भारतीय मानक
Indian Standard

IS 15999 (Part 4/Sec 1) : 2023
IEC 60034-4-1 : 2018

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भाग 4 तुल्यकालक मशीन की मात्राएँ
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(पहला पुनरीक्षण)

Rotating Electrical Machines
Part 4 Electrically Excited Synchronous Machine Quantities
Section 1 Test Methods
(First Revision)

ICS 29.160.01

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NATIONAL FOREWORD

This Indian Standard (Part 4/Section 1) (First Revision) which is identical with IEC 60034-4-1 : 2018 'Rotating electrical machines — Part 4-1: Methods for determining electrically excited synchronous machine quantities from tests' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Rotating Machinery Sectional Committee and approval of the Electrotechnical Division Council.

This Standard was first published in 2017 which was identical with IEC 60034-4 : 2008. This revision has been undertaken to align the standard with the latest version of IEC.

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

a) Wherever the words 'International Standard' appear referring to this standard, theyshould be read as 'Indian Standard'.

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

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

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60034-1 Rotating electrical machines — Part 1: Rating and performance	IS 15999 (Part 1) : 2016/IEC 60034-1 : 2010 Rotating electrical machines: Part 1 Rating and performance (*first revision*)	Identical with IEC 60034-1 : 2010
IEC 60034-2-1 Rotating electrical machines — Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)	IS 15999 (Part 2/Sec 1) : 2011 Rotating electrical machines: Part 2 Method of tests, Section 1 Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)	Identical with IEC 60034-2-1 : 2007
IEC 60051 (all parts) Direct acting indicating analogue electrical measuring instruments and their accessories	IS 1248 (all parts) Direct acting indicating analogue electrical measuring instruments and their accessories	Identical

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

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

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IS 15999 (Part 4/Sec 1) : 2023
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Indian Standard

ROTATING ELECTRICAL MACHINES
PART 4 ELECTRICALLY EXCITED SYNCHRONOUS MACHINE QUANTITIES
SECTION 1 TEST METHODS
(First Revision)

1 Scope

This part of IEC 60034 applies to three-phase synchronous machines of 1 kVA rating and larger.

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 should be taken against irreversible demagnetization.

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

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

2 Normative references

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

IEC 60034-1:2017, *Rotating electrical machines – Part 1: Rating and performance*

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

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.

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

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

3.1
<synchronous motors> initial starting impedance
quotient of the applied armature voltage and the sustained average armature current, the machine being at standstill

3.2
direct-axis synchronous reactance

quotient of the sustained value of that fundamental AC 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 AC component of this current, the machine running at rated speed

[SOURCE: IEC 60050-411:1996, 411-50-07]

3.3
direct-axis transient reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-09]

3.4
direct-axis sub-transient reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-11]

3.5
quadrature-axis synchronous reactance

quotient of the sustained value of that fundamental AC 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 AC component of this current, the machine running at rated speed

[SOURCE: IEC 60050-411:1996, 411-50-08]

3.6
quadrature-axis transient reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-10]

3.7
quadrature-axis sub-transient reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-12]

3.8
positive sequence reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-14]

3.9
negative sequence reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-15]

3.10
zero sequence reactance

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

[SOURCE: IEC 60050-411:1996, 411-50-16]

3.11
Potier reactance

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

[SOURCE: IEC 60050-411:1996, 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, referred 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, referred to a certain winding temperature

3.15
positive sequence resistance

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

[SOURCE: IEC 60050-411:1996, 411-50-18]

3.16
negative sequence resistance
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

[SOURCE: IEC 60050-411:1996, 411-50-19]

3.17
zero sequence resistance
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

[SOURCE: IEC 60050-411:1996, 411-50-20]

3.18
short-circuit ratio
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

[SOURCE: IEC 60050-411:1996, 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

[SOURCE: IEC 60050-411:1996, 411-48-27]

3.20
direct-axis transient short-circuit time constant
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

[SOURCE: IEC 60050-411:1996, 411-48-28]

3.21
direct-axis sub-transient open-circuit time constant

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

[SOURCE: IEC 60050-411:1996, 411-48-29]

3.22
direct-axis sub-transient short-circuit time constant
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

[SOURCE: IEC 60050-411:1996, 411-48-30]

3.23
quadrature-axis transient open-circuit time constant
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

[SOURCE: IEC 60050-411:1996, 411-48-32]

3.24
quadrature-axis transient short-circuit time constant
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

[SOURCE: IEC 60050-411:1996, 411-48-33]

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

[SOURCE: IEC 60050-411:1996, 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
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

[SOURCE: IEC 60050-411:1996, 411-48-35]

3.29
short-circuit time constant of armature windings
time required, following a sudden change in operating conditions, for the DC 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

[SOURCE: IEC 60050-411:1996, 411-48-31]

3.30
unit acceleration time

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

[SOURCE: IEC 60050-411:1996, 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

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

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 (phasor) 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 1 to entry: 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 document.

3.37
frequency response characteristic of quadrature-axis reactance

complex quotient expressed as a slip function of the sustained phasor 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 phasor 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

4 Symbols and units

f	Frequency
f_N	Rated frequency
$G\ (js)$	Complex frequency response characteristic of excitation factor
H	Stored energy constant
$I,\ i$	Current
I_N	Rated current
I_fk	Excitation current, for rated armature short-circuit current
I_fN	Rated excitation current
K_c	Short-circuit ratio
$R_{(0)}$	Zero-sequence resistance
$R_{(1)}$	Positive-sequence armature winding resistance
$R_{(2)}$	Negative-sequence resistance
R_a	Armature direct-current resistance
R_f	Excitation winding direct-current resistance
s	Slip
S_N	Rated apparent power
$U,\ u$	Voltage
U_N	Rated voltage
$X_{(0)}$	Zero-sequence reactance
$X_{(1)}$	Positive-sequence reactance
$X_{(2)}$	Negative-sequence reactance
X_d	Direct-axis synchronous reactance
X'_d	Direct-axis transient reactance
X''_d	Direct-axis sub-transient reactance
X_p	Potier reactance
X_q	Quadrature-axis synchronous reactance
X'_q	Quadrature-axis transient reactance
X''_q	Quadrature-axis sub-transient reactance
X_σ	Armature-leakage reactance
$X_\mathrm{d}\ (js)$	Complex frequency response characteristic of direct-axis reactance
$X_\mathrm{q}\ (js)$	Complex frequency response characteristic of quadrature-axis reactance
Z	Impedance
Z_N	Rated impedance
Z_st	Initial starting impedance of a synchronous motors
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	
	7.2.3	On-load measuring the load angle	6.9	
Direct-axis transient reactance X'_{d}	7.3.1	Sudden three-phase short-circuit	6.11	Preferred
	7.3.2	Voltage recovery	6.12	
	7.3.3	DC decay in the armature winding at standstill	6.14	
	7.3.4	Calculation from test values	-	
Direct-axis sub-transient reactance X''_{d}	7.4.1	Sudden three-phase short-circuit	6.11	Preferred
	7.4.2	Voltage recovery	6.12	
	7.4.3	Applied voltage test with rotor in direct and quadrature axis	6.15	
	7.4.4	Applied voltage with the rotor in arbitrary position	6.16	
Quadrature axis synchronous reactance X_{q}	7.5.1	Negative excitation	6.8	Preferred (unsaturated)
	7.5.2	Low slip	6.10	
	7.5.3	On-load measuring the load angle	6.9	
Quadrature-axis transient reactance X'_{q}	7.6.1	DC decay test at standstill	6.14	
	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	6.15	Preferred
	7.7.2	Applied voltage with the rotor in arbitrary position	6.16	

Quantity	Clause	Test description	Test	Preference/ uncertainty
Zero-sequence reactance $X_{(0)}$	7.8.1	Single-phase voltage application to the three phases	6.17	Preferred
	7.8.2	Line-to-line and to neutral sustained short-circuit	6.19	
Negative-sequence reactance $X_{(2)}$	7.9.1	Line-to-line sustained short-circuit	6.18	
	7.9.2	Negative-phase sequence	6.20	Preferred
	7.9.3	Calculation from test values	-	
	7.9.4	DC decay in the armature winding at standstill	6.14	
Armature leakage reactance X_{σ}	7.10	Rotor removed	6.22	
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	6.17	Preferred
	7.12.2	Line-to-line and to neutral sustained short-circuit	6.19	
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	6.18	
	7.14.2	Negative-phase sequence	6.20	Preferred
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	
Time constants				
Direct-axis transient short-circuit time constant τ'_{d}	7.16.1	Sudden three-phase short-circuit	6.11	Preferred
	7.16.2	DC decay in the armature winding at standstill	6.14	
Direct-axis transient open-circuit time constant τ'_{do}	7.17.1	Field current decay, with the armature winding open-circuited, at rated speed	6.21.1	Preferred
	7.17.2	Field current decay, with the armature winding open-circuited, at standstill	6.21.2	
	7.17.3	Voltage recovery	6.12	
	7.17.4	DC decay in the armature winding at standstill	6.14	
Direct-axis sub-transient short-circuit time constant τ''_{d}	7.18	Sudden three-phase short-circuit	6.11	
Direct-axis sub-transient open-circuit time constant τ''_{do}	7.19.1	Voltage recovery	6.12	
	7.19.2	DC decay in the armature winding at standstill	6.14	Preferred
Quadrature-axis transient short-circuit time constant τ'_{q}	7.20.1	Calculation from test values	-	
	7.20.2	DC decay in the armature winding at standstill	6.14	Preferred
Quadrature-axis transient open-circuit time constant τ'_{qo}	7.21	DC decay in the armature winding at standstill	6.14	

Quantity	Clause	Test description	Test	Preference/ uncertainty
Quadrature-axis sub-transient short-circuit time constant τ''_q	7.22.1	Calculation from test values	-	
	7.22.2	DC decay in the armature winding at standstill	6.14	Preferred
Quadrature-axis sub-transient open-circuit time constant τ''_{qo}	7.23	DC decay in the armature winding at standstill	6.14	
Armature short-circuit time constant τ_a	7.24.1	Sudden three-phase short-circuit	6.11	Preferred
	7.24.2	Calculation from test values	-	
Other quantities				
Unit acceleration time τ_J, stored energy constant H	7.25	No-load retardation	6.23	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, at rated armature short-circuit current i_{fk}	7.27.1	Sustained three-phase short-circuit test	6.5	Preferred
	7.27.2	Over-excitation at zero power-factor and variable armature winding voltage	6.26	
Frequency response characteristics	7.28.2	Asynchronous operation at reduced voltage	6.25	
	7.28.3	Applied variable frequency voltage at standstill	6.27	
	7.28.4	DC decay in the armature winding at standstill	6.14	Preferred
Short-circuit ratio K_c	7.29	No-load saturation, Sustained three-phase short-circuit	6.4 6.5	
Rated voltage regulation ΔU_N	7.30.1	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	6.24	

6 Test procedures

6.1 General

6.1.1 Instrumentation requirements

Digital instruments shall be used whenever possible.

The 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 DC resistances shall have an accuracy class of at least 0,2.

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

6.1.2 Excitation system requirements

In the 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 can give results different from those obtained with 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 document, shall correspond to an equivalent star-connected winding.

6.1.4 Per unit base quantities

All formulas 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

$$I_\mathrm{N} = \frac{S_\mathrm{N}}{\sqrt{3}\,U_\mathrm{N}}$$

and basic impedance

$$Z_\mathrm{N} = \frac{U_\mathrm{N}^2}{S_\mathrm{N}} = \frac{S_\mathrm{N}}{3I_\mathrm{N}^2}$$

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 document. Small letters designate the quantities in per unit values, and capital letters designate physical quantities.

In the formulae given in this document 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 document, 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 document 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 time function 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 ≈ 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.

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 $X'''_{\mathrm{d}}, \tau'''_{\mathrm{d}}$. Their determination may be performed as outlined in this document (see Annex B).

NOTE This document provides methods to determine the quadrature axis transient parameters $X'_{\mathrm{q}}, \tau'_{\mathrm{q}}, \tau'_{\mathrm{qo}}$ (see 6.14), though they are frequently not considered in conventional calculations when $X'_{\mathrm{q}} = X_{\mathrm{q}}$ 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 document, 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 AC 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 test permits 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 method of sudden three-phase short-circuit is preferred. It permits saturated and unsaturated values of X'_d to be determined.

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.

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. If the time constant τ_a is less than one fundamental cycle, its value is determined from the decrease of the aperiodic (DC) 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.

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 an automatic system may differ from that when the machine is separately excited (especially in machines with a static excitation system).

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

6.3 Direct-current winding resistance measurements

The resistance shall be measured according to IEC 60034-2-1.

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

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 60034-1:2017); 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.

For machines with ratings equal and above 10 MVA, the voltage should be limited to 1,2 rated voltage.

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

It is preferred to conduct test a) with a DC calibrated prime-mover or a torquemeter, 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.

This test is not applicable for permanent magnet machines.

6.4.2 No-load saturation characteristic determination

Represent 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 by multiplying the measured voltages with the ratio rated frequency to test 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) 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 DC 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.

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.

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.

This test is not applicable for permanent magnet machines.

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).

Represent 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 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 ± 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, if rated excitation current is not exceeded significantly.

This test is not applicable for permanent magnet machines.

6.8 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.

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

This test is not applicable for permanent magnet machines.

6.9 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 φ, 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.

6.10 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. 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).

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

6.11 Sudden three-phase short-circuit test

This test is conducted with running the machine at rated speed initially. 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.

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 DC component is not of importance. Use either non-inductive shunts or suitable current transformers to measure the short-circuit current. The latter should be used in dealing with AC 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 For machines with rated frequencies less than 60 Hz, DC shunts can be used.

Recording should continue for a time interval not less than $3\tau'_d$ after short-circuiting and the steady state values should also be recorded following the establishment of steady conditions. 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 represented against the initial values of AC 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 represented 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 the time functions of the armature current in each phase and excitation current during the short-circuiting period. The data are analysed according to 7.1.2.

This test can be applied to permanent magnet machines, if the design is safe against demagnetization of the magnets.

6.12 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 $\theta \leq 0{,}5 \cdot \tau''_{\mathrm{d}}$ (with τ''_{d} designated in electric degrees) but not later than 180 electrical degrees. Records of the time functions of one line-to-line voltage recovery and one armature current are required.

NOTE This test can be performed in a brushless machine if it is equipped with temporary slip-rings (excitation from separate exciter) or if the machine can 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 the time function of the armature current in each phase and excitation current after switching off the short-circuit.

Data are analysed according to 7.1.3.

This test is suitable but not relevant for permanent magnet machines.

6.13 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 6.11.

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.

6.14 Direct current decay test in the armature winding at standstill

The DC 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.

