
British Standard

General requirements for rotating electrical machines

Part 104. Methods of test for determining
synchronous machine quantities

Règles générales pour les machines électriques tournantes

Partie 104. Méthodes d'essai pour la détermination des grandeurs des machines synchrones

Allgemeine Anforderungen an umlaufende elektrische Maschinen

Teil 104. Verfahren zur Bestimmung der Kenngrößen von Synchronmaschinen

National foreword

This Part of BS 4999 has been prepared under the direction of the Power Electrical Engineering Standards Committee and supersedes BS 4296 : 1968, which is withdrawn.

This Part is identical with IEC Publication 34 ‘Rotating electrical machines’ Part 4 : 1985 ‘Methods for determining synchronous machine quantities from tests’, published by the International Electrotechnical Commission (IEC).

Terminology and conventions. The text of the international standard has been approved as suitable for publication as a British Standard without deviation. Some terminology and certain conventions are not identical with those used in British Standards.

Wherever page numbers are quoted in the text, they are IEC page numbers.

Cross-references

International standard	Corresponding British Standard
IEC 34-2 : 1972	BS 4999 General requirements for rotating electrical machines Part 102 : 1987 Methods for determining losses and efficiency from tests (excluding machines for traction vehicles) (Identical)
IEC 51 : 1973	BS 89 : 1977 Specification for direct acting indicating electrical measuring instruments and their accessories (Identical)

Additional information. In A2 an invitation is given to submit information to the ‘Secretariat of Sub-Committee 2G’. Such information should be forwarded to the secretary of BSI Technical Committee PEL/1 for consideration by the committee for submission to the IEC.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Amendment No. 1
published and effective from 15 November 1995
to BS 4999 : Part 104 : 1988

General requirements for rotating electrical machines
Part 104. Methods of test for determining synchronous
machine quantities

NOTE. The European Committee for Electrotechnical Standardization (CENELEC) has accepted IEC 34-4 : 1985, together with common modifications, as a European Standard designated EN 60034-4 : 1995. This amendment implements EN 60034-4 : 1995 as a British Standard.

Implementation of European Standard

Front cover

Delete the outside front cover and substitute the attached.

AMD 8875/November 1995

National foreword

Delete the existing paragraph 2 and substitute the following.

In 1995 the European Committee for Electrotechnical Standardization (CENELEC) accepted IEC 34-4 : 1985, modified, as a European Standard EN 60034-4 : 1995. As a consequence of implementing the European Standard this British Standard is renumbered as BS EN 60034-4 and any reference to BS 4999 : Part 104 should be read as a reference to BS EN 60034-4.

AMD 8875/November 1995

New EN title page and foreword

Immediately after the national foreword, insert the attached new EN title page and foreword page.

AMD 8875/November 1995

Common modifications

Amend the text of IEC 34-4 in accordance with the details given on the attached page.

AMD 8875/November 1995

New annex ZA (normative)

Immediately after table 1 insert the attached new annex ZA.

AMD 8875/November 1995

Rotating electrical machines

Part 4. Methods for determining synchronous machine quantities from tests

The European Standard EN 60034-4 : 1995 has the status of a
British Standard

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English version

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

(IEC 34-4 : 1985, modified)

Machines électriques tournantes
Partie 4: Méthodes pour la détermination à partir
d'essais des grandeurs des machines synchrones
(CEI 34-4 : 1985, modifiée)

Drehende elektrische Maschinen
Teil 4: Verfahren zur Ermittlung der Kenngrößen
von Synchronmaschinen durch Messungen
(IEC 34-4 : 1985, modifiziert)

This European Standard was approved by CENELEC on 1995-05-15. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

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

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Central Secretariat: rue de Stassart 35, B-1050 Brussels

Foreword

The text of the International Standard IEC 34-4 : 1985, prepared by SC 2G, Test methods and procedures, of IEC TC 2, Rotating machinery, together with common modifications prepared by the Technical Committee CENELEC TC 2, was approved by CENELEC as HD 53.4 S2 on 1988-06-28.

This Harmonization Document was submitted to the formal vote for conversion into a European Standard and was approved by CENELEC as EN 60034-4 on 1995-05-15.

The following date was fixed:

- latest date by which the EN
has to be implemented at
national level by publication
of an identical national
standard or by endorsement (dop) 1996-07-15

Annexes designated 'normative' are part of the body of the standard. In this standard, annex ZA is normative. Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 34-4 : 1985 was approved by CENELEC as a European Standard with agreed common modifications as given below.

Common Modifications

48 Line-to-line sustained short-circuit test

Figure 13 and Figure 14 have to be interchanged.

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

Figure 13 and Figure 14 have to be interchanged.

55 Determination of quantities from the line-to-line and to neutral sustained short-circuit test

In the formula replace factor '3' by factor ' $\sqrt{3}$ ' to read the first formula as follows:

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

Delete Appendix A 'Unconfirmed test methods for determining synchronous machine quantities from tests'.

