PAKISTAN STANDARD

ROTATING ELECTRICAL MACHINES –
PART 2-2: SPECIFIC METHODS FOR DETERMINING SEPARATE LOSSES OF LARGE MACHINES FROM TESTS

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ROTATING ELECTRICAL MACHINES – PART 2-2: SPECIFIC METHODS FOR DETERMINING SEPARATE LOSSES OF LARGE MACHINES FROM TESTS

0. FOREWORD

0.1 This Pakistan Standard was adopted by the authority of the Board of Directors for Pakistan Standards and Quality Control Authority after approval by the Technical Committee for "Rotating Electrical Machines Part 2-2: Specific methods for determining separate losses of large machines from tests" had been approved and endorsed by the Electrotechnical National Standards Committee on **19 January 2012.**

0.2 This Pakistan Standard was adopted on the basis of IEC: 60034-2-2-2010 since IEC Standard have been established in 2010, hence it is deemed necessary to adopt the International standard to keep abreast with the latest technology and as par with IEC standard.

0.3 This Pakistan Standard is an adoption of IEC: 60034-2-2-2010 Rotating Electrical Machines Part 2-2: Specific methods for determining separate losses of large machines from tests**"** and its use hereby acknowledged with thanks.

0.4 This standard is subject to periodical review in order to keep pace with the development in industry. Any suggestions for improvement shall be recorded and placed before the revising committee in due course.

0.5 This standard is intended chiefly to cover the technical provisions relating to this standard and it does not include all the necessary provisions of a Contract.

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ROTATING ELECTRICAL MACHINES –

Part 2-2: Specific methods for determining separate losses of large machines from tests – Supplement to IEC 60034-2-1

1 Scope

This part of IEC 60034 applies to large rotating electrical machines and establishes additional methods of determining separate losses and to define an efficiency supplementing IEC 60034-2-1. These methods apply when full-load testing is not practical and result in a greater uncertainty.

NOTE In situ testing according to the calorimetric method for full-load conditions is recognized.

The specific methods described are:

– Calibrated-machine method.

– Retardation method.

– Calorimetric method.

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, *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 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60034-1 and IEC 60034-2-1 apply, as well as the following.

3.1
calibrated machine
machine whose mechanical power input/output is determined, with low uncertainty, using measured electrical output/input values according to a defined test procedure

3.2
calibrated-machine method
method in which the mechanical input/output to/from an electrical machine under test is determined from the measurement of the electrical input/output of a calibrated machine mechanically coupled to the test machine

3.3
retardation method
method in which the separate losses in a machine under test are deduced from the measurements of the deceleration rate of its rotating components when only these losses are present

3.4
calorimetric method
method in which the losses in a machine are deduced from the measurements of the heat generated by them

3.5
thermal equilibrium
the state reached when the temperature rises of the several parts of the machine do not vary by more than a gradient of 2 K per hour

[IEV 411-51-08]

4 Symbols

In addition to the symbols in IEC 60034-2-1, the following apply.

4.1 Quantities

A	is an area, m^2,
C	is the retardation constant, kg m^2 min^2,
c_p	is the specific heat capacity of the cooling medium, J/(kg K),
h	is the coefficient of heat transfer, W/(m^2 K),
J	is the moment of inertia, kg m^2,
n	is the speed, min^{-1},
P_{1E}	is the excitation power supplied by a separate source, W,
P_k	is the constant loss, W,
P_{el}	is the electrical power, excluding excitation, W,
P_e	is the excitation power, W,
P_{Fe}	is the iron loss, W,
P_{fw}	is the friction and windage loss, W,
P_{sc}	is the short-circuit loss, W,
P_{mech}	is the mechanical power, W,
P_T	is the total loss, W,
Q	is the volume rate of flow of the cooling medium, m^3/s,
t	is the time, s,
v	is the exit velocity of cooling medium, m/s,
Δp	is the difference between the static pressure in the intake nozzle and ambient pressure, N/m^2,
$\Delta\theta$	is the temperature rise of the cooling medium, or the temperature difference between the machine reference surface and the external ambient temperature, K,
δ	is the per unit deviation of rotational speed from rated speed,
ρ	is the density of the cooling medium, kg/m^3,
θ	is the temperature, °C.

4.2 Subscripts

irs	for inside reference surface,
ers	for outside reference surface,
E	for exciter,
c	for the cooling circuit,

N for rated values,

rs for the reference surface,

t for a test procedure,

1 for input or initial condition,

2 for output condition.

5 Basic requirements

5.1 Direct and indirect efficiency determination

Tests can be grouped in the following categories.

5.1.1 Direct

Input-output measurements on a single machine are considered to be direct. This involves the measurement of electrical or mechanical power into, and mechanical or electrical power out of a machine.