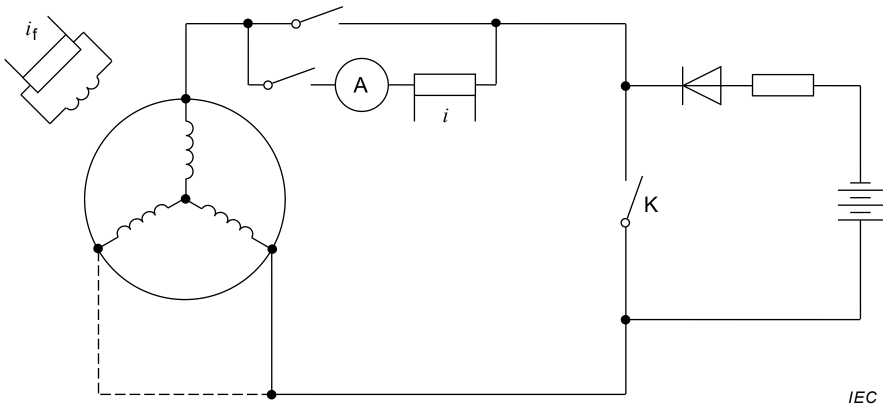


Figure 1 – Schematic for DC decay test at standstill

The resistance of the 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 DC 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 whole decay current should be carried out.

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 versus time. 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 versus time. The same applies to the test with the rotor position along the d-axis, with the excitation winding open-circuited.

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

Data are analysed according to 7.1.4.

This test is partly suitable for permanent magnet machines.

6.15 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.

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 I_N to 0,7 I_N).

The quantities are represented 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.

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

This test is not applicable for permanent magnet machines.

6.16 Applied voltage test with the rotor in arbitrary position

To conduct the test, AC 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.

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 AC 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 6.15.

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

This test is suitable but not relevant for permanent magnet machines.

6.17 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.

This test is not applicable for permanent magnet machines.

6.18 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.

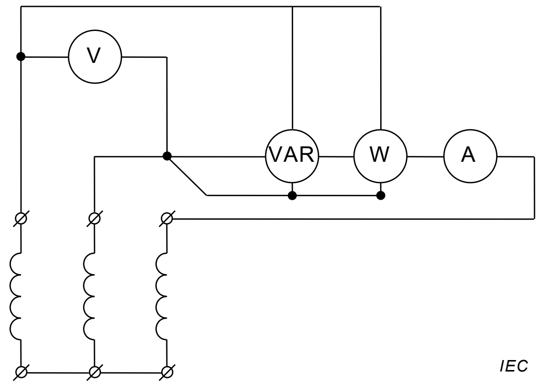


Figure 2 – Circuit diagram for line-to-line short-circuit test

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

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.

This test is partly suitable for permanent magnet machines.

6.19 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).

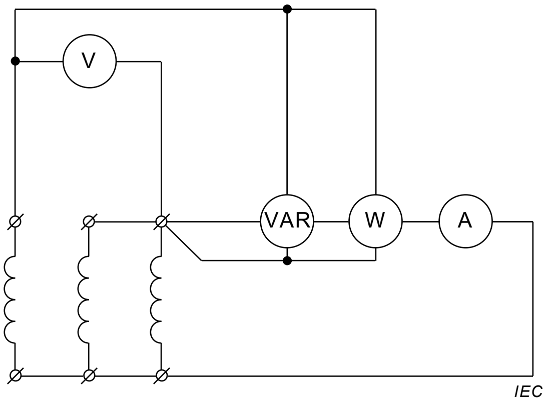


Figure 3 – Circuit diagram for line-to-line and to neutral sustained short-circuit test

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.

This test is partly suitable for permanent magnet machines.

6.20 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.

This test is not applicable for permanent magnet machines.

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

6.21.1 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 can be connected in series with its excitation winding to limit the DC supply short-circuit current.

Record the time function 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 time function and the residual voltage of the machine is represented against time on a semi-log scale.

This test is not applicable for permanent magnet machines.

6.21.2 Test at standstill

With the machine at standstill; the armature winding open-circuited; the excitation winding fed from a separate DC 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 can be connected in series with its excitation winding to limit the DC supply short-circuit current.

Record the time function of the excitation winding current, and represent against time on a semi-log scale.

This test is not applicable for permanent magnet machines.

6.22 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).

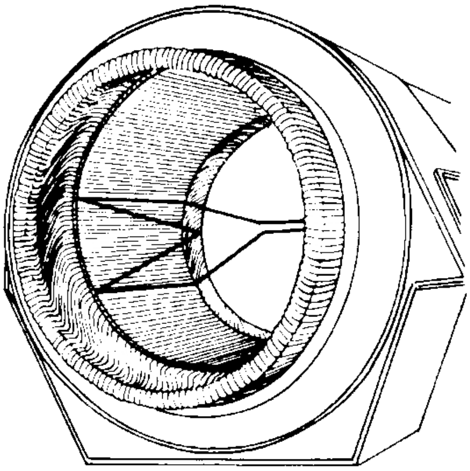


Figure 4 – Search coil installation with rotor removed

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.

This test is suitable for permanent magnet machines.

6.23 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.

This test is suitable for permanent magnet machines.

6.24 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).

This test is not applicable for permanent magnet machines.

6.25 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 transient 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).

This test is not applicable for permanent magnet machines.

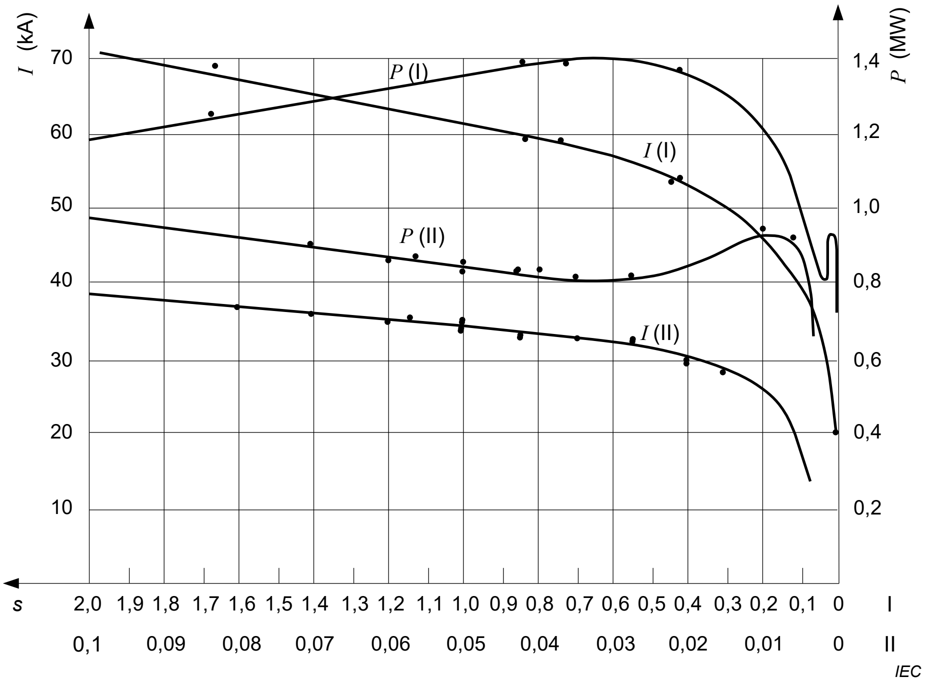


Figure 5 – Power and current versus slip (example)

6.26 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.

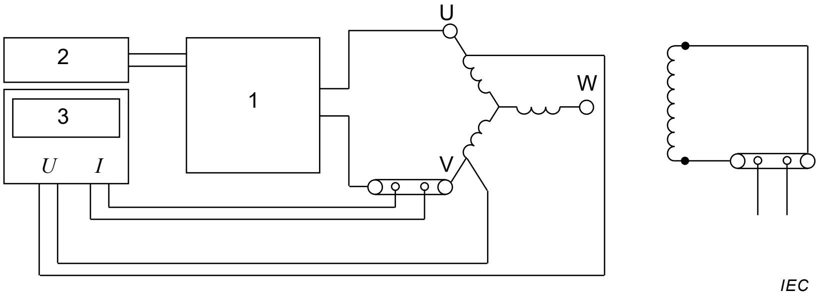
During the test, armature winding current is kept constant and equal to the rated value, armature voltage is varied from at least rated value down to the lowest value at which the machine remains stable. For reasonable accuracy, it is recommended that armature voltage should be decreased below 0,5 times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

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

This test is not applicable for permanent magnet machines.

6.27 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

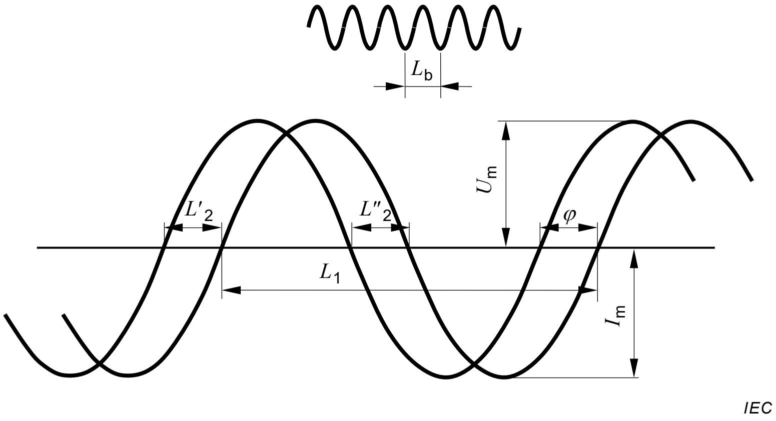
During the test, the rotor is oriented once in such a position as to have maximum current induced in the excitation winding (direct axis), and once to have minimum (practically zero) induced current (quadrature axis).

Supply voltage, armature winding current and phase angle between them are measured and recorded; for determination from a time function, see Figure 7.

Excitation winding current is recorded only for the purpose of the rotor position evaluation. For permanent magnet machines the rotor position has to be determined by other means.

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 DC current in the same armature winding superimposed on low-frequency current in such a way that the peak value of AC current is below the value of direct current. At all frequencies, the values of alternating and direct current should be about the same.



Key

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

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.

The inaccuracies may be considerably reduced if the armature circuit resistance voltage drop is compensated during the test.

The voltage drop in the shunt and the auxiliary resistance, proportional to the measuring current, then has to be subtracted from the voltage at the armature winding terminals.

7 Determination of quantities

7.1 Analysis of recorded data

7.1.1 No-load saturation and three-phase, sustained short-circuit curves

The data from 6.4.2 (No-load saturation characteristic) and 6.5.2 (Sustained short-circuit characteristic) are represented in a set of curves according to Figure 8.

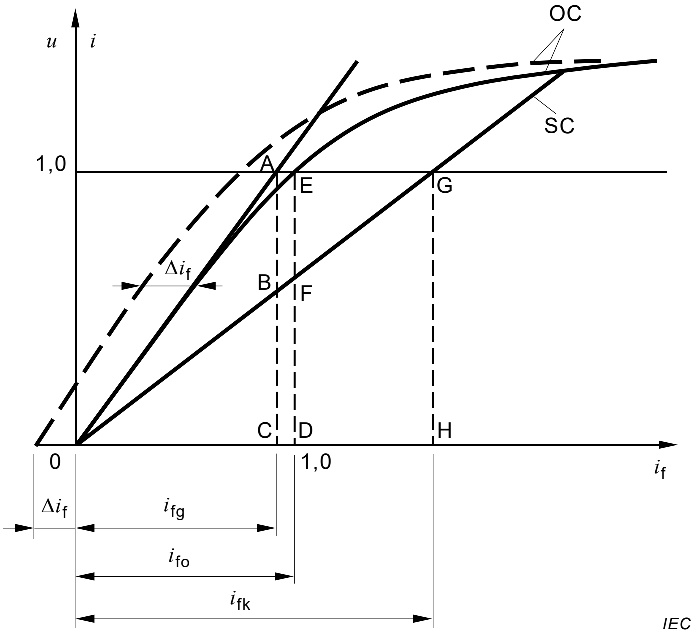


Figure 8 – Combined saturation and short-circuit curves

The curves are used used for determining direct axis synchronous reactance (7.2.1, 7.2.2) and short circuit ratio (7.29).

7.1.2 Sudden three-phase short-circuit test

The change with time of aperiodic and periodic armature current components in each phase is determined from the recordings of the three-phase short-circuit currents versus time (see 6.11).

Therefore, the envelopes of the short circuit currents have to be determined, which are running through the peaks of the oscillating phase currents.

The peaks on the upper and lower envelopes are not corresponding (see Figure 9). Corresponding intermediate points shall be calculated on both envelopes. For calculating the corresponding intermediate points on the envelopes, a suitable interpolation algorithm should be used.

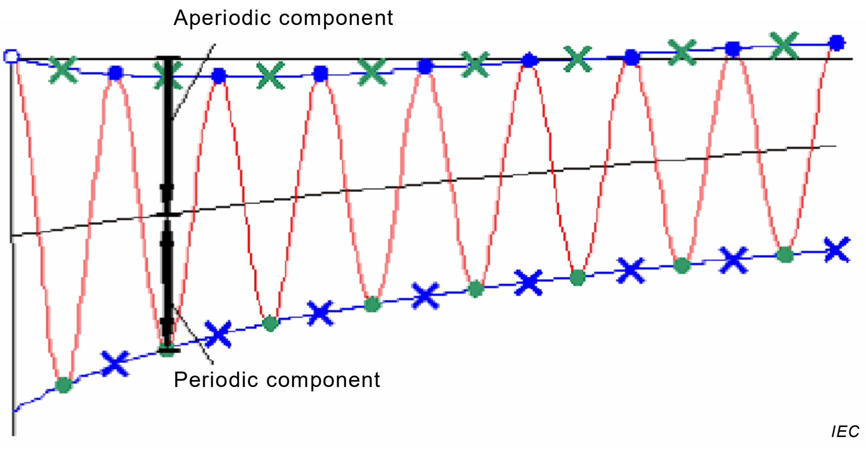


Figure 9 – Determination of intermediate points on the envelopes

The course of the aperiodic component of a phase current is obtained by adding the current values of the upper and lower envelope and dividing by 2. The initial values are found by extrapolation to the moment of short-circuit, $t = 0$.

The course of the periodic component of a phase current is obtained by subtracting the current values of the upper and lower envelope and dividing by 2. The initial values are found by extrapolation to the moment of short-circuit, $t = 0$.

Armature current periodic component at short-circuit is determined as a mean arithmetic value of the periodic components of the current envelopes of the three phases.

