IEC 60034-29

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Rotating electrical machines –
Part 29: Equivalent loading and superposition techniques – Indirect testing to determine temperature rise

Machines électriques tournantes –
Partie 29: Techniques par charge équivalente et par superposition – Essais indirects pour déterminer l'échauffement

IEC 60034-29:2008

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ROTATING ELECTRICAL MACHINES –

Part 29: Equivalent loading and superposition techniques – Indirect testing to determine temperature rise

FOREWORD

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International Standard IEC 60034-29 has been prepared by IEC technical committee 2: Rotating machinery. It cancels and replaces IEC 61986:2002 which is withdrawn.

The text of this standard is based on the following documents:

FDIS	Report on voting
2/1476/FDIS	2/1491A/RVD

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

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

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

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

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- withdrawn,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

INTRODUCTION

The object of this standard is to provide various indirect load tests, the purpose of which is to determine the temperature rise of rotating electrical machines, including a.c. induction machines, a.c. synchronous machines and d.c. machines. The test methods in some cases provide, in addition, means of measuring or estimating other parameters such as losses and vibration, but the methods are not designed specifically to provide such data.

The proposed test methods are considered equivalent, the choice relying only on the location, the testing equipment and the machine type, and the test result accuracy.

This standard should not be interpreted as requiring any or all of the tests on any given machine. Particular tests are subject to a special agreement between the manufacturer and the purchaser.

NOTE As the methods reproduce only approximately the thermal conditions of the machines under rated condition, temperature-rise measurement results achieved from tests with these methods may be taken as the basis for the evaluation of machine heating in accordance with 8.10 of IEC 60034-1 by agreement between the manufacturer and the purchaser.

ROTATING ELECTRICAL MACHINES –

Part 29: Equivalent loading and superposition techniques – Indirect testing to determine temperature rise

1 Scope

This International Standard applies to machines covered by IEC 60034-1 when they cannot be loaded to a specific condition (rated or otherwise). It is applicable to both motors and generators.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60034-1:2004, *Rotating electrical machines – Part 1: Rating and performance*

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

3 Symbols and units

For the purposes of this document, the following symbols and units apply.

K	slope factor of temperature rise, K/W

NOTE 1 The full name of *K* is “slope factor of the straight line characterizing variation of temperature rise with losses”, see IEC 60027-4, item 901.

$\Delta\theta$	temperature rise, K
θ	temperature, °C
P	power, loss, W
I	current, A
R	resistance, Ω
X	reactance, Ω
U	voltage, V
E	e.m.f., V
f	frequency, Hz
$f_{1,2}$	main/auxiliary frequency, Hz
Δt	time interval, s
T	torque, N·m
J	moment of inertia, kg·m^2
$\cos\varphi$	power factor
γ	method uncertainty, %

NOTE 2 The definition implies that $\gamma > 0$ means test temperature rise is higher than at actual load condition.

δ_f	amplitude of frequency deviation, Hz
λ	ratio of auxiliary voltage to main voltage
σ	correction factor
ω	angular frequency, rad/s

Subscripts

m, n, o, p	test conditions
1, 2, 3, etc.	machine component (e.g. stator winding, rotor winding, stator core, etc.)

NOTE 3 If not indicated otherwise, numbers 1, 2, 3 will be used as assigned above.

t	test
f	field
a	ambient, referring to reference coolant (see IEC 60034-1, 8.2)
c	due to constant losses
L	leakage
N	rated value
equiv	equivalent-load test
super	superposition test

4 General test requirements

Measurement of the electrical parameters shall be made as follows.

a) The class of accuracy of measuring instruments shall be not greater than 0,5.

b) The measuring range of analogue instruments shall be chosen with a view to the measured values being higher than 30 % of the full-scale range. These requirements need not be complied with in the case of the three-phase power measurement by means of two wattmeters, but the currents and voltages in the measured circuits shall be at least 20 % of the rated currents and voltages of the wattmeters being used. The range of the other measuring instruments shall be chosen in such a way that the measuring errors are not increased.

c) The waveform and symmetry of the supply voltage at the machine terminals shall be in accordance with the requirements of Clause 7 of IEC 60034-1.

d) Each line current shall be measured. The arithmetic average value shall be used to determine the machine operating point.