5.1.2 Indirect

Measurements of the separate losses in a machine under a particular condition are considered to be indirect. This is not usually the total loss but comprises certain loss components. The method may, however, be used to calculate the total loss or to calculate a loss component.

The determination of total loss shall be carried out by one of the following methods:

– direct measurement of total loss;

– summation of separate losses.

NOTE The methods for determining the efficiency of machines are based on a number of assumptions. Therefore, it is not possible to make a comparison between the values of efficiency obtained by different methods.

5.2 Uncertainty

Uncertainty as used in this standard is the uncertainty of determining a true efficiency. It reflects variations in the test procedure and the test equipment.

Although uncertainty should be expressed as a numerical value, such a requirement needs sufficient testing to determine representative and comparative values. This standard uses the following relative uncertainty terms:

– "low" applies to efficiency determinations based solely upon test results;

– "medium" applies to efficiency determinations based upon limited approximations;

– "high" applies to efficiency determinations based upon assumptions.

5.3 Preferred methods

It is difficult to establish specific rules for the determination of efficiency. The choice of test to be made depends on the information required, the accuracy required, the type and size of the machine involved and the available field test equipment (supply, load or driving machine).

Preferred methods for large machines are given in Table 1.

Table 1 – Preferred methods for large machines

Quantity to be determined	Test method	Clause	Uncertainty
Direct efficiency	Calibrated machine	7.1.4.1	medium
Total losses	Calorimetric [1]	7.3.3d)	low/medium
Friction and windage loss	Calibrated machine	7.1.4.2a)	medium
	Retardation	7.2.5.2	medium
	Calorimetric	7.3.3a)	low/medium
Active iron loss, and additional open-circuit losses in d.c. and synchronous machines	Calibrated machine	7.1.4.2b)	medium
	Retardation	7.2.5.3	medium
	Calorimetric	7.3.3b)	low/medium
Winding and additional-load losses	Calibrated machine	7.1.4.2c)	medium
	Retardation	7.2.5.5	medium
	Calorimetric	7.3.3c)	low/medium

6 Common determinations

These determinations are applicable to more than one of the listed methods.

6.1 Efficiency

Efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source;

P_T is the total loss according to 6.2.

NOTE 1 Input power P_1 and output power P_2 are as follows:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;

in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

NOTE 2 P_T includes the excitation power P_e of the machine where applicable.

6.2 Total loss

When the total loss is determined as the sum of the separate losses the following formulae apply:

For direct current machines:

$$P_T = P_k + P_a + P_b + P_{LL} + P_e$$

1 If the relative error in P_{irs} (see 7.3.1) is likely to be greater than 3 %, the calorimetric method is not recommended.

$$P_e = P_f + P_E$$

$$P_k = P_{fw} + P_{Fe}$$

For induction machines:

$$P_T = P_k + P_s + P_r + P_{LL}$$

$$P_k = P_{fw} + P_{Fe}$$

For synchronous machines:

$$P_T = P_k + P_a + P_{LL} + P_e$$

$$P_e = P_f + P_E + P_b$$

$$P_k = P_{fw} + P_{Fe}$$

where:

- P_a is the I^2R armature-winding loss (interpole, compensation and series field winding loss in case of d.c. machines),
- P_b is the brush loss,
- P_E is the exciter loss,
- P_e is the excitation power,
- P_f is the excitation (field winding) loss,
- P_{Fe} is the iron loss,
- P_{fw} is the friction and windage loss,
- P_k is the constant loss,
- P_{LL} is the additional load loss,
- P_r is the I^2R rotor winding loss,
- P_s is the stator I^2R winding loss,
- P_T is the total loss.

6.3 Load losses

Losses relative to machine load (with lowest uncertainty) are best determined from actual measurements. For example: measurements of current, resistance, etc. under full-load operation.

When this is not possible, these values shall be obtained from calculation of the parameters during the design stage.

Determination of losses not itemized in this part may be found in IEC 60034-2-1.

7 Methods

For the determination of performance when machine load and/or size exceed test capabilities (described in IEC 60034-2-1), the following test methods may be used.

NOTE These methods are generally applicable to large machines where the facility cost for other methods is not economical.

7.1 Calibrated machine method

The calibrated machine method may be used to determine the test machine efficiency either directly or by separate losses.

7.1.1 General

This method is generally applied as a factory test.

This method requires a calibrated machine mechanically coupled to the machine under test and is used when neither a torque meter nor dynamometer is available. The mechanical input of the tested machine is calculated from the electrical input of the calibrated machine.

7.1.2 Machine calibration

When a gear-box is directly connected to the machine it shall be considered as part of the calibrated machine.