The sustained short-circuit current $i(\infty)$ is to be evaluated as an average value of several successive amplitudes for the thoroughly decayed periodic short-circuit current or from the three-phase sustained short-circuit test of 6.5.

To determine the transient ($\Delta i'_{\mathrm{k}}$) current component, the value of the sustained short-circuit current $i(\infty)$ is subtracted from the armature current periodic component.

For determination of the transient component ($\Delta i'_{\mathrm{k}}$) the natural logarithm is applied to the remaining transient envelope of the periodic current values over a time interval between 5 times the approximate subtransient time constant τ''_{d} (or 0,2 s) and the approximate transient time constant τ'_{d}. The transient time constant is the inverse of the representative initial gradient of the logarithmized transient current. Intersection point of the representative straight line with the initial gradient and the ordinate axis of the diagram allows for calculating the initial transient current ($\Delta i'_{\mathrm{k}}$) (see Figure 10).

To determine the sub-transient ($\Delta i''_{\mathrm{k}}$) component, the values of the transient ($\Delta i'_{\mathrm{k}}$) and the sustained short-circuit current $i(\infty)$ are subtracted from the armature current periodic component.

For determination of the sub-transient component ($\Delta i''_{\mathrm{k}}$), the natural logarithm is applied to the remaining sub-transient envelope of the periodic current values within a time frame limited by the maximum time of 2 x τ''_{d}. The subtransient time constant is the inverse of the representative initial gradient of the logarithmized subtransient current values. Intersection point of the representative straight line with the initial gradient and the ordinate axis of the diagram allows for calculating the initial subtransient current ($\Delta i''_{\mathrm{k}}$) (see Figure 11).

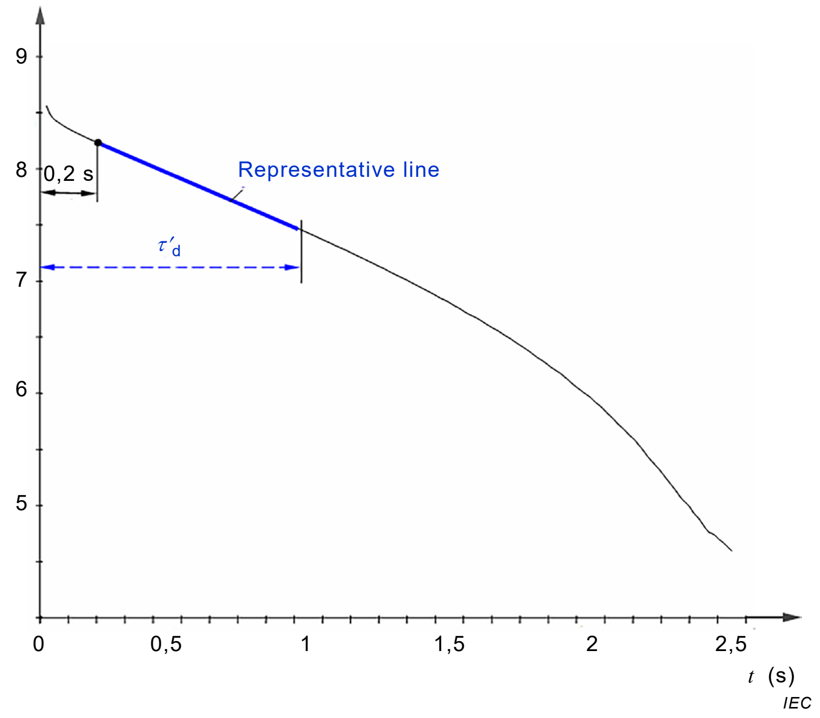


Figure 10 – Determination of transient component of short-circuit current

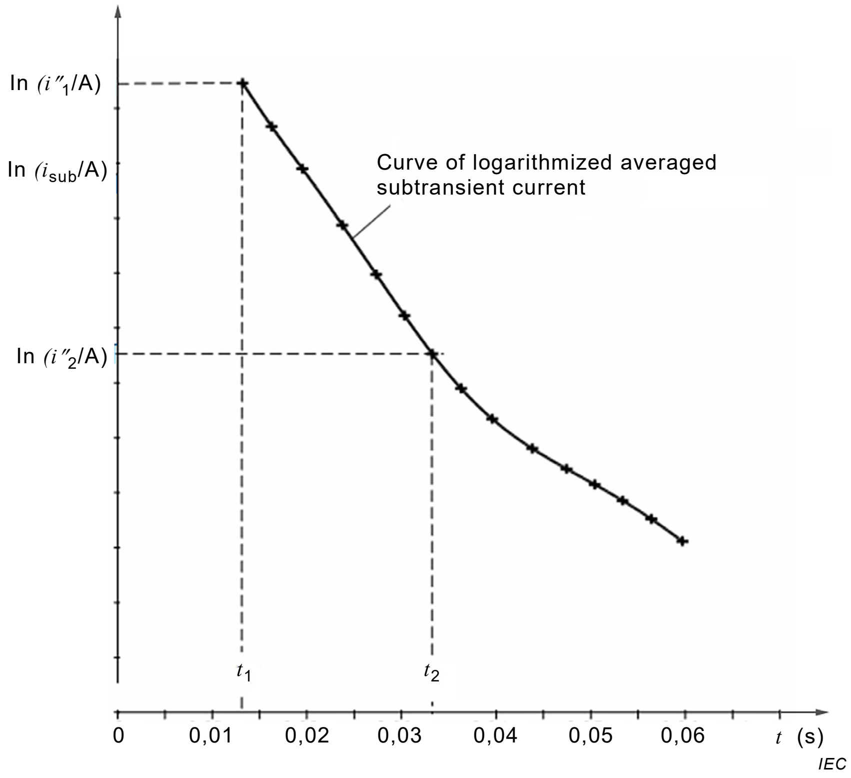


Figure 11 – Determination of sub-transient component of short-circuit current

The greatest possible value of the aperiodic component is determined analytically by the formula:

$$i_{\mathrm{amax}} = \frac{2}{\sqrt{3}} \sqrt{i_{\mathrm{a1}}^2 + i_{\mathrm{a2}}^2 + i_{\mathrm{a1}} i_{\mathrm{a2}}}$$

where

i_{a1}, i_{a2} are the initial aperiodic current components of any two of the three phases.

Values i_{a1}, i_{a2} shall be inserted with their sign, as obtained by the procedure to determine the initial aperiodic component values.

NOTE The formula is valid when $i_{\mathrm{a1}} + i_{\mathrm{a2}} + i_{\mathrm{a3}} = 0$, and the phase displacement of the current vectors is $2\pi/3$, respectively.

The curve of the periodic component of the excitation current against time is determined from the excitation current recording. Extrapolation of the curve to zero time gives the initial value of the periodic current component.

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 recordings (see 6.12) the difference between the sustained voltage and the voltage determined by the envelope of recovery voltage is calculated. Natural logarithm is applied to the remaining envelope of the periodic current values and 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.

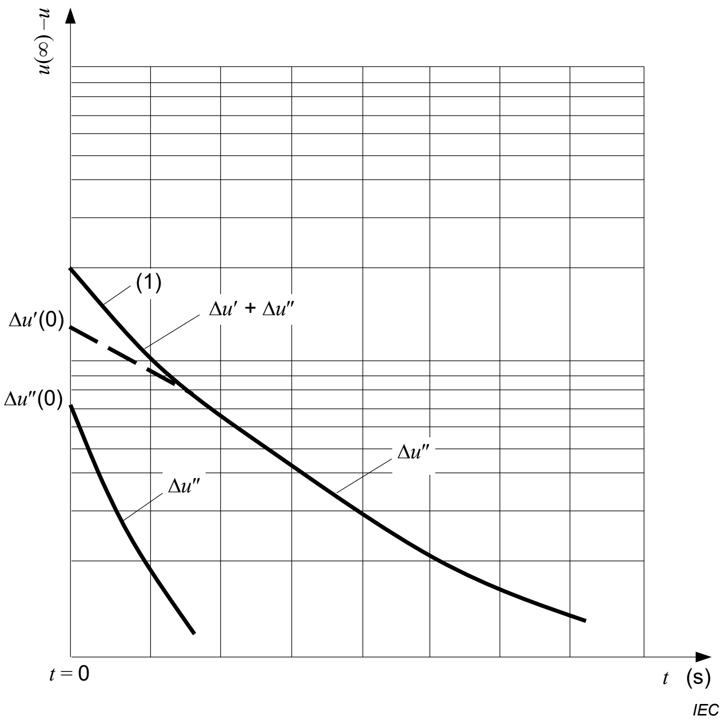


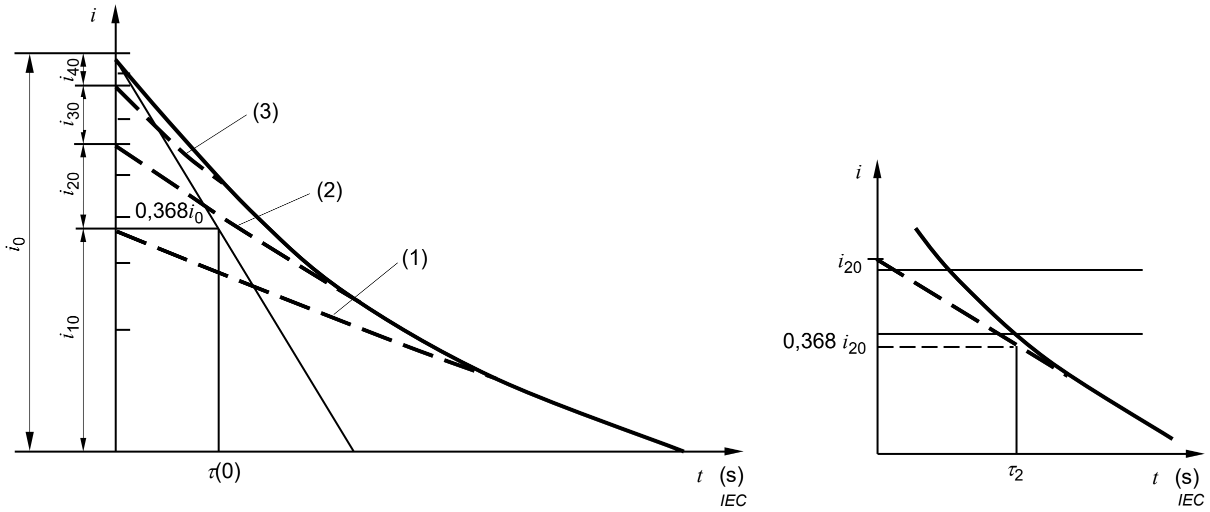
Figure 12 – Transient and sub-transient component of recovery voltage

7.1.4 Direct current decay in the armature winding at standstill

The test (see 6.14) 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 represented against time on a semi-logarithmic scale.

Transient and sub-transient initial values and the time constants of these decaying currents are found by linear extrapolation of the points of extremity (Figure 13 a). The intersection of the extrapolation 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 ≈ 0,368 of its initial value.



a) Initial amplitude i_{10} **b) Initial amplitude i_{20}**

Figure 13 – Semi-logarithmic plot of decay currents

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

Analysis of the data is continued in this manner until that point where non-linearity of the decaying curve is negligible.

The analysis of the decaying armature winding current and 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. To obtain sufficient accuracy in analysing the test data into exponentials, a suitable computer program shall be used.

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

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

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

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:

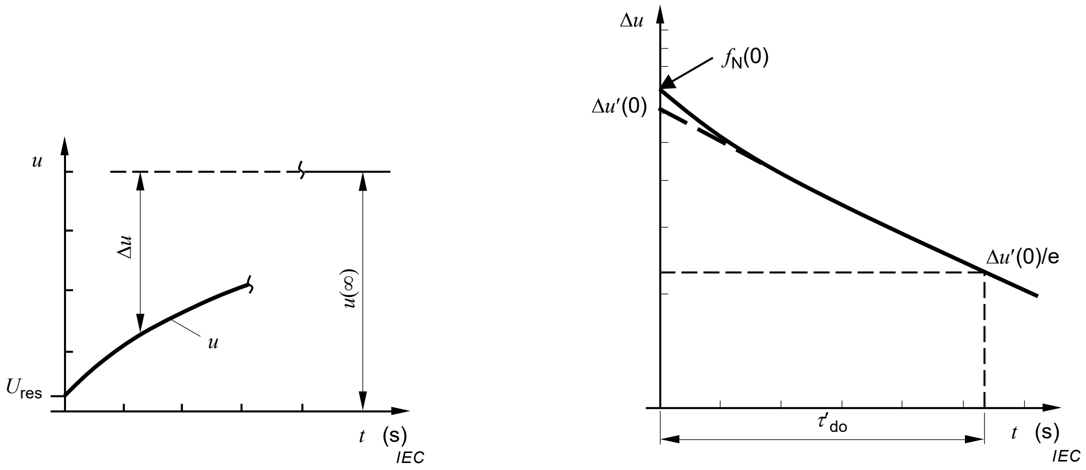
$$\tau'_q = \frac{1}{\omega\alpha'_{1q}}; \quad \tau''_q = \frac{1}{\omega\alpha'_{2q}}; \quad \tau'''_q = \frac{1}{\omega\alpha'_{3q}}$$

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

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 represented on a semi-logarithmic scale against time. This data is extrapolated to the instant of the exciter connection switch closure (see Figure 14) by a suitable interpolation algorithm. The linear 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 can usually be neglected.



a) Extrapolation to instant of switch closure

b) Initial value $\Delta u'(0)$

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):

$$X_d = \frac{U_N}{\sqrt{3}\, I_{BC}} \quad \left[x_d = \frac{AC}{BC} = \frac{0H}{0C} = \frac{i_{fk}}{i_{fg}} \right]$$

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

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

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

7.2.3 From on-load test measuring the load angle

The determination of X_d by the method of load angle measurement (see 6.9) is made using the formula:

$$X_\mathrm{d} = \frac{E_0 / \cos\delta - U}{\sqrt{3}\, I(\cos\varphi \tan\delta + \sin\varphi)} \quad ; \quad \left[x_\mathrm{d} = \frac{e_0 / \cos\delta - u}{i(\cos\varphi \tan\delta + \sin\varphi)} \right]$$

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 taken (similar to Figure 8) and 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.

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

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

where

$U(0)$ is the no-load voltage, measured immediately before the short-circuit (see 6.11);

$I(\infty)$, $\Delta I'_\mathrm{k}(0)$ are determined according to 7.1.2.

7.3.2 From voltage recovery test

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

$$X'_\mathrm{d} = \frac{U(\infty) - \Delta U'(0)}{\sqrt{3}\, I_\mathrm{k}} \quad ; \quad \left[x'_\mathrm{d} = \frac{u(\infty) - \Delta u'(0)}{i_\mathrm{k}} \right]$$

where input values are from test data (6.12) as analysed according to 7.1.3.