NOTE When using the two-wattmeter method, it is acceptable to measure only two currents.

e) Power input to a three-phase machine shall be measured by either two single-phase wattmeters connected as in the two-wattmeter method, or one polyphase wattmeter, or three single-phase wattmeters. The total power read on a wattmeter shall be reduced by the amount of the I^2R loss in the voltage circuits or in the current circuits of the instruments in accordance with their connection whenever this loss is a measurable portion of the total power.

Unless otherwise indicated all electrical quantities to be measured are root-mean-square values.

5 Superposition method

5.1 Basic principles

5.1.1 General

Superposition tests may be applied to any d.c. or a.c. machine. The method comprises a series of tests at operating conditions other than rated load, for example: reduced load, no load, short circuit, reduced voltage, positive (inductive) or negative (capacitive) reactive load.

The method allows the full-load temperature rise of various component parts of the machine to be deduced. For each component, the loss shall be known at each particular test condition and at full load. The machine should be tested with the same cooling conditions as when operating at rated load. Hence, a locked-rotor test will not be suitable as the air-flow distribution and magnitudes will be incorrect.

On completion of the individual tests, a series of equations based on equivalent thermal circuit theory is constructed, each equation being of the form:

$$\Delta\theta_{1\mathrm{m}} = K_{11}P_{1\mathrm{m}} + K_{12}P_{2\mathrm{m}} + K_{13}P_{3\mathrm{m}}$$

where

$\Delta\theta_{1\mathrm{m}}$	is the measured temperature rise of component 1 for test condition m;
$P_{1\mathrm{m}}$, $P_{2\mathrm{m}}$	etc. is the loss in component 1, 2, etc. for test condition m;
K_{11}, K_{12},	etc. are the slope factors of temperature rise determining the temperature rise of component 1 due to losses in component 1, and the temperature rise of component 1 due to losses in component 2, etc.

Components 1, 2, and 3 may be, for example, the stator winding, the rotor winding, and the stator iron.

In some test conditions, certain losses may be equal to zero, and hence the related term in the equation disappears. For example, using the above assigned subscripts, a synchronous machine has $K_{11}\,P_1 = 0$ at no load and $K_{13}\,P_3 = 0$ at short circuit.

The method is based on the principle that the coefficients K do not change from test to test, i.e. that the cooling conditions are invariable between tests, which requires the speed to be the same in each test. The method is also based on the principle of linear thermal conditions so that temperature rises in one case can be added to those for another case. It requires the losses in the relevant component parts to be known with sufficient accuracy for each case, either by calculation or measurement.

When the tests have been completed and the equations compiled, the coefficients K can be derived by simple arithmetic. These are then used in a final equation with the losses for the rated load condition to calculate the temperature rise of component 1. By similar means, the temperature rises at rated load of components 2, 3, etc. can be derived.

If any component loss is temperature dependent (for example, stator copper loss), then the calculation procedure has to be repeated using values for the loss corrected for the estimated temperature rise. It is normally necessary to do this iteration once only. For the calculation of winding temperature rises corrected to a reference ambient temperature equations in closed form are also provided.

The method may be used to determine the temperature rise of any component at any load if the losses at that load are known. The slope factors of temperature rise (K_{12}, etc.) may be useful in other thermal modelling studies, for example, in analysing the response to supply unbalance, voltage reduction, etc.

In all superposition tests, correction is necessary for variation in heat exchanger performance (if one is fitted to the machine), as the thermal performance of the heat exchanger will partly depend on the total loss in each test.

5.1.2 Temperature rise

When determining the temperature rise values of machine parts by superposition tests, the variations from the results that should be obtained at rated-load test are always to be considered. The uncertainty value γ(%) for rated load is defined:

$$\gamma = \left(\frac{\Delta\theta_{\mathrm{N,super}}}{\Delta\theta_{\mathrm{N}}} - 1\right) \times 100$$

NOTE 1 The uncertainty values obtained by superposition tests may be negative (test temperature rise is lower than under normal operation) or positive (test temperature rise is larger than under normal operation).

Consequently, for comparing with the temperature rise values given in IEC 60034-1, test results have to be multiplied with a correction factor σ:

$$\sigma = \frac{1}{1 + \frac{\gamma}{100}}$$

NOTE 2 For negative uncertainty values the correction factor is > 1.

5.1.3 Estimation of temperature rise from reduced load tests

When estimating the temperature rise from tests at reduced load, the losses should be separated into variable (load) losses and constant (iron, friction and windage) losses. For the adjustment of temperature rise values, the machine may be considered as a two-component system (see 5.1.1).

