure 7. Excitation winding current is

recorded only for the purpose of the rotor position evaluation. The phase angle may also be measured by some other method with adequate precision.

Certain precautions shall be taken during the test. It may be performed either at comparatively high currents (0,3 to 0,5 of the rated armature value) or at small armature currents (0,05 to 0,1 of the rated value) and additional magnetic flux produced by d.c. current in the same armature winding superimposed on low-frequency current in such a way that the peak value of a.c. current is below the value of direct current. At all frequencies, the values of alternating and direct current should be about the same.



Key

$$s = f_t / f_N = (f_b L_b) / (f_N L_1) \quad ; \quad \varphi = 2\pi \cdot (L'_2 + L''_2) / (2L_1)$$

where

L_b = calibrating frequency period; L_1 = test frequency period;

f_b = calibrating frequency; f_t = test frequency; f_N = rated frequency

Figure 7 – Recorded quantities from variable frequency test at standstill (example)

At frequencies of 5 Hz and below, the difference between impedances and resistances becomes small and the phase angle between voltage and current decreases, which introduces additional inaccuracies in measuring the angle on the oscillogram.

The inaccuracies may be considerably reduced if the armature circuit resistance voltage drop is compensated during the test. In an analogue method to do so, the voltage drop in the armature resistance is compensated using an operation amplifier and an auxiliary resistance. During the test, its temperature should be stable.

The voltage drop in the shunt and the auxiliary resistance, proportional to the measuring current, is subtracted from the voltage at the armature winding terminals with the help of the amplifier. By changing resistance at the input of the amplifier, its output voltage is adjusted to zero value, while d.c. flows in the armature winding, thus compensating armature resistance. To reduce the error due to heating of the winding during the test, the compensation ability shall be checked several times with d.c. in the armature winding each time adjusting the output voltage of the amplifier to zero.

current is $i_B = 1/e \cdot i_A$. The time constant τ'_d is taken as $(OB' - OA')$ seconds. The straight line through the values of current i_B and i_A is assumed to represent the equivalent value of $\Delta i'_k$ and, when it is extrapolated to zero time, it gives the initial value $\Delta i'_k(0)$ of the transient component of short-circuit current.

The sub-transient short-circuit current component is defined as the difference between the curve $(\Delta i'_k + \Delta i''_k)$ and the straight line representing the value of $\Delta i'_k$. The variation of the sub-transient current component with time is also plotted on the semi-log scale.

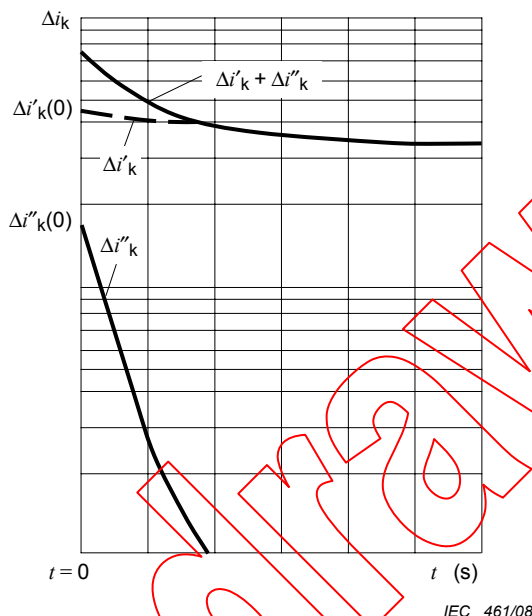


Figure 9 – Transient and sub-transient component of short-circuit current

The aperiodic current components of all the phases are plotted against time on semi-log scale. Extrapolation of these curves to zero time gives the initial values of the corresponding currents.

To find the greatest possible value of the aperiodic component, the initial values of the aperiodic components of separate phases obtained by extrapolation are laid off as vectors along three radial lines 60° apart, radiating from one origin, the largest of the three vectors being laid off on the middle line. Perpendiculars are drawn through the end of each vector. The vector drawn from the origin to the centre of the triangle formed by the intersections of these perpendiculars represents the largest possible aperiodic component equal to the initial value of the amplitude of the periodic component (see Figure 11).