7.3.3 From DC decay test in the armature winding at standstill

Calculate:

$$x'_{\mathrm{d}} = \frac{1}{\dfrac{1}{x_{\mathrm{d}}} + C_{1\mathrm{d}}}$$

where $C_{1\mathrm{d}}$ 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:

$$x_{\mathrm{d}} \cdot \tau'_{\mathrm{d}} = x'_{\mathrm{d}} \cdot \tau'_{\mathrm{do}}$$

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 time function (according to 7.1.2, Figure 9):

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

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.

$$X''_{\mathrm{d}} = \frac{U(\infty) - \left[\Delta U'(0) + \Delta U''(0)\right]}{\sqrt{3}\; I_{\mathrm{k}}} \quad ; \quad \left[x''_{\mathrm{d}} = \frac{u(\infty) - \left[\Delta u'(0) + \Delta u''(0)\right]}{i_{\mathrm{k}}} \right]$$

where input values are from test data (see 6.12) 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:

$$X''_{\mathrm{d}} = \sqrt{Z''^{2}_{\mathrm{d}} - R''^{2}_{\mathrm{d}}}$$

where $Z''_{\mathrm{d}} = \dfrac{U}{2I}$; $R''_{\mathrm{d}} = \dfrac{P}{2I^{2}}$; $\left[x''_{\mathrm{d}} = \sqrt{z''^{2}_{\mathrm{d}} - r''^{2}_{\mathrm{d}}};\; z''_{\mathrm{d}} = \dfrac{\sqrt{3}}{2} \cdot \dfrac{u}{i};\; r''_{\mathrm{d}} = \dfrac{3}{2} \cdot \dfrac{p}{i^{2}} \right]$

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 6.15.

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 6.16) 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:

$$x''_\mathrm{d} = x_\mathrm{av} \pm \Delta x$$

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

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.

7.5 Quadrature-axis synchronous reactance

7.5.1 From negative excitation test

The determination of X_q from the negative excitation test 6.8 is according to the formula:

$$x_\mathrm{q} = (x_\mathrm{d}) \cdot \frac{u_\mathrm{r}}{u_\mathrm{r} + (e)}$$

where

- (e) is the no-load e.m.f. determined for excitation current i_fr at which the machine slips one pole pitch; determined from the straightened no-load saturation characteristic drawn through the point corresponding to the voltage at the moment of slipping one pole pitch (see Figure 15);
- u_r is the voltage at the moment of slipping the pole pitch;
- (x_d) is the direct-axis synchronous reactance determined from the same straightened no-load saturation characteristic.

If during the test, the armature current i_r at which the machine slips one pole pitch is measured, x_q is determined using the formula:

$$X_\mathrm{q} = \frac{U_\mathrm{r}}{\sqrt{3}\, I_\mathrm{r}} \quad ; \quad \left[x_\mathrm{q} = \frac{u_\mathrm{r}}{i_\mathrm{r}} \right]$$

The value of x_q obtained from this test may, depending upon the value of u_r, include saturation. To obtain an unsaturated value, the applied voltage usually shall be reduced to 0,6 of rated value or lower.

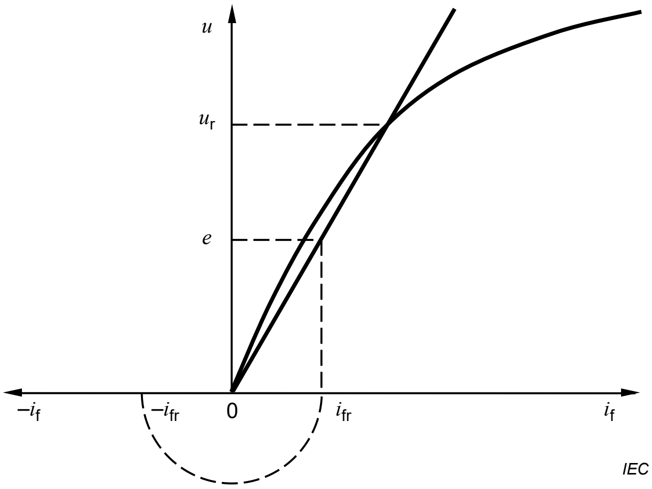


Figure 15 – No-load e.m.f. and excitation current for one pole-pitch slip

7.5.2 From low slip test

To determine X_q from the low slip test (see 6.10), armature current and voltage are measured at maximum excitation winding voltage U_{fo}, and X_q is calculated using the formula:

$$X_q = \frac{U_{min}}{\sqrt{3}\,I_{max}} \quad ; \quad \left[x_q = \frac{u_{min}}{i_{max}} \right]$$

If I_{max} does not coincide with U_{min}, use in calculations I_{max} as a base and its corresponding voltage.

If, during the test, the residual voltage of the machine U_{res} is within 0,1 to 0,3 of the supply test voltage, the value of the current is determined using the formula:

$$I_{max} = \sqrt{I_{av}^2 - \left(\frac{U_{res}}{\sqrt{3}X_d}\right)^2} \quad ; \quad \left[i_{max} = \sqrt{i_{av}^2 - \left(\frac{u_{res}}{x_d}\right)^2} \right]$$

where I_{av} is the half sum of two consecutive maxima of the current envelope curve (see Figure 16).

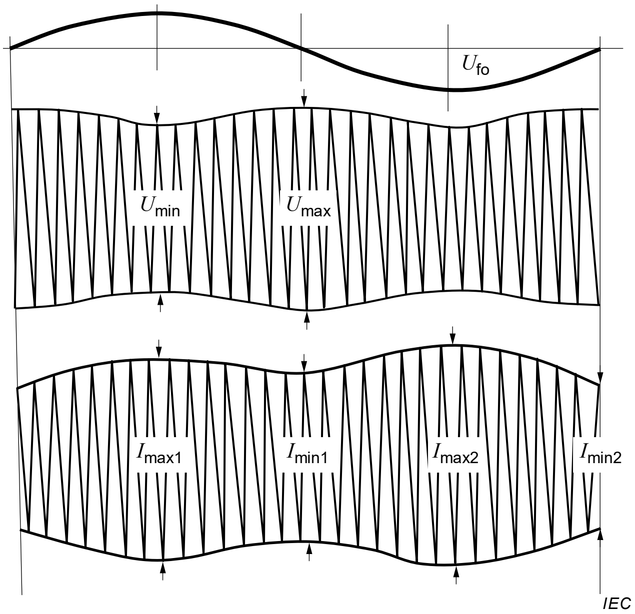


Figure 16 – Current envelope from low-slip test

A check of the measured value may be made by calculating X_d from the same test, using the results of the voltage and current measurements at the time when the voltage of the open-circuit excitation winding is equal to zero, and comparing it with its real value.

$$X_d = \frac{U_{max}}{\sqrt{3}\,I_{min}}; \quad \left[x_d = \frac{u_{max}}{i_{min}} \right]$$

With a residual voltage less than 0,3 of the supply test voltage, the half sum of two consecutive minima of the envelope curve represents I_{min}.

The results of X_q determined from the low slip test may be considered correct only if the value of X_d obtained from this test practically agrees with its value obtained from one of the tests given in 7.2. Otherwise, the test is repeated at several low values of the slip, followed by extrapolation of X_q values to zero slip. The value of quadrature-axis synchronous reactance obtained from this test practically corresponds to the unsaturated value.

7.5.3 From on-load test measuring the load angle

The determination of X_q by the method of load angle measurement (see 6.9) is made using the formula:

$$X_q = \frac{U \tan\delta}{\sqrt{3}\,I(\cos\varphi - \sin\varphi\tan\delta)}; \quad \left[x_q = \frac{u\tan\delta}{i(\cos\varphi - \sin\varphi\tan\delta)} \right]$$

where

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 Angle values in the formula to be inserted with 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.

7.6 Quadrature-axis transient reactance

7.6.1 From direct current decay test in the armature winding at standstill

Calculate

$$x'_\mathrm{q} = \frac{1}{\dfrac{1}{x_\mathrm{q}} + C_{l\mathrm{q}}}$$

where $C_{l\mathrm{q}}$ is as in Annex B. Calculation of x_q is indicated in 7.1.4.

7.6.2 Calculation from test values

The quantities x'_q, x_q, τ'_qo and τ'_q are related to each other by the following formula:

$$x_\mathrm{q} \cdot \tau'_\mathrm{q} = x'_\mathrm{q} \cdot \tau'_\mathrm{qo}$$

This relation is used for the determination of x'_q from the known values of x_q, τ'_q and τ'_qo .

7.7 Quadrature-axis sub-transient reactance

7.7.1 From applied voltage test with the rotor in direct and quadrature position

Sub-transient reactance X''_q from the applied voltage test is determined as in 7.4.3, but replacing index d by index q.

$$X''_\mathrm{q} = \sqrt{Z''^2_\mathrm{q} - R''^2_\mathrm{q}}$$

$$\text{where} \quad Z''_\mathrm{q} = \frac{U}{2I} \ ; \quad R''_\mathrm{q} = \frac{P}{2I^2} \ ; \quad \left[x''_\mathrm{q} = \sqrt{z''^2_\mathrm{q} - r''^2_\mathrm{q}};\ z''_\mathrm{q} = \frac{\sqrt{3}}{2} \cdot \frac{u}{i};\ r''_\mathrm{q} = \frac{3}{2} \cdot \frac{p}{i^2} \right]$$

The values of the voltage U, current I and power input P, measured for the rotor position which gives the minimum excitation winding current, are according to 6.15.

7.7.2 From applied voltage test with the rotor in arbitrary position

Sub-transient reactance X''_q from the stationary impedance test with the rotor in arbitrary position is determined similarly to the method described in 7.4.4, but using values according to 6.16.

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

7.8 Zero-sequence reactance

7.8.1 From single-phase voltage application to the three phases

The zero sequence reactance and resistance are determined from single-phase voltage test applied to the three phases (see 6.17) by

$$X_0 = \sqrt{Z_0^2 - R_0^2} \;; \qquad \left[x_0 = \sqrt{z_0^2 - r_0^2} \right]$$

where, dependent on the connection of the three phases:

- for series connection $Z_0 = \frac{U}{3I}$; $R_0 = \frac{P}{3I^2}$; $\left[z_0 = \frac{1}{\sqrt{3}} \cdot \frac{u}{i};\ r_0 = \frac{p}{i^2} \right]$; and
- for parallel connection $Z_0 = \frac{3U}{I}$; $R_0 = \frac{3P}{I^2}$; $\left[z_0 = 3\sqrt{3} \cdot \frac{u}{i};\ r_0 = \frac{9p}{i^2} \right]$

7.8.2 From line-to-line and to neutral sustained short-circuit test

The zero sequence reactance X_0 from the line-to-line and to neutral sustained short-circuit test (see 6.19) is determined using:

$$X_0 = \frac{U_0}{I_0}; \qquad \left[x_0 = \frac{3u_0}{i_0} \right]$$

when voltage or current harmonics may be ignored, or

$$X_0 = \frac{U_0^2}{Q} \cdot \frac{Q^2}{P^2 + Q^2}; \qquad \left[x_0 = \frac{u_0^2}{q} \cdot \frac{q^2}{p^2 + q^2} \right]$$

when the voltage or current harmonics shall be considered. In this case U, P and Q are measured values of the voltage, active and reactive power, respectively.

The zero sequence reactance is calculated for several neutral current values. Based on the test data, X_0 is plotted against neutral current.

NOTE The value of X_0 when the neutral current equals three times the rated phase current will be taken as the rated current value.

7.9 Negative-sequence reactance

7.9.1 From line-to-line sustained short-circuit test

Negative sequence reactance $X_{(2)}$ from the line-to-line sustained short-circuit test is determined using:

$$X_{(2)} = \frac{P}{\sqrt{3} I_{k2}^2} \;; \qquad \left[x_{(2)} = \sqrt{3} \frac{p}{i_{k2}^2} \right]$$

when voltage or current harmonics may be ignored, or

$$X_{(2)} = \frac{U^2}{P} \cdot \frac{P^2}{P^2 + Q^2} \frac{1}{\sqrt{3}} \;; \qquad \left[x_{(2)} = \frac{u^2}{p} \cdot \frac{p^2}{p^2 + q^2} \cdot \frac{1}{\sqrt{3}} \right]$$

when the voltage or current harmonics shall be considered.

Negative sequence reactance is determined for each measured short-circuit current value. On the basis of the test data $X_{(2)}$ is plotted against current.

NOTE 1 Different values might be obtained for this reactance if the fundamental component of a current, which also contains harmonics, is used. The correct value of X_2, however, is the one determined with sinusoidal current.

NOTE 2 The value of $X_{(2)}$ when the current equals $\sqrt{3}$ times the rated phase current will be taken as the rated current value.

7.9.2 From negative-phase sequence test

Negative sequence reactance and resistance from the negative-phase sequence test of 6.20 are determined by the formulae:

$$X_{(2)} = \sqrt{Z_{(2)}^2 - R_{(2)}^2} \quad ; \quad Z_{(2)} = \frac{U}{\sqrt{3}\,I} \quad ; \quad R_{(2)} = \frac{P}{3I^2}$$

$$\left[x_{(2)} = \sqrt{z_{(2)}^2 - r_{(2)}^2}; \quad z_{(2)} = \frac{u}{i}; \quad r_{(2)} = \frac{p}{i^2} \right];$$

where

P is the input power;

I is the average measured current;

U is the average measured voltage applied.

Negative sequence reactance and resistance are determined for each measured supply voltage. On the basis of the test data X_2 and R_2 are plotted against current.

7.9.3 Calculation from test values

Negative sequence reactance $X_{(2)}$ from known test values of X''_{d} (see 7.4) and X''_{q} (see 7.6) is calculated by the formula:

$$x_{(2)} = \frac{x''_{\mathrm{d}} + x''_{\mathrm{q}}}{2}$$

NOTE Experience shows that for salient pole machines $x''_{\mathrm{q}}/x''_{\mathrm{d}} \approx 1 \ldots 1{,}3$ for complete damper windings, connected between poles; $x''_{\mathrm{q}}/x''_{\mathrm{d}} \approx 1{,}8 \ldots 3$ for damper windings only in the d-axis with laminated poles; $x''_{\mathrm{q}}/x''_{\mathrm{d}} \approx 1{,}5 \ldots 1{,}8$ for solid steel pole shoes. For cylindrical, solid steel rotor machines it is found that $x''_{\mathrm{q}}/x''_{\mathrm{d}} \approx 1$.