NOTE Depending on the enclosure and pole number of the machine, the temperature rise due to the constant losses can be significant. Tests on large machines have shown that the separation of loss components results in better agreement between the reduced load estimation and the full load actual test.

When a load test is performed at currents different from rated current, the I^2R losses have to be converted to full load with the squared ratio of the currents, and the resistance R has to be corrected for total winding temperature. The following equation describes the adjustment of temperature rise to full load, neglecting the effect of constant losses and of additional load losses:

$$\Delta\theta_{1\mathrm{N}} = \left(\frac{I_{\mathrm{N}}}{I_{1\mathrm{t}}}\right)^2 \cdot \Delta\theta_{1\mathrm{t}} \cdot \left(\frac{235 + \theta_{\mathrm{at}}}{235 + \theta_{\mathrm{at}} + \Delta\theta_{1\mathrm{t}} - (\frac{I_N}{I_{1t}})^2 \cdot \Delta\theta_{1t}}\right)$$

where

I_{N} is the rated current;

$I_{1\mathrm{t}}$ is the measured stator current;

θ_{at} is the measured temperature of the reference coolant;

$\Delta\theta_{1\mathrm{t}}$ is the measured stator winding temperature rise.

In cases where the portion of the winding temperature rise due to the constant losses is not known, and the total temperature rise is assumed due to I^2R losses only, the calculated temperature rise will be too large. Therefore, this method can be used only when the effect of constant losses is low; in most cases, methods taking constant and load losses separately into account are preferred. Induction machines are tested according to 5.2.2.

When the temperature rise components due to load loss at reduced current and due to constant loss are known, the total temperature rise can be calculated by using an iteration procedure or, alternatively, by a closed-form equation. Annex A presents an example.

5.2 Induction motors

5.2.1 Applicable tests

In these methods the motor is tested at the following operating points as indicated:

Test m: reduced voltage, with the motor loaded to give rated current, giving I_{1m}, P_{1m} and $\Delta\theta_{1m}$ at U_m,

Test n: the same reduced voltage as in test m, but at no load, giving I_{1n}, P_{1n} and $\Delta\theta_{1n}$ at $U_n = U_m$,

Test o: rated voltage at no load, giving I_{1o}, P_{1o} and $\Delta\theta_{1o}$ at $U_o = U_N$,

Test p: rated voltage and frequency, at reduced load, giving I_{1p}, P_{1p} and $\Delta\theta_{1p}$ at $U_p = U_N$. Preferably I_{1p} is not less than 70 % of rated stator current,

Test q: reduced voltage, with the motor loaded, giving I_{1q}, P_{1q} and $\Delta\theta_{1q}$ at U_q. Preferably I_{1q} is not less than 70% of rated stator current.

NOTE 1 Lower values of I_1 in tests p and q may be used but will increase the uncertainty.

NOTE 2 Where applicable use $\Delta\theta_{2m}$, $\Delta\theta_{2n}$, $\Delta\theta_{2o}$, $\Delta\theta_{2p}$, $\Delta\theta_{2q}$ for the rotor winding of wound rotor machines.

5.2.2 Method of reduced voltage and rated current

5.2.2.1 General

The method requires a variable-voltage supply at rated frequency and either a loading generator or braking equipment with a rating much less than the rating of the motor under test. For each of the tests m, n, o the voltage, current, input power and stator winding temperature rise are measured:

$\Delta\theta_{1m}$ is the stator winding temperature rise due to rated stator current, quasi rated rotor current and reduced-voltage iron loss and full friction and windage losses;

$\Delta\theta_{1n}$ is the stator winding temperature rise due to reduced-voltage no-load stator current, reduced-voltage iron loss and full friction and windage losses;

$\Delta\theta_{1o}$ is the stator winding temperature rise due to rated-voltage no-load stator current, rated-voltage no-load iron loss and friction and windage losses.

It should be noted that with large induction motors there may be cases when test m is not practicable with a slip below the pull-out slip; operation above the pull-out slip is then an alternative. To measure the stator winding temperature rise by the resistance method when the machine is on no-load, some means to rapidly stop the motor should be employed when shutting down, or the resistance should be measured directly under load (see 8.6.2 of IEC 60034-1).

The method assumes that the cooling remains unchanged for each test, which implies that the speed is also virtually unchanged.

The quantity $\Delta\theta_{1n}$ can be determined with sufficient accuracy by using the following equation:

$$\Delta\theta_{1n} = \Delta\theta_{1o} P_{1n} / P_{1o}$$

By applying this relation a complete thermal test at reduced voltage (the no-load test for test condition n) can be saved. This should be taken up as an alternative for practical reasons.