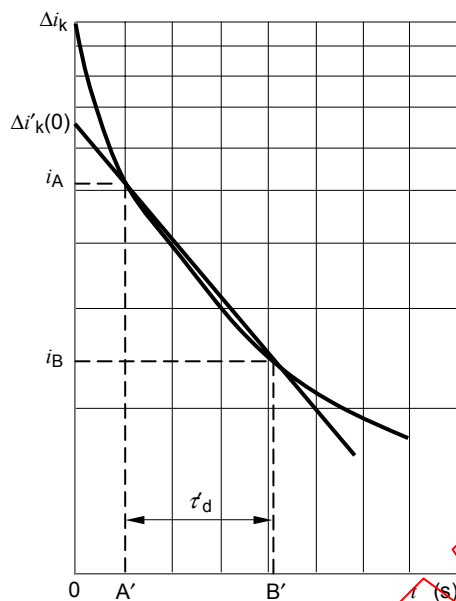


Figure 10 – Determination of transient component of short-circuit current

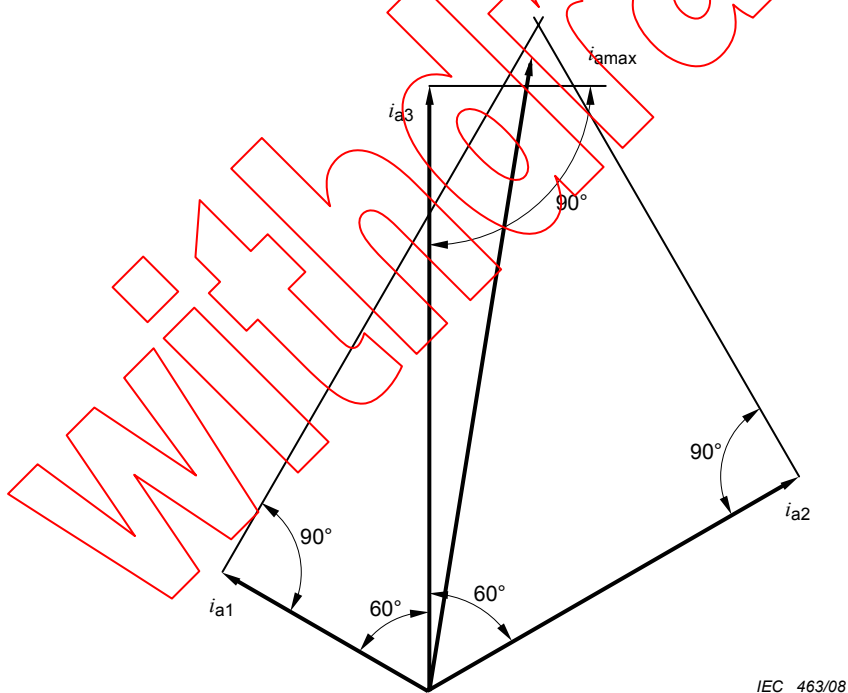


Figure 11 – Graphical determination of aperiodic component

The largest possible value of the aperiodic component of the current may be determined analytically (in per unit or physical values) by the formula:

$$i_{a \max} = \frac{2}{\sqrt{3}} \sqrt{i_{a1}^2 + i_{a2}^2 - i_{a1} i_{a2}}$$

where

i_{a1} is the highest absolute initial value (regardless of sign) of the aperiodic component of the current found from the test;

i_{a2} is the absolute initial value of the aperiodic current component in either of the two other phases.

The curve of the periodic component of the excitation current against time is determined from the excitation current oscillogram and is plotted on a semi-log scale. Extrapolation of the curve to zero time gives the initial value of the periodic current component.

NOTE If in brushless machines the excitation current cannot be recorded, the armature short-circuit time constant should be determined from the armature aperiodic current component decay.

7.1.3 Voltage recovery test

From the oscillogram (see 6.13) the difference between the sustained voltage and the voltage determined by the envelope of recovery voltage is plotted on a semi-log scale against time, and then extrapolated to the instant of the switching off the short-circuit (curve 1, Figure 12). The extrapolation of the straight portion of curve 1 to the ordinate gives the initial value of the transient voltage component $\Delta u'(0)$.

The difference between the voltage determined by curve 1 and the transient voltage component $\Delta u'$ gives the sub-transient voltage $\Delta u''$ for the corresponding instants.