7.9.4 From direct-current decay test at standstill

The negative sequence reactance, knowing the frequency response characteristics $x_{\mathrm{d}}(js)$ and $x_{\mathrm{q}}(js)$, is determined as an imaginary part:

$$x_{(2)} = \mathrm{Im}\left\{ \frac{j}{\dfrac{1}{2}\left[\dfrac{1}{x_{\mathrm{d}}(js)_{s=2}} + \dfrac{1}{x_{\mathrm{q}}(js)_{s=2}} \right]} \right\}$$

7.10 Armature leakage reactance

The armature-leakage reactance may be determined by the method of applying symmetrical three-phase voltage to the armature winding with rotor removed. Its determination requires some of the winding parameters to be known.

Leakage reactance X_σ from the applied voltage test with rotor removed (see 6.22) is calculated by the following formula:

$$X_\sigma = X_\mathrm{a} - X_\mathrm{b};$$

The total leakage reactance X_a with the rotor removed is determined by

$$X_\mathrm{a} = \sqrt{Z^2 - R^2}, \quad Z = \frac{U}{\sqrt{3}I}, \quad R = \frac{P}{3I^2}$$

The reactance X_b due to flux across the armature active surface created by the armature winding in the space which is normally occupied by the rotor is calculated (search coil placed according to 6.22):

– for integral slot windings $$X_\mathrm{b} = \frac{U_\mathrm{c}}{I}\frac{N\,k_\mathrm{w}}{N_\mathrm{c}};$$

– for fractional slot windings $$X_\mathrm{b} = \frac{U_\mathrm{c}}{I}\frac{Nk_\mathrm{w}}{N_\mathrm{c}\sin\left(\frac{q'}{3q}\frac{\pi}{2}\right)}$$

where

U_c is the search coil voltage;

I is the armature current;

N is the number of series-connected turns per circuit of a phase of the armature winding;

N_c is the number of search coil turns;

k_w is the armature winding factor;

q is the number of slots per pole pitch and phase (integral or fractional);

q' is the largest whole number of slots comprising the pole pitch.

NOTE The literature provides also a formula for the calculation of X_b from machine design parameters; however the test method is preferred.

7.11 Potier reactance

The Potier reactance is determined graphically according to Figure 17.

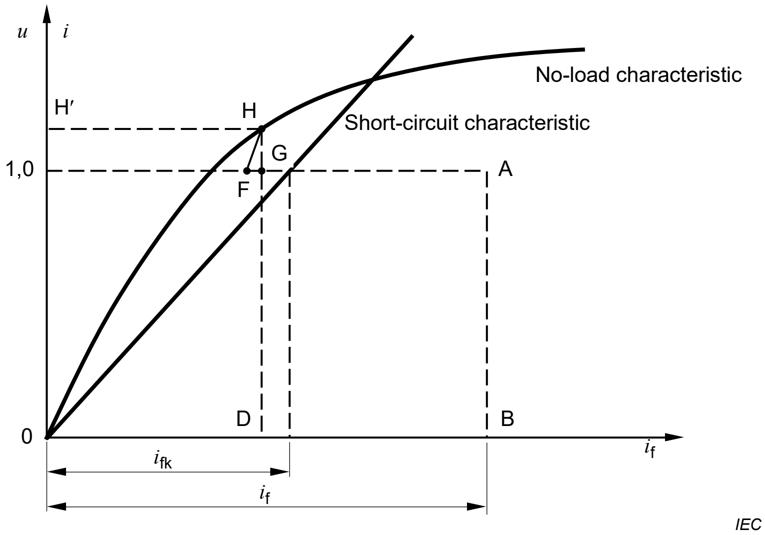


Figure 17 – Determination of Potier reactance

The no-load saturation and three-phase sustained short-circuit characteristics are plotted as in 7.1.1. The excitation current i_f from the test (see 6.26), measured at rated armature current and zero power-factor at overexcitation is laid off as 0B. Point A is the intersection of the rated voltage and the excitation current. To the left from point A, parallel to the abscissa, a length AF equal to the excitation current i_fk for the rated armature sustained short-circuit current is laid off. A line parallel to the initial lower portion of the no-load characteristic is drawn through the point F up to the intersection with the upper part of the no-load characteristic (point H). The length of perpendicular from point H to point G (intersection with AF line) represents the voltage drop on reactance X_p at rated armature current. Note that in per unit values x_p equals HG.

7.12 Zero-sequence resistance

7.12.1 From single-phase voltage test applied to the three phases

Zero-sequence resistance $R_{(0)}$ is determined from the test (see 6.17) together with $Z_{(0)}$ and $X_{(0)}$ according to 7.8.1.

7.12.2 From line-to-line and to neutral sustained short-circuit test

Zero-sequence resistance $R_{(0)}$ from the line-to-line and to neutral short-circuit test is determined by the following formula for several neutral current values:

$$R_{(0)} = \frac{U_0^2}{P} \cdot \frac{P^2}{P^2 + Q^2}; \quad \left[r_{(0)} = \frac{u_0^2}{p} \cdot \frac{p^2}{p^2 + q^2} \right]$$

On the basis of the test data, $R_{(0)}$ is plotted against neutral current.

NOTE 1 A number of levels of excitation is needed to get several values of neutral current.

NOTE 2 The value of $R_{(0)}$, when the neutral current equals three times the rated phase current, will be taken as the rated current value.

7.13 Positive-sequence armature winding resistance

Positive-sequence resistance $R_{(1)}$ is determined from the known losses, consisting of $P_{\text{cu}} = 3I^2R_{\text{a}}$ and additional load losses (stray losses) P_{LL} in the armature winding measured at rated current in accordance with IEC 60034-2-1, using:

$$R_{(1)} = \frac{P_{\text{cu}} + P_{\text{LL}}}{3I_{\text{N}}^2}; \quad \left[r_{(1)} = p_{\text{cu}} + p_{\text{LL}} \right]$$

This value of $R_{(1)}$ corresponds to the winding temperature at which the loss measurements were conducted.

7.14 Negative-sequence resistance

7.14.1 From line-to-line sustained short-circuit test

Negative-sequence resistance $R_{(2)}$ from the line-to-line sustained short-circuit test is determined using:

$$R_{(2)} = \frac{U^2}{Q} \cdot \frac{Q^2}{P^2 + Q^2} \frac{1}{\sqrt{3}} \; ; \quad \left[r_{(2)} = \frac{u^2}{q} \cdot \frac{q^2}{p^2 + q^2} \cdot \frac{1}{\sqrt{3}} \right]$$

Negative sequence resistance is determined for each measured short-circuit armature current. On the basis of the test data, $R_{(2)}$ is plotted against current.

NOTE 1 A different value might be obtained for this resistance if the fundamental component of a current, which also contains harmonics, is used.

NOTE 2 The value of $R_{(2)}$, when the current equals $\sqrt{3}$ times the rated phase current, will be taken as the rated current value.

7.14.2 From negative-phase sequence test

Negative sequence reactance and resistance are determined from the negative-phase sequence test by the formulae:

$$X_{(2)} = \sqrt{Z_{(2)}^2 - R_{(2)}^2} \; ; \quad Z_{(2)} = \frac{U}{\sqrt{3}\, I} \; ; \quad R_{(2)} = \frac{P}{3I^2}$$

$$\left[x_{(2)} = \sqrt{z_{(2)}^2 - r_{(2)}^2}; \quad z_{(2)} = \frac{u}{i}; \quad r_{(2)} = \frac{p}{i^2} \right];$$

where

P is the input power;

I is the average measured current;

U is the average measured voltage applied.

Negative sequence reactance and resistance are determined for each measured supply voltage. On the basis of the test data $X_{(2)}$ and $R_{(2)}$ are plotted against current.

7.15 Armature and excitation winding resistance

When using the volt-ampere method (see 6.3), the winding resistance is calculated from the formula:

$$R_a = \frac{U}{I}; \quad \left[r_a = 3 \cdot \frac{u}{i} \right]$$

where

U is the voltage applied to the winding;

I is the winding current.

The average value is taken for the resistance. In determining the average value, resistances which differ by more than ± 0,01 from the average per unit value should be disregarded.

When resistance measurements are made between each pair of the line terminals of the armature winding, the resistance R_1 of phase 1 is calculated from the formula (in physical quantities):

– for star-connected winding:

$$R_1 = \frac{R_{12} + R_{31} - R_{23}}{2}$$

– for delta-connected winding:

$$R_1 = \frac{2R_{12} \cdot R_{23}}{R_{12} + R_{23} - R_{31}} - \frac{R_{12} + R_{23} - R_{31}}{2}$$

where R_{12}, R_{23} and R_{31} are the resistances measured between terminals 1-2, 2-3 and 3-1.

The average value is taken for the resistance. In determining the average value, resistances which differ by more than ± 0,01 per unit value from the average should be disregarded.

7.16 Direct-axis transient short-circuit time constant

7.16.1 From sudden three-phase short-circuit test

Direct-axis transient short-circuit time constant τ'_d, as determined from the sudden three-phase short-circuit test, is the time required for the transient armature current component to decrease to 1/e ≈ 0,368 of its initial value (see 7.1.2).

7.16.2 From direct current decay test at standstill

Direct axis time constants are determined using known roots of characteristic formulas $D_d(p) = 0$ and $D'_d(p) = 0$ according to 7.1.4.

7.17 Direct-axis transient open-circuit time constant

7.17.1 From field current decay at rated speed with armature winding open

The direct-axis transient open-circuit time constant is determined from 6.21.1 as the time required for the voltage difference to decrease to 1/e ≈ 0,368 of its initial value.

7.17.2 From field current decay test at standstill with armature winding open

The direct-axis transient open-circuit time constant is determined from 6.21.2 as the time required for the field current to decrease to 1/e ≈ 0,368 of its initial value.

7.17.3 From voltage recovery test

The direct-axis transient open-circuit time constant is determined from 6.12 as the time required for the voltage difference to decrease to 1/e ≈ 0,368 of its initial value.

7.17.4 From direct-current decay test at standstill

Direct axis time constants of synchronous machines are determined using known roots of characteristic formulas $D_\mathrm{d}(p) = 0$ and $D'_\mathrm{d}(p) = 0$ according to 7.1.4.

7.18 Direct-axis sub-transient short-circuit time constant

τ''_d, as determined from the sudden three-phase short-circuit test, is the time required for the sub-transient armature current component to decrease to 1/e ≈ 0,368 of its initial value (see 7.1.2).

7.19 Direct-axis sub-transient open-circuit time constant

7.19.1 From voltage recovery test

The direct-axis open-circuit sub-transient time constant as determined from the voltage recovery test is the time required for the sub-transient component $\Delta U''$ determined in accordance with 7.1.3, to decrease to 1/e ≈ 0,368 of its initial value.

7.19.2 From direct-current decay test at standstill

Direct axis time constants are determined using known roots of the characteristic formulas $D_\mathrm{d}(p) = 0$ and $D'_\mathrm{d}(p) = 0$ according to 7.1.4.

7.20 Quadrature-axis transient short-circuit time constant

7.20.1 Calculation from test values

Quadrature-axis transient short-circuit time constant is determined by calculation from the test values x_q, x'_q and τ'_qo using the following formula:

$$\tau'_\mathrm{q} = \tau'_\mathrm{qo} \frac{x'_\mathrm{q}}{x_\mathrm{q}}$$

7.20.2 From direct-current decay test at standstill

Quadrature axis time constants are similarly determined as in 7.19.2 using the roots of characteristic formulas $D_\mathrm{q}(p) = 0$ and $D'_\mathrm{q}(p) = 0$ according to 7.1.4.

7.21 Quadrature-axis transient open-circuit time constant

Quadrature axis time constants are determined using known roots of the characteristic formulas $D_\mathrm{q}(p) = 0$ and $D'_\mathrm{q}(p) = 0$ according to 7.1.4.

7.22 Quadrature-axis sub-transient short-circuit time constant

7.22.1 Calculation from test values

Quadrature-axis sub-transient short-circuit time constant is determined by calculation from the test values x'_q (see 7.6.1), x''_q (see 7.7) and τ''_qo (see 7.23) using the following formula:

$$\tau''_{\mathrm{q}} = \tau''_{\mathrm{qo}} \frac{x''_{\mathrm{q}}}{x_{\mathrm{q}}}$$

7.22.2 Determination from direct-current decay test at standstill

Quadrature axis time constants are determined using the roots of characteristic formulas $D_{\mathrm{q}}(p) = 0$ and $D'_{\mathrm{q}}(p) = 0$ according to 7.1.4.

7.23 Quadrature-axis sub-transient open-circuit time constant

Quadrature axis time constants are similarly determined using the roots of characteristic formulas $D_{\mathrm{q}}(p) = 0$ and $D'_{\mathrm{q}}(p) = 0$ according to 7.1.4.

7.24 Armature short-circuit time constant

7.24.1 From sudden three-phase short-circuit test

Armature short-circuit time constant τ_{a} is determined as the time required for the excitation current periodic component to decrease to 1/e ≈ 0,368 of its initial current.

NOTE In a brushless machine excited from its own exciter without using temporary slip-rings, the time constant cannot be determined from the decrease of the excitation current periodic component.

In an alternative method, the time constant is determined from decrease of the aperiodic armature current components in each phase as the average time required for these components to decrease to 1/e ≈ 0,368 of their initial value. Any phase whose initial aperiodic component is less than 0,4 of the initial maximum resolved value should be disregarded in determining the armature short circuit time-constant.

Determination of the armature short-circuit time constant from the decrease of the aperiodic armature current component is permissible, provided the armature current during the sudden short-circuit test is measured by non-inductive shunts.

7.24.2 Calculation from test values

Armature short-circuit time constant τ_{a} at rated frequency f_{N} from known test values of $X_{(2)}$ (see 7.9) and R_{a} (see 7.15) is calculated using the formula:

$$\tau_{\mathrm{a}} = \frac{x_{(2)}}{2\pi f_{\mathrm{N}} r_{\mathrm{a}}}$$

Use a saturated value of $x_{(2)}$.

7.25 Rated acceleration time and stored energy constant

Acceleration time of the machine and stored energy constant from the no-load retardation test (see 6.23) are determined using the formulae:

$$\tau_{\mathrm{J}} = \omega_{\mathrm{N}} \frac{\Delta t}{\Delta \omega} \cdot \frac{P_{\mathrm{mech}} + P_{\mathrm{Fe}}}{P_{\mathrm{N}}}; \qquad H = \frac{\omega_{\mathrm{N}}}{2} \cdot \frac{\Delta t}{\Delta \omega} \cdot \frac{P_{\mathrm{mech}} + P_{\mathrm{Fe}}}{S_{\mathrm{N}}}$$

where

P_{mech} is the mechanical losses at rated speed, in kW;

P_{Fe} is the core losses at rated speed and corresponding value of test voltage, in kW;

ω_{N} is the rated angular speed, in rad/s.