The uncertainty of determining temperature rises is within $\gamma = \pm 6$ % for all types and ratings of machines. The method is preferable for cage induction motors where the uncertainty can be estimated within $\gamma = \pm 3$ %.

NOTE 1 When this method is used for wound rotor machines, the same procedure can be applied for the temperature rise of the stator winding to get similar uncertainty. For the calculation of rotor winding temperature a similar uncertainty is expected with the procedure listed in the subsequent subclause.

NOTE 2 For motors >500 kW, when test m involves a forward short circuit heat run, i.e. operation well above the pull-out slip, γ will always be positive.

The results can be analysed either by means of calculation (see 5.2.2.2) or using a graphical method (see 5.2.2.3).

5.2.2.2 Determination of temperature rise by calculation method

The calculation method assumes that the stator winding temperature rise at rated voltage for a particular load is a linear function as follows:

$$\Delta\theta_1 = \Delta\theta^*_{1c} + K^*_{11} \times P_{11}$$

where

$\Delta\theta^*_{1c}$ is the stator winding temperature rise at rated voltage and zero stator current, i.e. the rise due to the iron loss and friction and windage losses;

P_{11} is the stator winding loss at the particular load;

K^*_{11} is the slope factor of stator temperature rise due to stator winding loss, rotor winding loss and additional load loss.

The terms $\Delta\theta^*_{1c}$ and K^*_{11} can be found from tests m, n and o as follows:

$$\Delta\theta^*_{1c} = \Delta\theta_{1o} - K^*_{11} P_{1o} \quad \text{and} \quad K^*_{11} = \frac{\Delta\theta_{1m} - \Delta\theta_{1n}}{P_{1m} - P_{1n}}$$

The stator winding total temperature rise at rated current and voltage is calculated from:

$$\Delta\theta_{1N} = \Delta\theta^*_{1c} + K^*_{11} P_{1m}$$

The full load temperature rise corrected to a reference coolant temperature is obtained from:

$$\Delta\theta_{1Nc} = \frac{\Delta\theta^*_{1c} + K^*_{11}.P_{1m} \dfrac{235 + \theta_{aN}}{235 + \theta_a + \Delta\theta_{1m}}}{1 - K^*_{11}.P_{1m} \dfrac{1}{235 + \theta_a + \Delta\theta_{1m}}}$$

where

P_{1m} is the stator winding I^2R loss at rated current I_{1N} from test at coolant temperature θ_a;

θ_a is the coolant temperature at the test;

θ_{aN} is the reference coolant temperature;

$\Delta\theta_{1m}$ is the temperature rise of the stator winding for rated current from test at θ_a;

235 is the reciprocal value of the temperature coefficient of resistances for copper, in K.

NOTE 1 θ_{aN} is, more exactly, the reference temperature of the reference coolant.

For wound rotor induction machines, determine the rotor winding temperature rise from the temperature rises of the rotor for each test:

$$\Delta\theta_{2\mathrm{N}} = \Delta\theta_{2\mathrm{m}} + (\Delta\theta_{2\mathrm{o}} - \Delta\theta_{2\mathrm{n}})$$

NOTE 2 The difference of temperature rises $\Delta\theta_{2\mathrm{o}}$ and $\Delta\theta_{2\mathrm{n}}$ is usually negligible.

5.2.2.3 Determination of temperature rise by graphical method

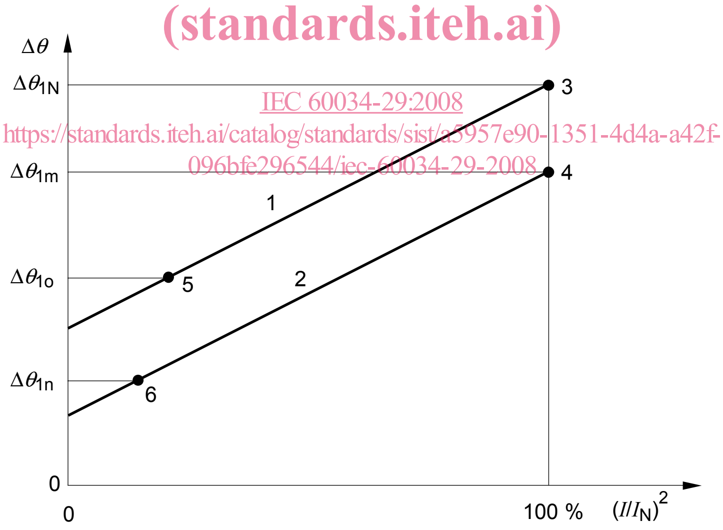
The graphical method is based on the following assumptions.

a) The load losses depend solely on current, and the no-load losses depend solely on voltage.

b) The temperature rises can be added, i.e. the effect of radiation is negligible, and the slope factors of temperature rise are independent of temperature.

c) The load-dependent stray-load loss depends on the current only.