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

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

Publication	Year	Title	EN/HD	Year
IEC 51	series	<i>Direct acting indicating analogue electrical-measuring instruments and their accessories</i>	EN 60051	series

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British Standard

General requirements for rotating electrical machines

Part 104. Methods of test for determining synchronous machine quantities

SECTION ONE — SCOPE AND OBJECT

1. Scope

This standard applies to three-phase synchronous machines of 1 kVA rating and larger with rated frequency of not more than 400 Hz and not less than 15 Hz.

The test methods are not intended to apply to special synchronous machines such as permanent-magnet field machines, inductor type machines, etc.

While the tests also apply in general to brushless machines, certain variations do exist and special precautions should be taken.

2. Object

The object of this standard is to establish methods for determining characteristic quantities of three-phase synchronous machines from tests.

It is not intended that this standard should be interpreted as requiring the carrying out of any or all of the tests described therein on any given machine. The particular tests to be carried out shall be subject to a special agreement.

SECTION TWO — GENERAL

3. General

Tests for determining synchronous machine quantities should be conducted on a completely sound machine, all the devices for automatic regulation being switched off.

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

- 3.1 Indicating measuring instruments and their accessories, such as measuring transformers, shunts and bridges used during tests, unless otherwise stated, should have an accuracy class not above 1.0 (IEC Publication 51: Direct Acting Indicating Analogue Electrical Measuring Instruments and their Accessories). The instruments used for determining d.c. resistances should have an accuracy class not above 0.5.

It is not intended at this stage to specify an accuracy class for the oscillographic measuring equipment. This should, however, be chosen, having due regard to the rated frequency of the machine to be tested, so that the readings are taken in a linear portion of the vibrator amplitude against frequency characteristic.

The measurement of the speed of rotation, of synchronous machines may be conducted by means of a stroboscopic method or by using tachometers (mechanical or electrical).

Instead of measuring the speed of rotation, it is permissible to measure frequency by means of a frequency meter when the machine is running synchronously with any other machine or running on its own.

- 3.2 The temperature of the windings is measured in those tests when the quantities to be determined depend on it or when knowledge of it is required by the safety considerations of the machine 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.

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

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

- 3.4 All the quantities and characteristics should be designated in per unit values considering rated values of the voltage (U_n), and the apparent power (S_n) as basic ones. In this case basic current will be:

$$I_n = \frac{S_n}{\sqrt{3} U_n}$$

and basic impedance:

$$Z_n = \frac{U_n^2}{S_n} = \left[\frac{S_n}{3I_n^2} \right] \Omega$$

The intermediate calculations, if it is convenient, 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.

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

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

- 3.5 In the formulae given in this standard for determining synchronous machine 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 must be considered as approximate.

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

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

These time constants are based on the assumption of an exponential decrease of the particular components of quantities involved (currents, voltages, etc.). If the plot of the measured component under consideration does not decrease as a pure exponential, as in the case, for example, of a solid rotor machine, the time constant should normally be interpreted as the time required for the component to decrease to $1/e \approx 0.368$ of its initial value. Exponential decay curves corresponding to these time constants should be considered as equivalent curves replacing the actual measured ones.

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

In this standard, unless otherwise stated, the “saturated value” of reactances and resistances will be taken as the rated (armature) voltage value of the quantity, and their “unsaturated value” will be taken as the rated (armature) current value, except synchronous reactance which is not defined as saturated.

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

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

SECTION THREE — TERMINOLOGY AND METHODS OF DETERMINATION

4. Direct-axis synchronous reactance X_d

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

- 4.1 The direct-axis synchronous reactance X_d corresponding to the unsaturated state is determined (see Clause 27) from the no-load saturation (see Sub-clause 25.1) and sustained three-phase short circuit (see Sub-clause 26.1) characteristics.

5. Short-circuit ratio K_c

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

- 5.1 The short-circuit ratio is determined (see Sub-clause 27.1) from the no-load saturation (see Sub-clause 25.1) and sustained three-phase short circuit (see Sub-clause 26.1) characteristics.

6. Quadrature-axis synchronous reactance X_q

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

6.1 Quadrature-axis synchronous reactance is determined by the following methods:

- a) negative excitation (see Clauses 34 and 35);
- b) low slip (see Clauses 36 and 37);
- c) on load measurement of the load angle (see Clauses 38 and 39).

The first two methods are preferred.

7. Direct-axis transient reactance X'_d

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

7.1 Direct-axis transient reactance is determined by the following methods:

- a) sudden three-phase short circuit (see Clauses 40 and 41);
- b) voltage recovery (see Clauses 42 and 43);
- c) calculation from the test values of X_d (see Clause 4), τ'_{do} (see Clause 17) and τ'_d (see Clause 18) by the formula given in Clause 72.

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

8. Direct-axis subtransient reactance X''_d

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

8.1 Direct-axis subtransient reactance is determined by the following methods:

- a) sudden three-phase short circuit (see Clause 40 and Sub-clause 41.1);
- b) voltage recovery (see Clause 42 and Sub-clause 43.1);
- c) applied voltage with the rotor in the direct and quadrature axis positions with respect to the armature winding field axis (see Clauses 44 and 45);
- d) applied voltage with an arbitrary position of the pole axis (see Clauses 46 and 47).