7.26 Rated excitation current

7.26.1 From direct measurement

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

The rated excitation current is determined by direct measurement during operation under rated conditions (see 6.2).

7.26.2 Potier diagram

To determine the rated excitation current by Potier's diagram, use is made of the no-load saturation characteristic (see 6.4.2), sustained short-circuit characteristic (see 6.5.2) and Potier reactance X_p.

With the rated armature current vector i_N laid off along the abscissa as the base, the measured power-factor angle φ_N (which is considered to be positive for an overexcited generator) is used to draw the rated voltage vector u_N (see Figure 18).

The vector of the voltage drop ($x_p i_N$) in the Potier reactance at the rated armature current is drawn from the end of the voltage vector as a perpendicular to the armature current vector. The voltage drop in the armature winding resistance is usually neglected. If necessary, it may be taken into account by drawing the vector of positive phase sequence voltage drop in the positive phase sequence armature winding resistance from the end of the voltage vector parallel to the current vector.

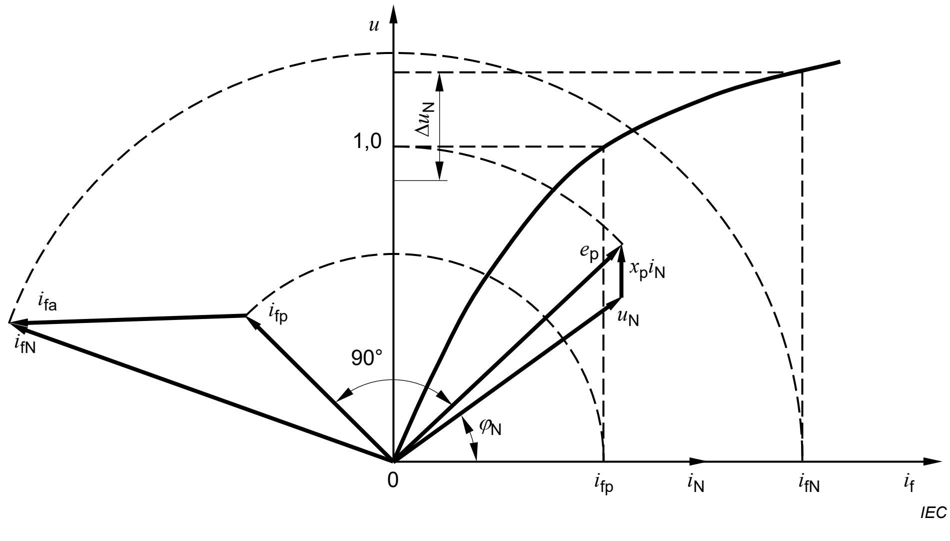


Figure 18 – Potier's diagram

This vector should be laid off on the diagram (see Figure 18) in the direction of the armature current vector for generators and in the opposite direction for motors.

The vector sum of the rated voltage and the voltage drop in the reactance X_p gives e.m.f. vector e_p; excitation current, i_{fp}, corresponding to this e.m.f. is determined from the no-load curve and is laid off from the origin at 90° to the e.m.f. vector.

The excitation current component compensating armature reaction at rated armature current i_{fa} is determined as the difference between the excitation current corresponding to the rated armature current on the sustained three-phase short-circuit characteristic, and the excitation current corresponding to the voltage drop in X_p due to armature rated current on the no-load saturation characteristic (see Figure 17). Vector i_{fa} is laid off from the end of the vector i_{fp} parallel to the armature current vector. The rated excitation current i_{fn} is the vector sum of i_{fp} and i_{fa}.

If the value of the excitation current obtained from the Potier diagram (as well as from ASA and Swedish diagrams) is used only to estimate the rated value of excitation current, the Potier reactance X_p if unknown may be replaced in the construction of Figure 18 for machines with rated frequency below 100 Hz by (ax_a), where x_a is the armature reactance measured without rotor, and a is a factor taken equal to 1,0 for salient pole machines and 0,6 (0,65) for non-salient pole machines (unless more precise figures are available from previous experience on machines of similar construction). If the value of the excitation current obtained from the Potier diagram (as well as from ASA and Swedish diagrams) is used to determine the temperature rise of the excitation winding from the zero power factor loading test, the Potier reactance should be determined from no-load and sustained three-phase characteristics and the excitation current corresponding to the rated voltage and rated armature current at zero power-factor.

The test with rotor removed (6.22) is conducted with three-phase voltage at rated frequency applied to terminals of the armature winding. The applied voltage is so chosen that the armature current is near the rated value. During the test, measurements are made of the terminal voltage U, line current I and supplied active power P.

7.26.3 ASA diagram

To determine the rated excitation current of the machine by the ASA vector diagram (see Figure 19), use is made of the no-load saturation characteristic (see 6.4.2), the sustained three-phase short-circuit characteristic (see 6.5.2) and the Potier reactance.

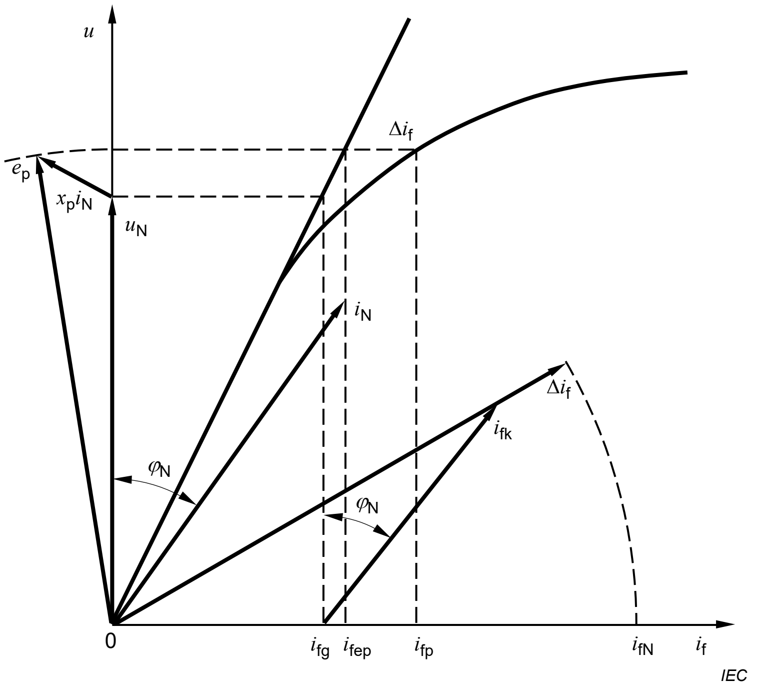


Figure 19 – ASA diagram

The determination of e.m.f. e_p is made in accordance with 7.1.1. The excitation current for the air-gap line at the rated armature voltage i_{fg} is determined from the no-load saturation characteristic. The vector current i_{fg} is laid off from the origin along the abscissa axis. From its end, at the rated power-factor angle φ_N (which is considered to be positive for an overexcited generator) to the right of the vertical, the vector of excitation current i_{fk} corresponding to rated armature current on the sustained three-phase short-circuit characteristic (see 7.1.1) is laid off.

The vector current corresponding to the difference Δi_f between the excitation currents of the no-load saturation characteristic i_fp and on the air-gap line i_fep, both for the voltage e_p (see Figure 19) is laid off along the geometrical vector sum of the excitation currents. The sum of the three vectors corresponds to the rated excitation current.

The rated excitation current may also be determined using the following formula (in per unit or physical values):

$$i_\text{fN} = \Delta i_\text{f} + \sqrt{(i_\text{fg} + i_\text{fk} \sin \varphi_\text{N})^2 + (i_\text{fk} \cos \varphi_\text{N})^2}$$

If the Potier reactance is unknown and the ASA diagram is used to estimate the rated value of the excitation current only (without zero-power loading test) then the Potier reactance may be replaced in the construction of Figure 19 by ax_a (see 7.26.2).

7.26.4 Swedish diagram

To determine rated excitation current of the machine by the Swedish diagram, use is made of the no-load saturation characteristic (see 6.4.2), the sustained three-phase short-circuit characteristic (see 6.5.2) and the excitation current corresponding to the rated voltage and armature current at zero power-factor (overexcited) (see 6.7).

Three values of the excitation current are laid off on the abscissa axis (see Figure 20):

OD corresponding to the rated voltage on the no-load curve;

OB corresponding to the rated voltage and armature current at zero power-factor;

OC corresponding to the rated armature current on the sustained short-circuit characteristic.

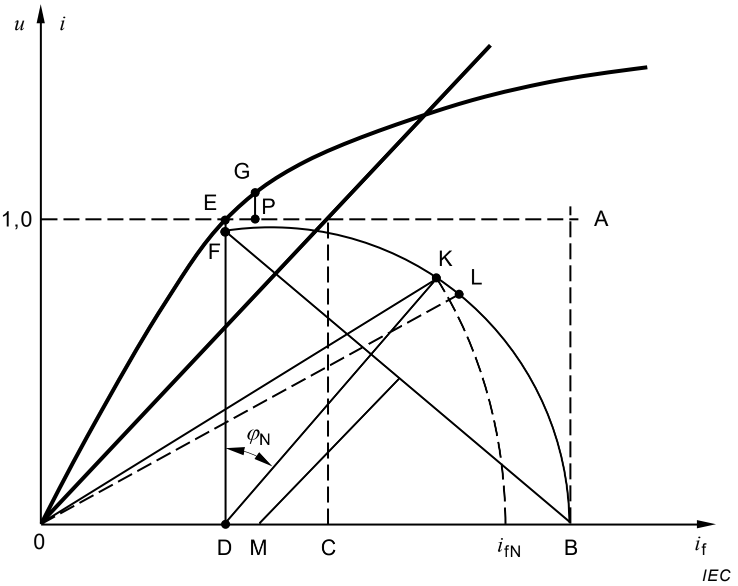


Figure 20 – Swedish diagram

From point D a perpendicular to the abscissa axis is drawn on which the length FD equal to 1,05 OC is laid off. Points F and B are connected by a straight line and a perpendicular is drawn from the centre of this line down to the intersection with the abscissa axis in point M. From point M, as a centre, a circular arc is drawn through points F and B.

From point D at the power-factor angle φ_N (which is considered to be positive for an overexcited generator) to FD, a line is drawn to intersect with the arc FB at point K. The length OK corresponds to the rated excitation current of the machine.

If necessary, the voltage drop in the armature resistance may be accounted for as follows:

The length KL is laid off along the arc FKB. This length is equal to the excitation current component EP required to increase the no-load voltage by the value of PG, representing the voltage drop in the positive sequence armature resistance at rated current. The length OL represents the required excitation current.

When the machine operates as a motor, the voltage drop in the positive sequence armature resistance is laid off downward from the point E, and point L is laid off to the left from point K.

If the excitation current at rated voltage and current and zero power-factor is lacking, the following method may be used for its determination while using the Swedish diagram. Along the ordinate axis, the voltage drop in ax_a (see 7.26.2) at rated armature current is added to the rated armature voltage (point H′, see Figure 17).

A line parallel to the abscissa axis is drawn form point H′ to intersect with the no-load characteristic in point H. From that point, a perpendicular is drawn to the intersection with the abscissa-axis (point D – see Figure 17). To the right of point D, vector i_{fa} (length DB) is added along the abcissa. The excitation current equal to the length OB is the required current to be used in drawing the Swedish diagram.

7.27 Excitation current referred to rated armature sustained short-circuit current

7.27.1 From sustained three-phase short-circuit test

From test of 6.5, the short-circuit curve is drawn as shown in Figure 8 to determine the excitation current at rated armature short-circuit current.

7.27.2 From over-excitation test at zero power factor

From the tests of 6.26 performed at rated armature current i_N the experimental points are represented on a diagram voltage over field current, see Figure 21. A curve is drawn forming the upper portion of the zero power-factor curve. On the same diagram, the no-load saturation curve (see 7.1.1) is also drawn. Then the zero power factor curve is extrapolated parallel to the no-load curve until it intersects with the abscissa. The length OD represents the excitation current corresponding to the rated armature sustained short-circuit current i_{fk}. On the zero power factor curve point A corresponds to rated voltage. The length OB on the abscissa is then equal to the excitation current for rated voltage and rated current at over-excitation and zero power factor.

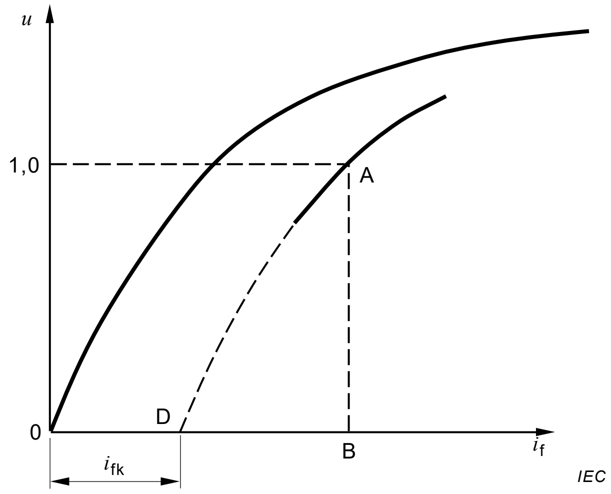


Figure 21 – Excitation current from over-excitation test at zero power factor

7.28 Frequency response characteristics

7.28.1 General

Frequency response characteristics are specialized transfer functions of Park′s synchronous machine formulas. These transfer functions may be used in transient phenomena studies of synchronous machines. They are of special importance for solid rotor machines.

For a machine at standstill, the transfer functions may be expressed as follows:

$$u_\mathrm{d}(p)=\left[r+p\,x_\mathrm{d}(p)\right]\cdot i_\mathrm{d}(p)+G(p)\cdot i_\mathrm{f}(p)$$

$$u_\mathrm{q}(p)=\left[r+p\,x_\mathrm{q}(p)\right]\cdot i_\mathrm{q}(p)$$

where

p	is the Laplace operator;
$i_\mathrm{d}(p)$, $i_\mathrm{q}(p)$, $i_\mathrm{f}(p)$	are d- and q-axis armature current components and field current;
$x_\mathrm{d}(p)$, $x_\mathrm{q}(p)$	are d- and q-axis reactance operators;
$G(p)$	is the transfer operator.

NOTE The definition of the Laplace transform of a function $f(t)$ is: $F(p)=\int_0^\infty f(t)\mathrm{e}^{-pt}\mathrm{d}t$.

The frequency response characteristics $\frac{1}{x(js)}$ and $G(js)$ are complex expressions for $p = js$.