These assumptions are fundamentally the same as those in the calculation method described in 5.2.2.2. A graph can be drawn of the measured temperature rise values from tests m, n, o (see 5.2.1), plotted against the square of the stator current as shown in Figure 1. First a straight line is drawn through the two points at reduced voltage ($\Delta\theta_{1\mathrm{m}}$ and $\Delta\theta_{1\mathrm{n}}$), then a parallel line is drawn through $\Delta\theta_{1\mathrm{o}}$. The temperature rise at rated load $\Delta\theta_{1\mathrm{N}}$ is obtained as shown in Figure 1.



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Key

1 curve for rated voltage

2 curve for reduced voltage

3, 4 test points for rated current, referred to 1, 2 resp.

5, 6 test points for no-load, referred to 1, 2 resp.

Figure 1 – Graphical superposition method for induction motors

If the stator currents for tests n and o are sufficiently small (and not too dissimilar) compared with the rated current, then the stator winding temperature rise at rated voltage and rated load is given by:

$$\Delta\theta_{1N} = \Delta\theta_{1m} + \Delta\theta_{1o} - \Delta\theta_{1n}$$

NOTE Temperature rise may also be expressed in terms of total losses when stator winding losses, iron losses, friction and windage losses and additional load losses are known, and in the tests with the motor loaded, the slip is additionally recorded in order to determine the rotor I^2R losses.

5.2.3 Method of rated voltage and reduced current

This method requires a loading generator or braking equipment with a rating less than the rating of the motor under test. The loading may be either by the actual loading method or equivalent loading method. For each of the tests o and p, voltage, current, stator input power and stator winding temperature rise are measured. The test conditions are as follows:

$\Delta\theta_{1o}$ is the stator winding temperature rise due to rated-voltage, no-load stator current, rated-voltage no-load iron loss and friction and windage losses (see 5.2.2.1);

$\Delta\theta_{1p}$ is the stator winding temperature rise due to rated voltage, reduced load current, rated voltage iron loss and friction and windage losses.

For wound rotor machines the rotor winding temperature rise can be measured in a similar way. In this case the slip is also measured for the determination of rotor copper losses.

The full load temperature rise is calculated by a linear function using

$$\Delta\theta_{1N} = \Delta\theta'_{1c} + K'_{11} P_{1N}$$

where

$\Delta\theta'_{1c}$ is the stator winding temperature rise at rated voltage and zero stator current, i.e. the rise due to the iron loss and friction and windage losses;

P_{1N} is the stator winding loss at rated load;

K'_{11} is the slope factor of stator temperature rise due to stator winding loss, rotor winding loss and additional load loss.

The terms $\Delta\theta'_{1c}$ and K'_{11} can be found from tests o and p as follows:

$$\Delta\theta'_{1c} = \frac{P_{1p}\cdot\Delta\theta_{1o} - P_{1o}\cdot\Delta\theta_{1p}}{P_{1p} - P_{1o}} \quad \text{and} \quad K'_{11} = \frac{\Delta\theta_{1p} - \Delta\theta'_{1c}}{P_{1p}}$$

where

P_{1p} is the stator winding loss at test p;

P_{1o} is the stator winding loss at test o.

The stator total temperature rise at full load is calculated from:

$$\Delta\theta_{1N} = \frac{(\Delta\theta_{1p} - \Delta\theta'_{1c})\times\frac{I_{1N}^{2}}{I_{1p}^{2}}\times\frac{235+\theta_{ap}}{235+\theta_{ap}+\Delta\theta_{1p}} + \Delta\theta'_{1c}}{1-\frac{I_{1N}^{2}}{I_{1p}^{2}}\times\frac{\Delta\theta_{1p}-\Delta\theta'_{1c}}{235+\theta_{ap}+\Delta\theta_{1p}}}$$

where

$\Delta\theta_{1p}$ is the temperature rise of the stator winding for test p;

θ_{ap} is the coolant temperature at test p.