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 (c and d) may be used for the unsaturated value of X''_d , but are usually not practicable for the saturated value because of the large current required and possible overheating of solid parts.

9. Quadrature-axis subtransient reactance X''_q

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

9.1 The quadrature axis subtransient reactance is determined by the following methods:

- a) applied voltage with the rotor in the direct and quadrature axis positions with respect to the armature winding field axis (see Clause 44 and Sub-clause 45.1);
- b) applied voltage with the pole axis in any arbitrary position (see Clause 46 and Sub-clause 47.1).

Both these methods are practically equivalent and may be used to determine the unsaturated value. These methods are usually not practicable for the determination of the saturated value because of the large current required and possible overheating of solid parts.

10. **Negative-sequence reactance X_2**

The quotient of the reactive fundamental component of negative-sequence armature voltage due to sinusoidal negative-sequence armature current of rated frequency, and the value of this current, the machine running at rated speed.

Note. — A different value 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.

11. **Negative-sequence resistance R_2**

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

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

11.1 Negative-sequence reactance and resistance are determined by the following methods:

- a) line-to-line sustained short circuit (see Clauses 48 and 49 and Sub-clause 49.1);
- b) negative-phase sequence (see Clauses 50 and 51);
- c) negative-sequence reactance may also be determined by calculation from the test values of X_d'' (see Clause 8) and X_q'' (see Clause 9); the calculation is made using the equation given in Sub-clause 72.1.

The line-to-line sustained short-circuit method is preferred.

12. **Zero-sequence reactance X_0**

The quotient of the reactive fundamental component of a zero-sequence armature voltage, due to the presence of fundamental zero-sequence armature current of rated frequency, and this component of current, the machine running at rated speed.

13. **Zero-sequence resistance R_0**

The quotient of the in-phase fundamental component of zero-sequence armature voltage, due to the presence of fundamental zero-sequence armature current of rated frequency, and the value of this current, the machine running at rated speed.

13.1 Zero-sequence reactance and resistance are determined by the following methods:

- a) single-phase voltage application to the three-phases connected in series (an open delta) or parallel (see Clauses 52 and 53);
- b) line-to-line and to neutral sustained short-circuit (see Clauses 54 and 55 and Sub-clause 55.1).

The method of single-phase voltage application to the three phases connected in series is preferred.

14. Potier reactance X_p

An equivalent reactance used in place of the armature leakage reactance to calculate the excitation on load by means of the Potier method. It takes into account the additional leakage of the field winding on load and in the overexcited region and is greater than the real value of the armature leakage reactance.

14.1 The Potier reactance is determined in accordance with Clause 30.

15. Armature and excitation winding direct-current resistance R_a and R_f

Direct-current winding resistance is determined by the following methods:

- a) voltmeter and ammeter (see Clauses 56 and 57);
- b) single and double bridge (see Clause 56 and Sub-clause 57.1).

The single bridge method is not permissible for measuring resistances less than $1\ \Omega$.

16. Positive-sequence armature winding resistance R_1

The quotient of the in-phase component of positive sequence armature voltage corresponding to direct-load losses in the armature winding and stray load losses in conductors, due to the sinusoidal positive sequence armature current, and of this current, the machine running at rated speed.

16.1 The positive-sequence armature winding resistance is determined in accordance with Sub-clause 72.2.

17. Direct-axis transient open-circuit time constant τ'_{do}

The time required for the slowly changing component of the open-circuit armature voltage which is due to the direct-axis flux, following a sudden change in operating conditions, to decrease to $1/e \approx 0.368$ of its initial value, the machine running at rated speed.

17.1 The direct-axis transient open-circuit time constant is determined by the following methods:

- a) field current decay with open-circuit armature winding (see Clauses 58 and 59);
- b) voltage recovery (see Clause 42 and Sub-clause 43.2);
- c) calculation from the test values of X_d (see Clause 4), X'_d (see Clause 7) and τ'_d (see Clause 18) by the formula given in Clause 72.

The field current decay method is preferred.

18. Direct-axis transient short-circuit time constant τ'_d

The time required for the slowly changing component of direct-axis short-circuit armature current following a sudden change in operating conditions, to decrease to $1/e \approx 0.368$ of its initial value, the machine running at rated speed.

18.1 The direct-axis transient short circuit time constant is determined by the following methods:

- a) sudden three-phase short circuit (see Clause 40 and Sub-clause 41.2);

- b) field current decay with armature winding short-circuited (see Clauses 60 and 61);
- c) calculation from the test values of X_d (see Clause 4), X'_d (see Clause 7) and τ'_{do} (see Clause 17) by the formula given in Clause 72.

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

19. Direct-axis subtransient short-circuit time constant τ''_d

The time required for the rapidly changing component, present during the first few cycles in the direct-axis short-circuit armature current, following a sudden change in operating conditions, to decrease to $1/e \approx 0.368$ of its initial value, the machine running at rated speed.