7.28.2 From asynchronous operation at reduced voltage

Impedances, resistances and reactances for each speed step (slip) are calculated using the following formulae (see 6.25):

$$Z(s) = \frac{U_{\text{av}}}{\sqrt{3}\, I_{\text{av}}}\,; \quad \left[z(s) = \frac{u_{\text{av}}}{i_{\text{av}}} \right]$$

$$R(s) = \frac{P_{\text{av}}}{3\, I_{\text{av}}^{2}}\,; \quad \left[r(s) = \frac{p_{\text{av}}}{i_{\text{av}}^{2}} \right]$$

$$X(s) = \sqrt{Z^{2}(s) - R^{2}(s)}\ ; \quad \left[x(s) = \sqrt{z^{2}(s) - r^{2}(s)} \right]$$

Then the values obtained are plotted against slip to obtain the frequency response characteristics at low frequencies.

NOTE 1 Due to low applied voltages, core losses are neglected and the reactances obtained are unsaturated.

NOTE 2 The reactances obtained correspond approximately to the unsaturated half sum of sub-transient reactances at standstill and to the half sum of synchronous reactances at zero slip.

Values of average impedance for each slip are plotted as in Figure 22. It is helpful to have plotted on the same diagram values of power factor against slip.

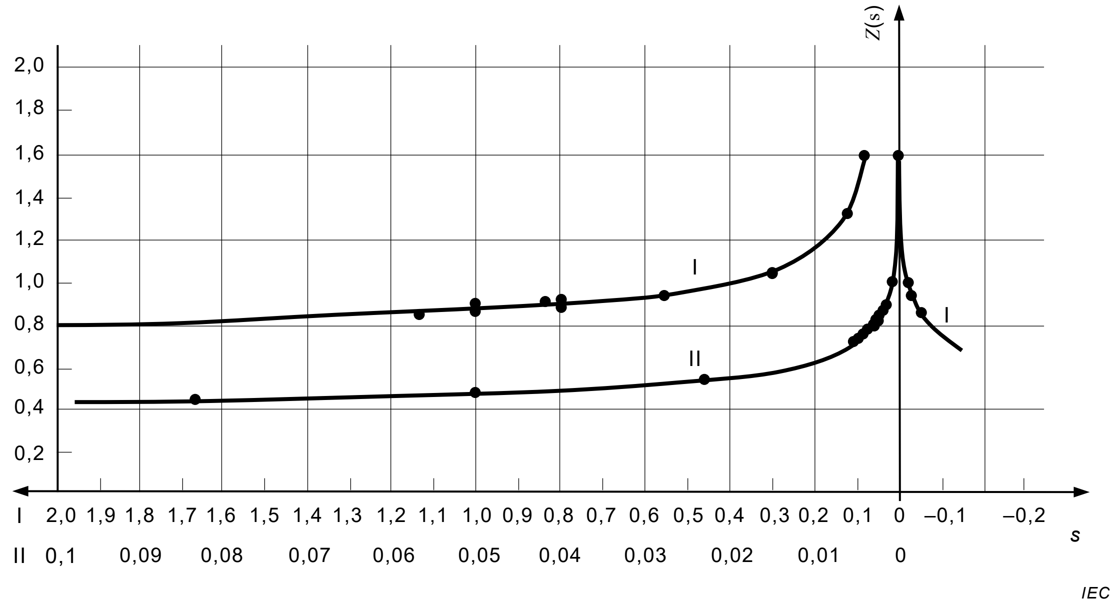


Figure 22 – Frequency response characteristics at low frequencies (example)

7.28.3 From applied variable frequency voltage test at standstill

Quantities for each frequency are obtained separately for the direct- and the quadrature-axis. The formulae correspond for the d- and q-axes, so that the following illustrates calculations for one axis only. Having obtained from the recordings U and I for the particular test frequency f_{t} and their phase difference (see 6.27), the impedance of the circuit at standstill is determined from

$$Z_{\text{stat}}\left(js\right)=\frac{U\left(js\right)}{I\left(js\right)}K_{\text{con}}$$

where

Z_{stat} is the steady state impedance of the machine determined for each frequency of applied voltage along the q- and d-axes;

U is the applied voltage at frequency f_{t}, expressed as slip $s = f_{\text{t}} / f_{\text{N}}$;

I is the measured current;

K_{con} is a factor depending upon connections of the armature winding. If voltage is applied to the terminals with the third one open, then K_{con} = 1/2; if two phases being connected in parallel are in series with the third one K_{con} = 2/3.

For the machine rotating at slip s with applied rated frequency voltage, its impedance is determined using the following formula:

$$Z\left(js\right)=\frac{Z_{\text{stat}}\left(js\right)-R_{1\text{s}}}{s}+R_1$$

where

$Z_{\text{stat}}\ (js)$ is as above;

$R_{1\text{s}}$ is the AC armature winding resistance at applied voltage and frequency. It may be determined from the test with rotor removed at a frequency corresponding to s, or may be calculated as:

$$R_{1\text{s}}\approx R_{\text{s}}\left[1+\left(R_1-R_{\text{a}}\right)\left(\frac{f}{f_{\text{n}}}\right)^2\right]$$

NOTE For slip values of 0,25 and less, $R_{1\text{s}} \approx R_{\text{a}}$, with an error within 5 %.

Admittances of the machine may be determined as inverse value of $Z\ (js)$:

$$Y\left(js\right)=\frac{1}{Z\left(js\right)}$$

Using angle φ between voltage and current as obtained from the recordings or by means of some suitable device, the values of reactances and resistances referred to a rotating machine with a certain slip may be calculated as follows:

$$X\left(js\right)=\text{Im}\left[Z_{\text{stat}}\left(js\right)\right]\frac{\left|Z_{\text{stat}}\left(js\right)\right|\sin\phi}{s}$$

$$R\left(js\right)=\text{Re}\left[Z_{\text{stat}}\left(js\right)\right]+R_1=\frac{\left|Z_{\text{stat}}\left(js\right)\right|\cos\phi-P_{1\text{s}}}{s}+R_1$$

Values obtained from this test are unsaturated quantities.

The frequency response characteristic of the machine is represented by curves of the obtained quantities as functions of slip for each of the axes.

Quantities of synchronous machines (reactances, resistances and time constants) may be obtained, using frequency response characteristics. Reactances and resistances at unity slip are approximately equal to sub-transient values. Reactances and resistances extrapolated to zero slip represent synchronous values.

7.28.4 From direct current decay test in the armature winding at standstill

In the following, the characteristics are expressed in per unit values. Use the values obtained from test 6.14 according to 7.1.4:

$i(t)$ is the ratio of armature winding test current (or the difference of the test curve and sustained value) and the initial value of this current;

$i_f(t)$ is the field winding decaying current in per unit value;

i_0 is the initial value of armature winding current along the d- or q-axis in per unit value;

r is the phase armature winding circuit resistance in per unit value: $r = r_a + K_{con}\,\Delta r$

where

r_a is the DC armature winding resistance in per unit value;

Δr is the additional (external) armature circuit resistance in per unit value;

K_{con} is the armature winding connection factor depending on the connection of the armature winding. If the voltage is applied to two terminals with the third one open, K_{con} = 1/2; if two phases connected in parallel are in series with the the third one K_{con} = 2/3.

For practical calculation of the frequency response functions, see Annex B.

A check of the quantities X_d, X''_d, X_q and X''_q shall be made with the values obtained by the recommended methods given in this document, and the frequency response characteristics correspondingly corrected. If the divergence is more than 10 %, the DC decay shall be repeated so as to obtain closer identity with actual frequency response characteristics.

7.29 Short-circuit ratio

Short-circuit ratio K_c is determined from the no-load saturation and three-phase sustained short-circuit characteristics as a quotient of the excitation current corresponding to the rated voltage on the no-load saturation curve and the excitation current corresponding to the rated current on the short-circuit curve (see Figure 8):

$$K_c = \frac{\mathrm{OD}}{\mathrm{OH}} = \frac{i_{fo}}{i_{fk}}$$

7.30 Rated voltage regulation

7.30.1 From direct measurement

The rated voltage regulation ΔU_N is determined by direct measurement (see 6.2).

7.30.2 From no-load saturation characteristic and known field current at rated load

The rated voltage regulation ΔU_N is determined graphically from the no-load characteristic (see 6.4) and the rated excitation current I_{fN} according to 7.26.

The method of direct measurement is preferred. 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 on test shall 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 the machines with a static excitation system).

7.31 Initial starting impedance of synchronous motors

The initial starting impedance may be determined from the locked rotor test (see 6.24) as:

$$Z_{\mathrm{st}} = \frac{U}{\sqrt{3}\,I_{\mathrm{av}}}\ ; \quad \left[z_{\mathrm{st}} = \frac{u}{i_{\mathrm{av}}} \right]$$

where

U is the applied line-to-line voltage;

I_{av} is the average of three-line steady state currents measured during the test.

If the test is performed at several reduced voltages, then the value of the initial starting impedance is determined for each voltage and the rated voltage value may be determined by extrapolation of the initial starting impedance to the rated voltage value from the curve of Z_{st} plotted against the applied voltage.

If the power input is measured, the initial starting resistance and reactance are determined as:

$$R_{\mathrm{st}} = \frac{P}{3 I_{\mathrm{av}}^2}\ ; \quad \left[r_{\mathrm{st}} = \frac{p}{i_{\mathrm{av}}^2} \right]$$

$$X_{\mathrm{st}} = \sqrt{Z_{\mathrm{st}}^2 - R_{\mathrm{st}}^2}\ ; \quad \left[x_{\mathrm{st}} = \sqrt{z_{\mathrm{st}}^2 - r_{\mathrm{st}}^2} \right]$$

Annex A
(informative)

Testing cross-reference

Table A.1 – Test cross-reference

Test		Quantity	
Clause	**Description**	**Description**	**Clause**
6.2	Direct measurement	Rated excitation current i_{fN}	7.26.1
		Rated voltage regulation ΔU_{N}	7.30.1
6.3	Ammeter-voltmeter or bridge	Armature resistance R_{a}	7.15
		Excitation winding resistance R_{f}	7.15
6.4.2	By diagram from no-load saturation characteristic and known i_{fN}	Rated voltage regulation ΔU_{N}	7.30.2
6.4 and 6.5	No-load saturation, sustained three-phase short-circuit	Direct-axis synchronous reactance X_{d}	7.2.1
		Potier reactance X_{p}	7.11
		Excitation current at rated armature short-circuit current i_{fk}	7.27.1
		Short-circuit ratio K_{c}	7.29
6.6	Motor no-load	Direct-axis synchronous reactance X_{d}	7.2.2
6.7	Over-excitation at zero power-factor	Rated excitation current (Swedish diagram)	7.26.4
6.8	Negative excitation	Quadrature-axis synchronous reactance X_{q}	7.5.1
6.9	On-load measuring load angle	Direct-axis synchronous reactance X_{d}	7.2.3
		Quadrature-axis synchronous reactance X_{q}	7.5.3
6.10	Low slip	Quadrature-axis synchronous reactance X_{q}	7.5.2
6.11	Sudden three-phase short-circuit	Direct-axis transient reactance X'_{d}	7.3.1
		Direct-axis sub-transient reactance X''_{d}	7.4.1
		Direct-axis transient short-circuit time constant τ'_{d}	7.16.1
		Direct-axis sub-transient short-circuit time constant τ''_{d}	7.18
		Armature short-circuit time constant τ_{a}	7.24.1

Test		Quantity	
Clause	**Description**	**Description**	**Clause**
6.12	Voltage recovery	Direct-axis transient reactance X'_{d}	7.3.2
		Direct-axis sub-transient reactance X''_{d}	7.4.2
		Direct-axis transient open-circuit time constant τ'_{do}	7.17.3
		Direct-axis sub-transient open-circuit time constant τ''_{do}	7.19.1
6.13	Suddenly applied short circuit following disconnection	See 6.11	
6.14	DC decay in the armature winding at standstill, calculation from test values	Direct-axis transient reactance X'_{d}	7.3.3
		Quadrature-axis transient reactance X'_{q}	7.6.1
		Negative-sequence reactance $X_{(2)}$	7.9.4
		Direct-axis transient short-circuit time constant τ'_{d}	7.16.2
		Direct-axis transient open-circuit time constant τ'_{do}	7.17.4
		Direct-axis sub-transient open-circuit time constant τ''_{do}	7.19.2
		Quadrature-axis transient short-circuit time constant τ'_{q}	7.20.2
		Quadrature-axis transient open-circuit time constant τ'_{qo}	7.21
		Quadrature-axis sub-transient short-circuit time constant τ''_{q}	7.22.2
		Frequency response characteristic	7.28.4
6.15	Applied voltage test with rotor in direct and quadrature axis	Quadrature-axis sub-transient reactance X''_{q}	7.7.1
		Direct-axis sub-transient reactance X''_{d}	7.4.3
6.16	Applied voltage with the rotor in arbitrary position	Direct-axis sub-transient reactance X''_{d}	7.4.4
		Quadrature-axis sub-transient reactance X''_{q}	7.7.2
6.17	Single-phase voltage applied to the three phases	Zero-sequence reactance $X_{(0)}$	7.8.1
		Zero-sequence resistance $R_{(0)}$	7.12.1 (7.8.1)
6.18	Line-to-line sustained short-circuit	Negative-sequence reactance $X_{(2)}$	7.9.1
		Negative-sequence resistance $R_{(2)}$	7.14.1
6.19	Line-to-line and to neutral sustained short-circuit	Zero-sequence reactance $X_{(0)}$	7.8.2
		Zero-sequence resistance $R_{(0)}$	7.12.2
6.20	Negative-phase sequence	Negative-sequence reactance $X_{(2)}$	7.9.2
		Negative-sequence resistance $R_{(2)}$	7.14.2
6.21.1	Field current decay, with the armature winding open-circuited, at rated speed	Direct-axis transient open-circuit time constant τ'_{do}	7.17.1
6.21.2	Field current decay, with the armature winding open-circuited at standstill	Direct-axis transient open-circuit time constant τ'_{do}	7.17.2

Test		**Quantity**	
Clause	**Description**	**Description**	**Clause**
6.22	Applied voltage, rotor removed	Armature leakage reactance X_σ	7.10
6.23	No-load retardation	Acceleration time τ_J, stored energy constant H	7.25
6.24	Locked rotor	Initial starting impedance of synchronous motors Z_{st}	7.31
6.25	Asynchronous operation at reduced voltage	Frequency response characteristic	7.28.2
6.26	Over-excitation at zero power-factor and variable armature voltage	Excitation current at rated armature short-circuit current i_{fk}	7.27.2
6.27	Applied variable frequency voltage at standstill	Frequency response characteristic	7.28.3

Annex B
(informative)

Calculation scheme for frequency response characteristics

B.1 Basics

A function $f(t)$ obtained from tests is approximated by a sum of exponential functions. Let $f(t)$ be a short circuit current function $i_\mathrm{k}(t)$, consisting of n components characterized by an initial value i_k0 and an exponent α_k:

$$i_k(t) = i_{k0} \cdot \mathrm{e}^{\alpha_k t}; \quad k = 1 \dots n$$

In the functions considered here, α_k is real, and corresponds to the time constant $\tau_\mathrm{k} = \dfrac{-1}{\alpha_\mathrm{k}}$

The relevant Laplace-transform is: $i_\mathrm{k}(p) = \dfrac{i_\mathrm{k0}}{p + \alpha_\mathrm{k}}$

Current time function and Laplace transform of the current become:

$$i(t) = \sum_{k=1}^{n} i_\mathrm{k}(t); \quad \rightarrow \quad i(p) = \sum_{k=1}^{n} \frac{i_\mathrm{k0}}{p + \alpha_k}$$

The current function may contain a constant component; in this case $\alpha_\mathrm{k} = 0$. The Laplace transform may be expressed as polynomial function in p.