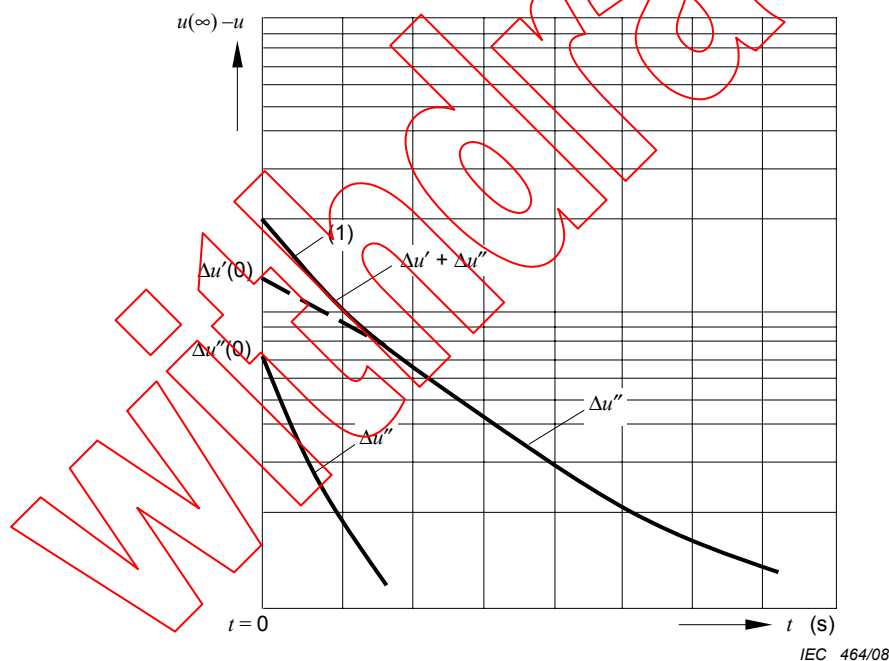


Figure 12 – Transient and sub-transient component of recovery voltage

7.1.4 Direct current decay in the armature winding at standstill

The test (see 6.15) may be made with the rotor in direct or quadrature axis position. The value of the current decay in the armature winding is considered as the ratio of the current at any instant $i(t)$ and the initial current $i(0)$.

Similarly, for the test with the rotor in direct axis position, the decaying induced current in the excitation winding is considered as the ratio of decaying induced current and the initial induced current. These values of decaying currents are plotted against time.

From a semi-logarithmic plot of the decay currents, transient and sub-transient initial values and their time constants are found. To do so, a straight line is drawn through the

extremity (Figure 13 a). The intersection of this straight line with the ordinate axis gives the initial amplitude of the first exponential (i_{10}). Its time constant (τ_1) is the highest and is found as the time necessary for i_{10} to decrease to $1/e \approx 0,368$ of its initial value.