- 19.1 The direct-axis subtransient short-circuit time constant is determined by the sudden three-phase short-circuit method (see Clause 40 and Sub-clause 41.3).

20. Armature short-circuit time constant τ_a

The time required for the aperiodic d.c. component present in the short-circuit armature current, following a sudden change in operating conditions, to decrease to $1/e \approx 0.368$ of its initial value, the machine running at rated speed.

- 20.1 The armature short-circuit time constant is determined from the sudden three-phase short-circuit test by the following methods:

- a) by decrease of the periodic (a.c.) component in the excitation winding current (see Clause 40 and Sub-clause 41.4);
- b) by decrease of the aperiodic (d.c.) components of the current in the armature winding phases (see Clause 40 and Sub-clause 41.5);
- c) calculation from the test values of X_2 (see Clause 10) and R_a (see Clause 15) by the formula given in Sub-clause 72.3.

The method of measurement of the decrease of periodic component in the excitation winding current is preferred.

21. Acceleration time τ_j

The time required to bring rotating parts of the synchronous machine from rest to rated speed, the accelerating torque being constant and equal to the quotient of the rated active power (output) and of the rated angular velocity.

Notes 1. — For synchronous condensers, the rated active power (output) is replaced by the rated apparent power.

- 2. — When the acceleration time is determined for a group of mechanically coupled machines, the accelerating torque is calculated for rated active power and rated angular velocity of the base synchronous machine.

22. Stored energy constant H

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

- 22.1 The acceleration time of a machine or group of machines and the stored energy constant are determined by the following methods:

- a) suspended rotor oscillation (see Clauses 62 and 63);

- b)* auxiliary pendulum swing (see Clauses 64 and 65);
- c)* no-load retardation (see Clauses 66 and 67);
- d)* on-load retardation with the machine operating as a motor (see Clauses 68 and 69);
- e)* acceleration after sudden unloading with the machine operating as a generator (see Clauses 70 and 71).

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.

23. **Rated excitation current I_{fn}**

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

23.1 The rated excitation current is determined by the following methods:

- a)* direct measurement during operation under rated conditions;
- b)* graphically, by Potier's vector diagram (see Clause 31) or by the ASA diagram (see Clause 32) or by the Swedish diagram (see Clause 33).

The method of direct measurement is preferred, but the graphical methods are practically equivalent to it.

24. **Rated voltage regulation ΔU_n**

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

The rated voltage regulation is determined by the following methods:

- a)* direct measurement;
- b)* graphically, from the no-load characteristic (see Sub-clause 25.1) and the rated excitation current (see Clause 23 and Sub-clause 23.1) obtained from tests.

SECTION FOUR — DESCRIPTION OF THE TESTS AND DETERMINATION OF MACHINES QUANTITIES FROM THESE TESTS

25. **No-load saturation test**

The no-load saturation test is conducted:

- a)* by driving the tested machine as a generator by some prime-mover;
- b)* by running the tested machine as a motor without shaft load from a source of alternating symmetrical three-phase voltage;
- c)* during retardation of the tested machine.

During the no-load saturation test, excitation current, line voltage and frequency (or speed) should be measured simultaneously. When making the no-load test, excitation changes should be made in gradual steps from high to low voltage with points distributed evenly; 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.

When the excitation current is decreased to zero, the residual voltage of the generator is measured.

If the no-load saturation test is conducted when the synchronous machine is running as an unloaded motor, then in addition to the measured quantities mentioned above, it is necessary to

measure armature current. At each voltage step, readings should be taken for minimum armature current which corresponds to unity power-factor.

The no-load saturation test during retardation of the tested machine may be performed with due precision provided its rate of deceleration is not more than 0.04 of the rated speed per second.

If 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 armature voltage and speed (frequency) are taken simultaneously with constant excitation current. The retardation test may be repeated to obtain all the steps required.

- 25.1 The no-load saturation characteristic—the relationship between the armature open-circuit winding voltage at the terminals and the excitation current at rated speed (frequency)—is drawn from the data of the no-load test. If, due to high residual voltage, the no-load characteristic cuts the axis above the origin, a correction should be introduced. To determine this, 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 which should be added to all the measured values of the excitation current (Figure 1, page 33).

If the frequency while conducting the test differs from the rated value, all the measured voltage values should be referred to the rated frequency.

26. Sustained three-phase short-circuit test

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

- a) driving the tested machine as a generator by some prime-mover;
- b) during retardation of the tested machine.

The short circuit should be made as close to the machine terminals as possible, the excitation current being applied after closing the short-circuit.

During the sustained three-phase short-circuit test, excitation current and armature line current should be measured simultaneously. One of the readings is taken at a current close to the rated armature current. The speed of rotation (or frequency) may differ from the rated value but should not fall below 0.2 of rated value.

The sustained three-phase short-circuit test during retardation of the tested machine may be performed with due precision, provided its rate of deceleration is not more than 0.10 rated speed per second. If the machine under test has a rate of deceleration above 0.04 rated speed per second, excitation from a separate source is required in order to have more stable excitation during the test.