B.2 Parameter calculation

Given the currents $i(t)$ and $i_\mathrm{f}(t)$ obtained from the procedure described in 6.14 and 7.1.4, and their representation by exponential functions, the reactance and the transfer operators are calculated as follows:

$$\frac{1}{x_\mathrm{d}(p)} = \frac{1}{x''_\mathrm{d}} \frac{D_\mathrm{d}(p)}{D'_\mathrm{d}(p)} = \frac{1}{x''_\mathrm{d}} \frac{(\alpha_\mathrm{1d} + p)(\alpha_\mathrm{2d} + p)\dots(\alpha_\mathrm{nd} + p)}{(\alpha'_\mathrm{1d} + p)(\alpha'_\mathrm{2d} + p)\dots(\alpha'_\mathrm{nd} + p)}$$

$$\frac{1}{x_\mathrm{q}(p)} = \frac{1}{x''_\mathrm{q}} \frac{D_\mathrm{q}(p)}{D'_\mathrm{q}(p)} = \frac{1}{x''_\mathrm{q}} \frac{(\alpha_\mathrm{1q} + p)(\alpha_\mathrm{2q} + p)\dots(\alpha_\mathrm{nq} + p)}{(\alpha'_\mathrm{1q} + p)(\alpha'_\mathrm{2q} + p)\dots(\alpha'_\mathrm{nq} + p)}$$

$$G(p) = N \frac{A(p)}{D_\mathrm{d}(p)} = N \frac{(\gamma_1 + p)(\gamma_2 + p)\dots(\gamma_\mathrm{n\text{-}1} + p)}{(\alpha_\mathrm{1d} + p)(\alpha_\mathrm{2d} + p)\dots(\alpha_\mathrm{nd} + p)}$$

The frequency response characteristics $\dfrac{1}{x_\mathrm{d}(js)}$, $\dfrac{1}{x_\mathrm{q}(js)}$, and $G(js)$ follow when setting $p = js$.

The parameters are obtained from calculating the roots of the characteristic formulas $D_{\mathrm{d}}(p) = 0$; $D'_{\mathrm{d}}(p) = 0$; $D_{\mathrm{q}}(p) = 0$; $D'_{\mathrm{q}}(p) = 0$ and $A(p) = 0$. They may also be determined by using the amplitude of i_{k0} and the decrement factors of the exponentials λ_{k} of the current decay curves according to 7.1.4.

- Roots $-a_1, -a_2, \ldots -a_{\mathrm{n}}$ of $D(p) = 0$ are roots of the formula $\sum_{k=1}^{n} \frac{i_k \lambda_k}{p+\lambda_k} = 0$
- Roots $-a'_1, -a'_2, \ldots -a'_{\mathrm{n}}$ of $D'(p) = 0$ are roots of the formula $\sum_{k=1}^{n} \frac{i_k}{p+\lambda_k} = 0$
- Roots $-\gamma_1, -\gamma_2, \ldots -\gamma_{\mathrm{n-1}}$ of $A(p) = 0$ are roots of the formula $\sum_{k=1}^{n} \frac{i_{k\mathrm{f}}}{p+\lambda_{k\mathrm{f}}} = 0$

Using known values of the roots of the characteristic formulas, the frequency response characteristics are calculated:

$$\frac{1}{X_{\mathrm{d}}(js)} = \frac{1}{X_{\mathrm{d}}} + \sum_{k=1}^{n} \left[\frac{C_{k\mathrm{d}}}{1+\left(\frac{\alpha'_{k\mathrm{d}}}{s}\right)^2} + j\frac{C_{k\mathrm{d}}\frac{\alpha'_{k\mathrm{d}}}{s}}{1+\left(\frac{\alpha'_{k\mathrm{d}}}{s}\right)^2} \right]$$

$$\frac{1}{X_{\mathrm{q}}(js)} = \frac{1}{X_{\mathrm{q}}} + \sum_{l=1}^{m} \left[\frac{C_{l\mathrm{q}}}{1+\left(\frac{\alpha'_{l\mathrm{q}}}{s}\right)^2} + j\frac{C_{l\mathrm{q}}\frac{\alpha'_{l\mathrm{q}}}{s}}{1+\left(\frac{\alpha'_{l\mathrm{q}}}{s}\right)^2} \right]$$

$$G(js) = \sum_{k=1}^{n} \left[\frac{A_k \alpha_{k\mathrm{d}}}{\alpha_{k\mathrm{d}}^2 + s^2} - j\frac{A_k s}{\alpha_{k\mathrm{d}}^2 + s^2} \right]$$

where

$$C_{k\mathrm{d}} = \frac{1}{X''_{\mathrm{d}}} \frac{(\alpha_{1\mathrm{d}} - \alpha'_{k\mathrm{d}})(\alpha_{2\mathrm{d}} - \alpha'_{k\mathrm{d}}) \ldots (\alpha_{n\mathrm{d}} - \alpha'_{k\mathrm{d}})}{(\alpha_{1\mathrm{d}} - \alpha'_{k\mathrm{d}}) \ldots (\alpha'_{k\text{-1, d}} - \alpha'_{k\mathrm{d}})\, \alpha'_{k\mathrm{d}}\, (\alpha'_{k+1,\,\mathrm{d}} - \alpha'_{k\mathrm{d}}) \ldots (\alpha'_{n\mathrm{d}} - \alpha'_{k\mathrm{d}})}$$

$$C_{l\mathrm{q}} = \frac{1}{X''_{\mathrm{q}}} \frac{(\alpha_{1\mathrm{q}} - \alpha'_{l\mathrm{q}})(\alpha_{2\mathrm{q}} - \alpha'_{l\mathrm{q}}) \ldots (\alpha_{m\mathrm{q}} - \alpha'_{l\mathrm{q}})}{(\alpha'_{1\mathrm{q}} - \alpha'_{l\mathrm{q}}) \ldots (\alpha'_{l-1,\mathrm{q}} - \alpha'_{l\mathrm{q}})\, \alpha'_{l\mathrm{q}}\, (\alpha'_{l+1,\mathrm{q}} - \alpha'_{l\mathrm{q}}) \ldots (\alpha'_{m\mathrm{q}} - \alpha'_{l\mathrm{q}})}$$

$$A_k = N \frac{(\gamma_1 - \alpha_{k\mathrm{d}})(\gamma_{n-1} - \alpha_{k\mathrm{d}})}{(\alpha_{1\mathrm{d}} - \alpha_{k\mathrm{d}}) \ldots (\alpha_{k-1,\mathrm{d}} - \alpha_{k\mathrm{d}})(\alpha_{k+1,\mathrm{d}} - \alpha_{k\mathrm{d}}) \ldots (\alpha_{n\mathrm{d}} - \alpha_{k\mathrm{d}})} \quad \text{where} \quad N = \frac{\alpha_{1\mathrm{d}}\alpha_{1\mathrm{d}} \ldots \alpha_{n\mathrm{d}}}{\gamma_1 \gamma_2 \ldots \gamma_{n-1}} \frac{\sum_{\mathrm{k}=1}^{\mathrm{n}+1} \frac{i_{k\mathrm{f}}}{\lambda_{k\mathrm{f}}}}{i_{\mathrm{od}}}$$

Note that

$X_{\mathrm{d}} = r\sum_{k=1}^{n+1} \frac{i_{k\mathrm{d}}}{\lambda_{k\mathrm{d}}}$; $X_{\mathrm{q}} = r\sum_{l=1}^{m+1} \frac{i_{l\mathrm{q}}}{\lambda_{l\mathrm{q}}}$; $X''_{\mathrm{d}} = \frac{r}{\sum_{k=1}^{n+1} i_{k\mathrm{d}}\, \lambda_{k\mathrm{d}}}$; $X''_{\mathrm{q}} = \frac{r}{\sum_{l=1}^{m+1} i_{l\mathrm{q}}\, \lambda_{l\mathrm{q}}}$, where r is from 7.28.4.

Annex C
(informative)

Conventional electrical machine model

On the basis of Park's formulas, the machine may be represented by an equivalent circuit model in d,q-components. The model in Figure C.1 is for a salient pole machine, containing one amortisseur mesh in each axis; it allows for a magnetic leakage flux coupling of field and direct axis damper windings.

NOTE 1 The model in Figure C.1 is drawn in the motor reference system.

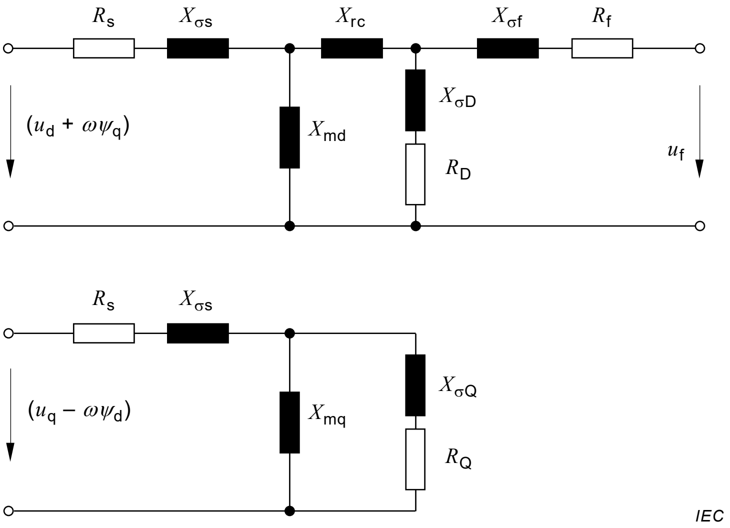


Figure C.1 – Equivalent circuit model of a salient pole machine

The definition of flux linkages is:

$$\begin{bmatrix} \omega\psi_d \\ \omega\psi_D \\ \omega\psi_f \end{bmatrix} = \begin{bmatrix} X_d & X_{md} & X_{md} \\ X_{md} & X_D & X_{Df} \\ X_{md} & X_{Df} & X_f \end{bmatrix} \begin{bmatrix} i_d \\ i_D \\ i_f \end{bmatrix}; \qquad \begin{bmatrix} \omega\psi_Q \\ \omega\psi_Q \end{bmatrix} = \begin{bmatrix} X_q & X_{mq} \\ X_{mq} & X_Q \end{bmatrix} \begin{bmatrix} i_q \\ i_Q \end{bmatrix}$$

where the reactance components are

$$X_d = X_{md} + X_{\sigma s} \qquad X_q = X_{mq} + X_{\sigma s}$$

$$X_D = X_{Df} + X_{\sigma D} = X_{md} + X_{rc} + X_{\sigma D}\ ; \qquad X_Q = X_{mq} + X_{\sigma Q}$$

$$X_d = X_{Df} + X_{\sigma f} = X_{md} + X_{rc} + X_{\sigma f}$$

NOTE 2 The coupling reactance value X_{rc} can be positive (as in turbogenerators) or negative (as in many salient-pole machines).

NOTE 3 Frequently, the machine model is simplified using X_{rc} = 0, resulting in larger errors of calculated rotor quantities.

Parameters obtained by the procedures described in this standard are expressed by the equivalent circuit parameters as follows:

– Reactances:

$$X_{\mathrm{d}}' = X_{\mathrm{d}} - \frac{X_{\mathrm{md}}^2}{X_{\mathrm{f}}}$$

$$X_{\mathrm{d}}'' = X_{\mathrm{d}} - \frac{X_{\mathrm{md}}^2}{X_{\mathrm{f}}} \frac{(X_{\mathrm{f}} - X_{\mathrm{md}})^2}{\mathrm{X}_{\mathrm{D}} X_{\mathrm{f}} - X_{\mathrm{md}}^2} \quad ; \quad X_{\mathrm{q}}'' = X_{\mathrm{d}} - \frac{X_{\mathrm{mq}}^2}{X_{\mathrm{Q}}}$$

– Time constants:

$$\tau_{\mathrm{a}} = \frac{1}{\omega R_{\mathrm{s}}} \frac{2}{1/X_{\mathrm{d}}'' + 1/X_{\mathrm{q}}''}$$

$$\tau_{\mathrm{kd0}} = \frac{X_{\mathrm{D}}}{\omega R_{\mathrm{D}}} \quad ; \quad \tau_{\mathrm{kd}} = \frac{X_{\mathrm{D}} - X_{\mathrm{md}}^2 / X_{\mathrm{d}}}{\omega R_{\mathrm{D}}}$$

$$\tau_{\mathrm{d0}}' = \frac{X_{\mathrm{f}}}{\omega R_{\mathrm{f}}} \quad ; \quad \tau_{\mathrm{d0}}'' = \frac{X_{\mathrm{D}} - X_{\mathrm{md}}^2 / X_{\mathrm{f}}}{\omega R_{\mathrm{D}}} \quad ; \quad \tau_{\mathrm{q0}}'' = \frac{X_{\mathrm{Q}}}{\omega R_{\mathrm{Q}}}$$

$$\tau_{\mathrm{d}}' = \frac{X_{\mathrm{d}}'}{X_{\mathrm{d}}} \tau_{\mathrm{fd0}} \quad ; \quad \tau_{\mathrm{d}}'' = \frac{X_{\mathrm{d}}''}{X_{\mathrm{d}}'} \tau_{\mathrm{d0}}'' \qquad \tau_{\mathrm{q}}'' = \frac{X_{\mathrm{q}}''}{X_{\mathrm{q}}} \tau_{\mathrm{q0}}''$$

NOTE 4 The circuit model in Figure C.1 provides no transient quadrature-axis quantities. Here, the corresponding order numbers (Annex A) are $n_{\mathrm{d}} = 3$; $n_{\mathrm{q}} = 2$.

Bibliography

IEC 60050-411:1996, I*nternational Electrotechnical Vocabulary – Chapter 411: Rotating machinery*

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