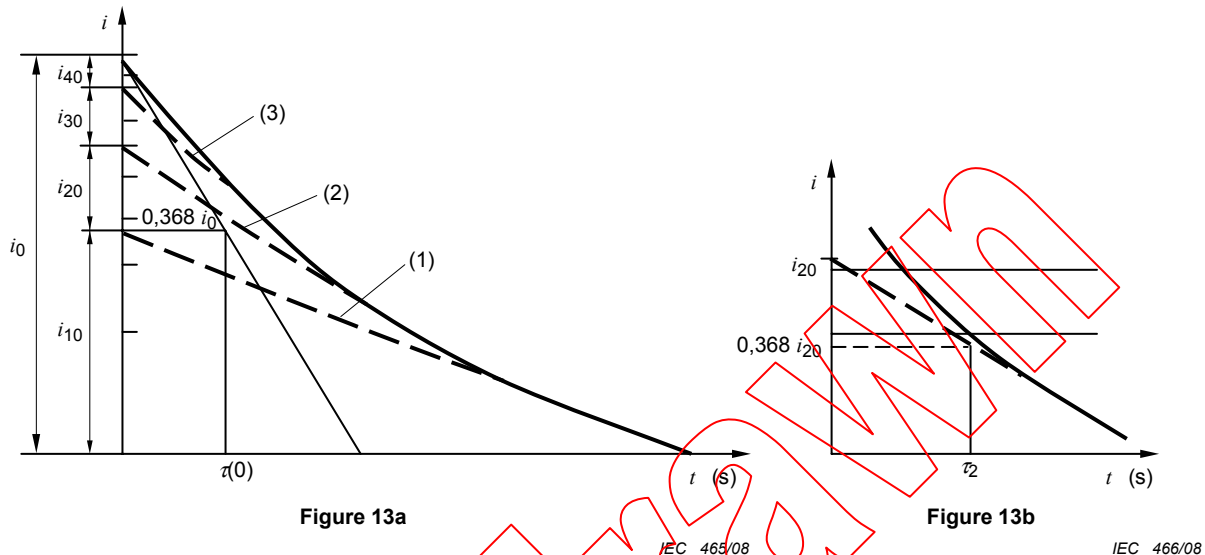


Figure 13 – Semi-logarithmic plot of decay currents

The difference between the initial curve and the first exponential is again plotted on a semi-logarithmic graph, and the amplitude i_{20} and the time constant of the second exponential τ_2 are determined (Figure 13 b).

Analysis of the curve is continued in this manner until that point where non-linearity of the decaying curve cannot be observed.

The analysis of the decaying armature winding current and of the induced excitation winding current from the same test should be done simultaneously, having in mind equality of time constants τ_k and τ_{kf} for solid rotors. By doing so, a higher accuracy in frequency response characteristics is obtained. While analysing the test curve of the armature winding current decay, it is recommended to draw a sum of exponentials as close as possible to the test curve, so as to have:

$$\sum_k \frac{i_{ko}}{\tau_k} = \frac{i_0}{\tau(0)}$$

where

$\tau(0)$ is the equivalent time constant of the decaying armature current curve at the initial moment. This time constant $\tau(0)$ is obtained from a plot of the initial portion of the current decay curve on a semi-logarithmic graph by drawing the tangent to it at zero time (Figure 13a). The initial time constant $\tau(0)$ will be found along this tangent line as the time necessary for the initial value of the current to decrease to its $1/e \approx 0,368$ value.

NOTE Sufficient accuracy in analysing the test curve into exponentials may be obtained using a suitable computer program.

Direct axis time constants of synchronous machines are determined using known roots a_{kd} , a'_{kd} of characteristic equations $D_d(p) = 0$ and $D'_d(p) = 0$ (see Annex B) as:

$$\tau'_d = \frac{1}{\omega\alpha'_{1d}}; \quad \tau''_d = \frac{1}{\omega\alpha'_{2d}}; \quad \tau'''_d = \frac{1}{\omega\alpha'_{3d}}; \dots$$

$$\tau'_{do} = \frac{1}{\omega\alpha_{1d}}; \quad \tau''_{do} = \frac{1}{\omega\alpha_{2d}}; \quad \tau'''_{do} = \frac{1}{\omega\alpha_{3d}}; \dots$$

where:

$$\omega = 2\pi f.$$

Similarly, quadrature axis time constants are determined using known roots a_{kq} , a'_{kq} of equations $D_q(p) = 0$ and $D'_q(p) = 0$ (see Annex B) as:

$$\tau'_q = \frac{1}{\omega\alpha'_{1q}}; \quad \tau''_q = \frac{1}{\omega\alpha'_{2q}}; \quad \tau'''_q = \frac{1}{\omega\alpha'_{3q}}$$

$$\tau'_{qo} = \frac{1}{\omega\alpha_{1q}}; \quad \tau''_{qo} = \frac{1}{\omega\alpha_{2q}}; \quad \tau'''_{qo} = \frac{1}{\omega\alpha_{3q}}; \dots$$

7.1.5 Suddenly applied excitation test with armature winding open-circuited

The difference between the sustained armature voltage and the voltage determined by the envelope of the rising armature voltage is plotted on a semi-logarithmic scale against time, and then extrapolated to the instant of the exciter connection switch closure (see Figure 14). The extrapolation of the straight portion of this curve to the ordinate axis gives the initial value of the transient component $\Delta u'(0)$.

NOTE For large machines, the residual voltage may usually be neglected.