- 26.1 The 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.

27. Determination of quantities from the no-load saturation and sustained three-phase short-circuit characteristics

Direct-axis synchronous reactance (see Clause 4 and Sub-clause 4.1) is determined from the no-load saturation and three-phase sustained short-circuit characteristics as a quotient of the

no-load voltage taken from the air-gap line at some excitation and the sustained short-circuit current value taken from the short-circuit characteristic at the same excitation current (Figure 1):

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

The value of X_d determined in such a way corresponds to an unsaturated state of the machine.

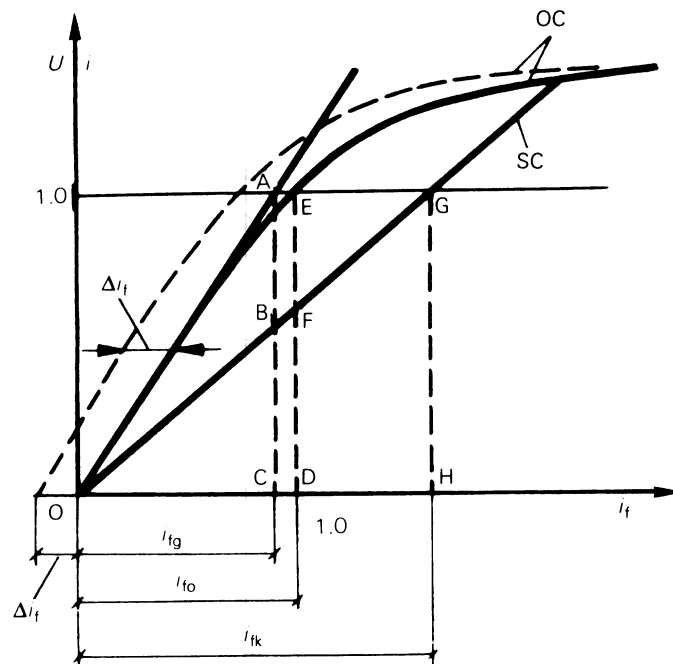


FIGURE 1

- 27.1 Short-circuit ratio (see Clause 5 and Sub-clause 5.1) 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 (Figure 1):

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

28. Overexcitation test at zero power-factor

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

29. **Determination of the excitation current corresponding to the rated voltage and rated armature current at zero power-factor (overexcitation)**

If, during the overexcitation test at zero power-factor, the voltage differs from the rated value by not more than ± 0.15 per unit, a graphical method is used for the determination of the excitation current corresponding to the rated voltage and current, using the data of the test and the no-load saturation (see Sub-clause 25.1) and sustained three-phase short circuit (see Sub-clause 26.1) characteristics.

An experimental point is plotted on a diagram with the no-load saturation curve of the test machine. This point corresponds to zero power-factor and the measured values of the current i , voltage u and excitation current i_f (point C, Figure 2).

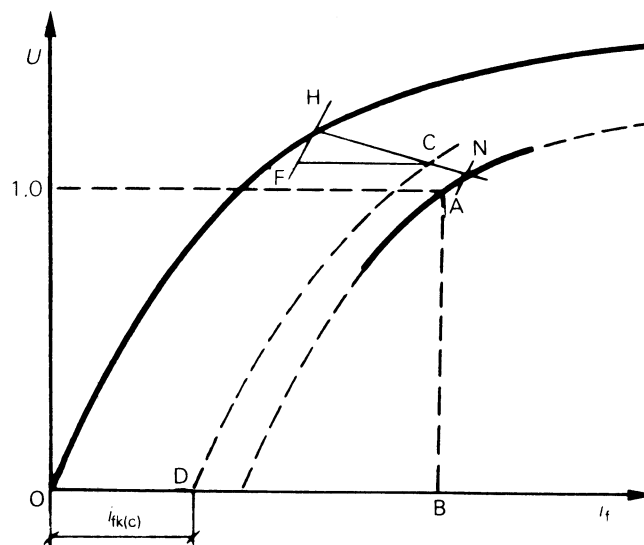


FIGURE 2

Vector OD equal to the excitation current, corresponding to the armature current i on the three-phase short-circuit curve, is laid off along the abscissa axis. From the point C, a length CF equal to OD is laid off towards the no-load saturation characteristic and parallel to the abscissa axis. A line FH is then drawn parallel to the extended straight line portion of the no-load saturation characteristic intersecting the latter at H. Line HC is extended to a point N such that:

$$\frac{HN}{HC} = \frac{1}{i}$$

where i is the current corresponding to point C.

The no-load saturation curve is then transferred to the right and downwards parallel to itself and by a distance HN.

Point A is found on this curve which corresponds to the rated voltage. The abscissa of this point (OB) represents the excitation current corresponding to the rated voltage and armature current at zero power-factor (overexcitation).

30. **Determination of Potier reactance from the no-load and sustained three-phase short-circuit characteristics and the excitation current corresponding to the rated voltage and rated armature current at zero power-factor (overexcited)**

The Potier reactance (Clause 14) is determined graphically. The no-load and three-phase sustained short-circuit characteristics are plotted on a diagram (Figure 3) as well as a point the ordinate of which is the rated voltage and the abscissa—the excitation current, measured at rated armature current and zero power-factor at overexcitation (point A).

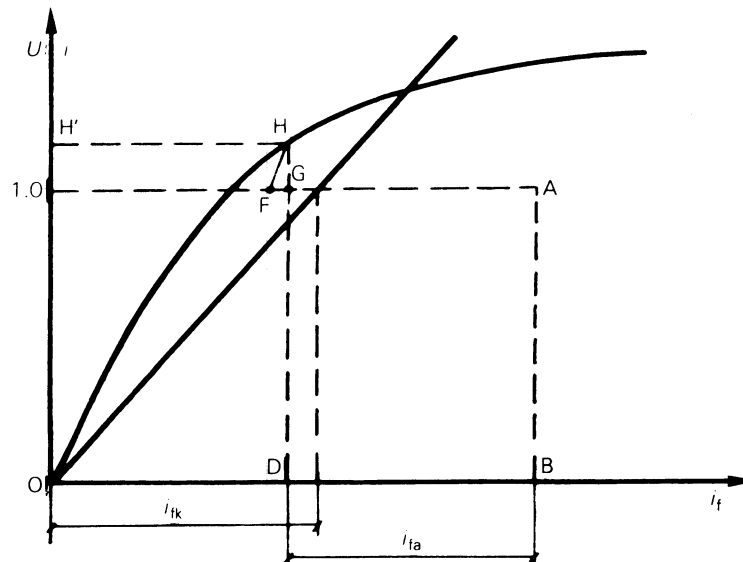


FIGURE 3

To the left from the 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 the rated armature current. In per unit values $x_p = HG$.

31. **Determination of the rated excitation current by the Potier diagram**

To determine the rated excitation current (see Clause 23) by Potier's diagram, use is made of the no-load saturation characteristic (see Sub-clause 25.1), sustained short-circuit characteristic (see Sub-clause 26.1) and Potier reactance x_p (see Clauses 14 and 30).

The vector of the rated armature current (i_n) of the tested machine is laid off along the abscissa. At the power-factor angle φ_n (which is considered to be positive for an overexcited generator) to it draw the rated voltage vector (u_n). (Figure 4, page 39).

The vector of the voltage drop ($i_n x_p$) 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 (see Clause 16) from the end of the voltage vector parallel to the current vector.

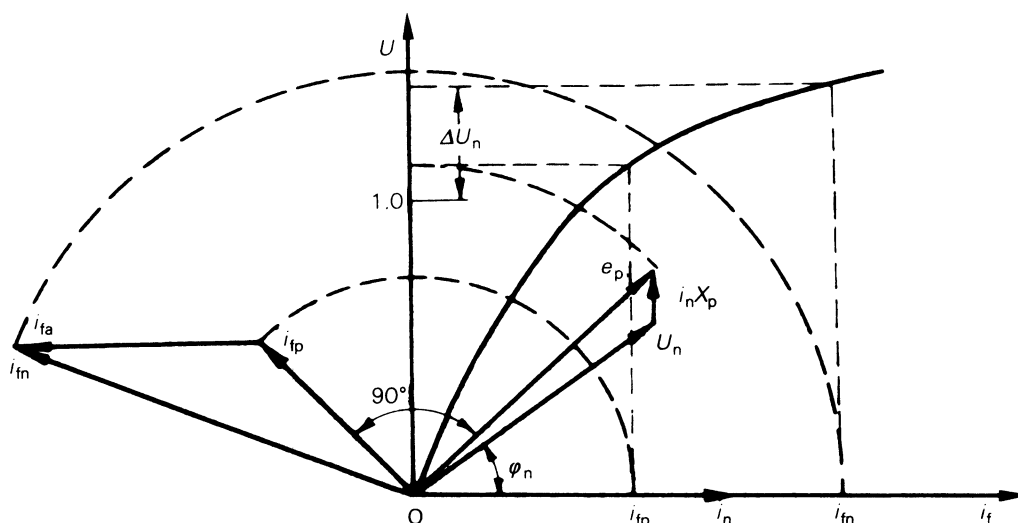


FIGURE 4

This vector should be laid off on the diagram (Figure 4) 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 (Figure 3, page 37). 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 Potier reactance x_p is unknown, it may be replaced in the construction of Figure 4 by (ax_a) , where x_a is the armature reactance measured without rotor (see Sub-clause 31.2), 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).

- 31.1 The test without rotor 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).
- 31.2 The armature reactance without rotor (X_a) is calculated from the following relations:

$$X_a = \sqrt{Z^2 - R^2} \, \Omega$$

where:

$$Z = \frac{U}{\sqrt{3} I} \, \Omega; \quad R = \frac{P}{3 I^2} \, \Omega;$$

$$\left[x_a = \sqrt{z^2 - r^2}; \quad z = \frac{u}{i}; \quad r = \frac{p}{i^2} \right]$$

32. Determination of the rated excitation current by the ASA diagram

To determine the rated excitation current of the machine (see Clause 23) by the ASA vector diagram (Figure 5), use is made of the no-load saturation characteristic (see Sub-clause 25.1), the sustained three-phase short-circuit characteristic (see Sub-clause 26.1) and the Potier reactance (see Clause 14).