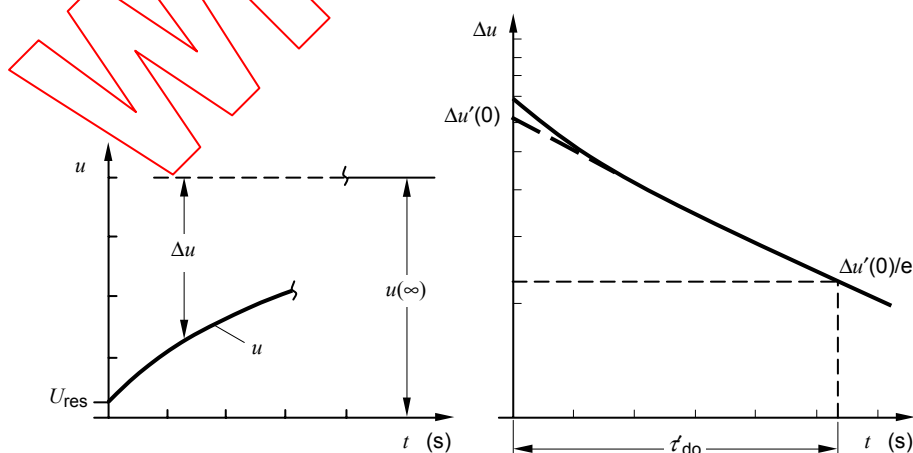


Figure 14a

Figure 14b

IEC 467/08

IEC 468/08

Figure 14 – Suddenly applied excitation with armature winding open-circuited

7.2 Direct-axis synchronous reactance

7.2.1 From no-load saturation and three-phase sustained short-circuit test

The unsaturated value of X_d is determined from curves plotted according to 7.1.1 (see Figure 8):

$$X_d = \frac{U_N}{\sqrt{3} I_{BC}} \left[x_d = \frac{AC}{BC} = \frac{OH}{OC} = \frac{i_{fk}}{i_{fg}} \right]$$

where

AC represents the no-load voltage taken from the air-gap line at some excitation current;
BC represents the sustained short-circuit current value taken from the short-circuit characteristic at the same excitation current.

7.2.2 From motor no-load test

An unsaturated value of X_d is determined from (see Figure 8)

$$X_d = \frac{U}{\sqrt{3} I} ; \left[x_d = \frac{u}{i} \right]$$

where terminal voltage U and armature-winding current I are from 6.6.

7.2.3 From phase shifting test

A value of X_d is determined from

$$X_d = \left(\frac{U}{\sqrt{3} I} \right)_{\max} ; \left[x_d = \left(\frac{u}{i} \right)_{\max} \right]$$

where values are from 6.7.

7.2.4 From on-load test measuring the load angle

The determination of X_d by the method of load angle measurement (see 6.10) is made using the formula:

$$X_d = \frac{E_0 / \cos \delta - U}{\sqrt{3} I (\cos \varphi \tan \delta + \sin \varphi)} ; \left[x_d = \frac{e_0 / \cos \delta - u}{i (\cos \varphi \tan \delta + \sin \varphi)} \right]$$

where:

E_0 is the synchronous internal voltage corresponding to excitation current for the actual load. To determine E_0 , the no-load saturation curve (see 6.4) is plotted on a diagram and, similar to Figure 8, a straight line is drawn from the origin through the point of rated voltage. E_0 is the ordinate value on this straight line corresponding to the actual excitation current on the abscissa.

U, I are armature voltage and current;

φ is the phase angle, determined by the two wattmeter method or by calculating $\cos \varphi = P / (\sqrt{3} UI)$;

δ is the load angle measured by the stroboscopic method or any other accurate method.

NOTE 1 The formula is based on the two-axes machine model, neglecting the armature resistance.

NOTE 2 In the formula, the angle values have a magnitude and a sign:

Load angle δ is positive in generator operation and negative in motor operation. Phase angle φ is in the generator reference system, i.e. $\varphi = 0$ ($\cos\varphi = 1$) for the generator and $\varphi = \pi$ ($\cos\varphi = -1$) for motor operation, at zero reactive load.

7.3 Direct-axis transient reactance

7.3.1 From sudden three-phase short-circuit test

A value of X'_d is determined from

$$X'_d = \frac{U(0)}{\sqrt{3}} \frac{1}{[I(\infty) + \Delta I'_k(0)]} ; \quad \left[x'_d = \frac{u(0)}{i(\infty) + \Delta i'_k(0)} \right]$$

where:

$U(0)$ is the no-load voltage, measured immediately before the short-circuit (see 6.12);

$I(\infty)$, $\Delta I'_k(0)$ are determined according to 7.1.2.