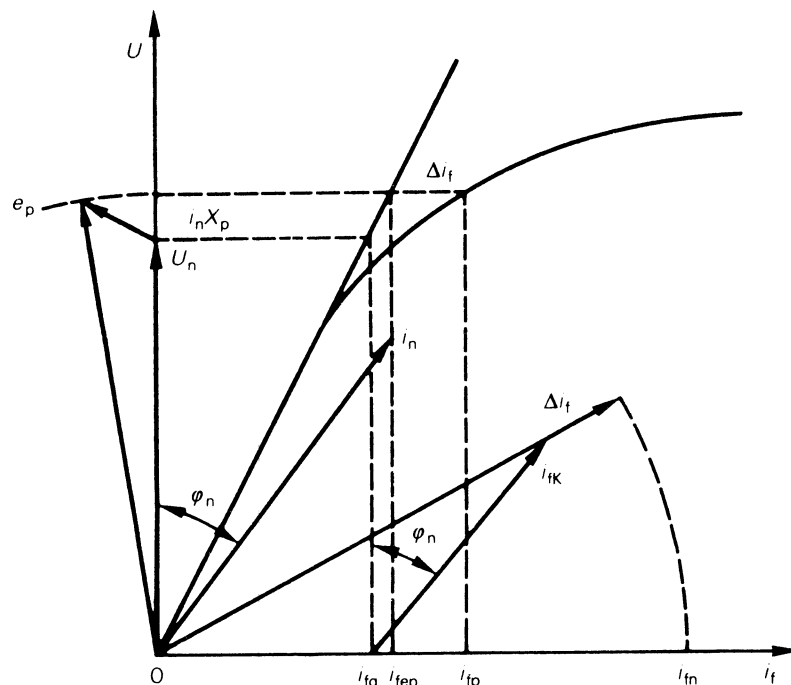


FIGURE 5

The determination of e.m.f. e_p is made in accordance with Clause 31. 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 Clause 30) is laid off.

The vector current corresponding to the difference (Δi_p) 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 5) 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 equation (in per unit or physical values):

$$i_{fn} = \Delta i_f + \sqrt{(i_{fg} + i_{fk} \sin \varphi_n)^2 + (i_{fk} \cos \varphi_n)^2}$$

If the Potier reactance is unknown, it may be replaced in the construction of Figure 5 by ax_a (see Clause 31).

33. Determination of the rated excitation current by the Swedish diagram

To determine rated excitation current of the machine (see Clause 23) by the Swedish diagram, use is made of the no-load saturation characteristic (see Sub-clause 25.1), the sustained three-phase short-circuit characteristic (see Sub-clause 26.1) and the excitation current corresponding to the rated voltage and armature current at zero power-factor (overexcited) (see Clause 29).

Three values of the excitation current are laid off on the abscissa axis (see Figure 6):
 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.

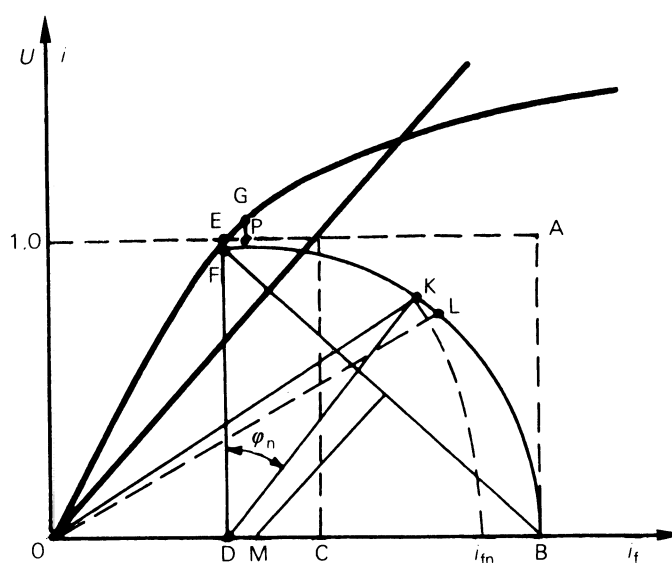


FIGURE 6

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 (see Clause 16 and Sub-clause 72.2) 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 Clause 31) at rated armature current is added to the rated armature voltage (point H' — Figure 3, page 37).

A line parallel to the abscissa axis is drawn from 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 — Figure 3). To the right of point D, vector i_{fa} (length DB) is added along the abscissa-axis (see Clause 31). The excitation current equal to the length OB is the required current to be used in drawing the Swedish diagram.

34. Negative excitation test

The test is conducted with the machine operating under no-load in parallel with the network. 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. The values of the voltage, armature current and excitation current are measured during the test up to the moment when the machine begins to slip.

35. Determination of X_q from the negative excitation test

The determination of X_q (see Clause 6) from the negative excitation test is made using the formula (in per unit or physical values):

$$x_q = (x_d) \cdot \frac{u_r}{u_r + (e)}$$

where:

(e) = no-load e.m.f. for the excitation current i_{fr} at which the machine slips one pole pitch; it is determined from the straightened no-load saturation characteristic drawn through the point corresponding to the voltage at the moment of slipping one pole pitch (Figure 7, page 47)

u_r = voltage at the moment of slipping the pole pitch

(x_d) = 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 the pole pitch is measured, x_q is determined using the formula:

$$X_q = \frac{U_r}{\sqrt{3} I_r} \Omega; \quad \left[x_q = \frac{u_r}{i_r} \right]$$

The value of x_q obtained from this test may, depending upon the value of u_r , include saturation. To obtain an unsaturated value, applied voltage usually must be lowered to 0.6 of rated value or lower.

36. 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

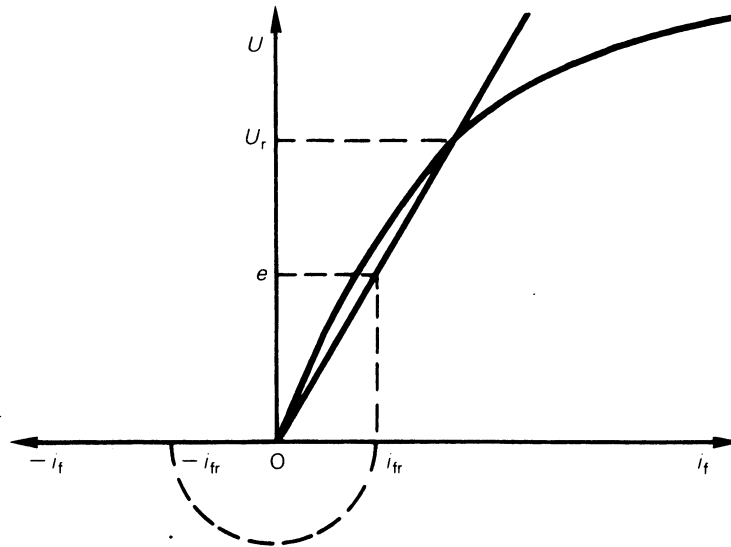


FIGURE 7

does not pull in. The excitation winding should be open-circuited, the rotor should be 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 should be closed (short-circuited or through a discharge resistance) to avoid possible damage. Armature current and voltage and the slip-ring voltage and slip are measured by indicating instruments or recorded by oscillograph. If the residual voltage measured before the test is larger than 0.3 of the supply test voltage, the rotor should be demagnetized. Demagnetizing 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).

37. Determination of X_q from the low slip test

To determine X_q (see Clause 6) from the low slip test, armature current and voltage are measured at maximum excitation winding voltage (U_{fo}), and X_q is calculated using the formula:

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

Note. — 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 in the limits of 0.1-0.3 of the supply test voltage, the value of the current is determined using the formula:

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

where I_{av} is the half sum of the two consecutive maxima of the current envelope curve (Figure 8).

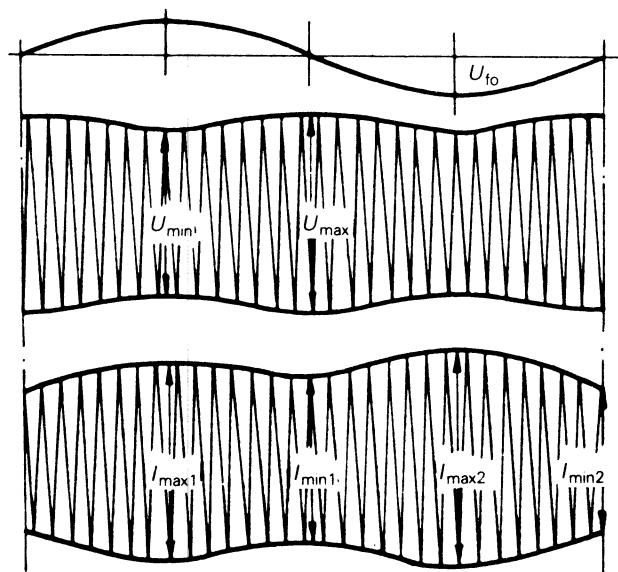


FIGURE 8

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. Then,

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

With a residual voltage less than 0.3 of the supply test voltage, the half sum of the two consecutive minima of the envelope curve represents $I_{\min}$.

The results of X_q measurements 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 in accordance with Clause 27. 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.

38. On-load test measuring the load angle δ

The test is conducted with the machine operating in parallel with the network. The loading of the machine should not be less than 0.5 of the rated active load at rated power-factor.

When conducting the test, measurements are made of the armature current (i) and voltage (u), angle φ between the voltage and the current (using the two wattmeter method) and load angle δ (the internal angle between the terminal voltage and e.m.f.). The load angle may be measured by using the stroboscopic method or any other accurate method.