7.3.2 From voltage recovery test

A value of X'_d (unsaturated) is determined from

$$X'_d = \frac{U(\infty) - \Delta U'(0)}{\sqrt{3} I_k} ; \quad \left[x'_d = \frac{u(\infty) - \Delta u'(0)}{i_k} \right]$$

where input values are from test data (6.13) as analysed according to 7.1.3.

7.3.3 From d.c. decay test in the armature winding at standstill

Calculate:

$$x'_d = \frac{1}{\frac{1}{x_d} + C_{1d}}$$

where C_{1d} is as in Annex B. Calculation of x_d is indicated in 7.1.4.

7.3.4 Calculation from test values

The quantities x'_d , x_d , τ'_{do} and τ'_d are related with each other by the following formula:

$$x_d \cdot \tau'_d = x'_d \cdot \tau'_{do}$$

This relation is used for determination of x'_d from known values of x_d , τ'_d and τ'_{do} .

7.4 Direct-axis sub-transient reactance

7.4.1 From sudden three-phase short-circuit test

Sub-transient reactance X''_d , as determined from the sudden short-circuit test, is the ratio of the no-load voltage, measured immediately before the short-circuit, to the initial value of the periodic component of the short-circuit current, obtained from the analysis of the oscillogram (according to 7.1.2, Figure 9):

$$X_d'' = \frac{U(0)}{\sqrt{3}} \frac{1}{[I(\infty) + \Delta I_k'(0) + \Delta I_k''(0)]} ; \quad \left[x_d'' = \frac{u(0)}{i(\infty) + \Delta i_k'(0) + \Delta i_k''(0)} \right]$$

7.4.2 From voltage recovery test

Sub-transient reactance X_d'' is determined from the voltage recovery test as the ratio of the difference between the sustained voltage $u(\infty)$ and the sum of the initial values of transient $\Delta u'(0)$ and sub-transient $\Delta u''(0)$ voltage components of the armature current (i_k) measured immediately before the disconnection of the short-circuit.

$$X_d'' = \frac{U(\infty) - [\Delta U'(0) + \Delta U''(0)]}{\sqrt{3} I_k} ; \quad \left[x_d'' = \frac{u(\infty) - [\Delta u'(0) + \Delta u''(0)]}{i_k} \right]$$

where input values are from test data (see 6.13) as analysed according to 7.1.3.

7.4.3 From applied voltage test with the rotor in direct and quadrature axis

Sub-transient reactance X_d'' from the applied voltage test is determined using the formula:

$$X_d'' = \sqrt{Z_d''^2 - R_d''^2}$$

where $Z_d'' = \frac{U}{2I} ; R_d'' = \frac{P}{2I^2} ; \left[x_d'' = \sqrt{z_d''^2 - r_d''^2} ; z_d'' = \frac{\sqrt{3}}{2} \cdot \frac{u}{i} ; r_d'' = \frac{3}{2} \cdot \frac{p}{i^2} \right]$

The values of voltage U , current I and input power P , measured for the rotor position which gives the maximum excitation winding current, are according to 6.17.

7.4.4 From applied voltage test with the rotor in arbitrary position

Sub-transient reactance X_d'' from the applied voltage test (according to 6.18) with the rotor in any arbitrary position is determined as follows:

The direct-axis sub-transient reactance is calculated (in per unit or physical quantities) from the formula:

$$x_d'' = x_{av} \pm \Delta x$$

$$\text{where } x_{av} = \frac{x_{12} + x_{23} + x_{31}}{3} ; \quad \Delta x = \frac{2}{3} \sqrt{x_{12}(x_{12} - x_{23}) + x_{23}(x_{23} - x_{31}) + x_{31}(x_{31} - x_{12})}$$

The reactances x_{12} , x_{23} and x_{31} between each pair of the line terminals of the armature-winding are calculated from the formulae given in 7.4.3 (replacing subscript “d” by subscripts 12, 23 and 31 according to the terminals between which voltage is applied).

The sign before Δx is plus (+), if the maximum of the three measured values of the excitation circuit current corresponds to the largest measured armature reactance; and minus (–), if the maximum of the three measured current values of the excitation circuit corresponds to the smallest measured reactance between a pair of the armature winding line terminals.