Calibrate an electric machine, preferably a direct-current machine, according to one of the procedures in IEC 60034-2-1 at a sufficient number of thermally stable loads (including no-load) to determine an accurate relationship of output power as a function of input power adjusted for the temperature of the cooling air/medium at inlet. This is generally developed in the form of a curve.

NOTE It is generally advisable to take several readings of all instruments at each load-point during short periods of time and average the results to obtain a more accurate test value.

7.1.3 Test procedure

The tested machine shall be equipped with winding ETDs.

The tested machine shall be completely assembled with essential components as for normal operation.

Before starting the test, record the winding resistances and the ambient temperature.

The machine for which the performance is to be determined shall be mechanically coupled to the calibrated machine and be operated at a speed equivalent to its synchronous/rated speed.

Operate the calibrated machine with the test machine at either rated-load, partial-load; no-load not excited, with or without brushes; no-load excited at rated voltage; or short-circuited, which enables specific categories of losses to be determined.

When the test machine is operated at each specified test condition and has reached thermal stability, record:

NOTE The following example represents testing with a motor as the calibrated machine.

– for the calibrated machine

  P_1 = power

  U_1 = input voltage

  I_1 = current

  θ_{1c} = temperature of inlet cooling air

  θ_{1w} = winding temperature (by variation of resistance if possible)

  n_1 = speed

– for the test machine (direct determination as a generator)

  P_2 = output power

U_2 = output voltage

I_2 = armature load current

θ_{2w} = windings temperature (either directly by ETDs or by resistance variation)

n_2 = speed

– for the unloaded test machine (as a generator)

U_2 = armature voltage (when excited open-circuit)

I_2 = armature current (when excited short-circuit)

θ_{2w} = windings temperature (either directly by ETDs or by resistance variation)

n_2 = speed

Upon completion of each test, stop the machines and record in the given order:

– test machine winding resistance;
– calibrated machine winding resistance.

Finally operate the calibrated machine without electrical connection to the test machine and record as specified above.

7.1.4 Determination of performance

From the curve developed in 7.1.2 and using the calibrated machine input values, select the appropriate output power to the test machine.

Adjust the output power for the standardized coolant temperature.

Determination of excitation power shall be in accordance with IEC 60034-2-1.

7.1.4.1 Direct efficiency determination

When tested according to 7.1.3 the test machine efficiency is:

$\eta = \frac{P_2}{P_1}$ test machine working as a generator, calibrated machine working as a motor

where

P_2 is the output power of test generator

P_1 is the calculated input power to the test generator according to 7.1.3.

and:

$\eta = \frac{P_2}{P_1}$ test machine working as a motor, calibrated machine working as a generator

where

P_1 is the input power to test motor

P_2 is the calculated output power from the test motor.

7.1.4.2 Separate losses

Using values of P determined from the calibrated machine curve, it is possible to determine the power dissipated by the test machine for other selected conditions that may be used to determine efficiency according to 6.1.

a) Friction and windage loss at rated speed (when the test machine is not electrically connected);

b) Active iron loss, and additional open-circuit losses in d.c. and synchronous machines, (when tested at no-load, open-circuit, excited at rated voltage, minus the windage and friction loss). Field losses from a separate source;

c) Armature-winding loss and additional-load loss in synchronous machines, (when tested under short-circuit conditions, excited at rated armature current, minus the windage and friction loss). Field losses from a separate source.

7.2 Retardation method

The retardation method can be used in determining the separate losses of rotating electrical machines having an appreciable rotational inertia.

The retardation method is used to determine:

– sum of the friction loss and windage loss ("mechanical losses") in machines of all types;

– sum of losses in active iron and additional open-circuit losses in d.c. and synchronous machines;

– sum of I^2R losses in an operating winding and additional-load losses ("short-circuit losses") in synchronous machines.

7.2.1 Fundamentals

The recorded test loss P_t which retards the machine is proportional to the product of the speed at which this loss corresponds and the deceleration at that speed:

$$P_t = -Cn\frac{dn}{dt}$$

where:

P_t	is the loss being measured, W;
C	is the retardation constant according to 7.2.4;
n	is the speed, min^{-1};
dn/dt	is the deceleration from 7.2.3.

NOTE The accuracy of the retardation method is directly related to the accuracy of the retardation constant C which depends solely on the moment of inertia J (see 7.2.4).

7.2.2 Test procedure

7.2.2.1 Assembly of test machine

The test machine shall be assembled, with all essential components, as for normal operation, but uncoupled from other rotating parts. A suitable speed sensor shall be attached to the rotating element.

NOTE When the machine cannot be uncoupled, all possible steps should be taken to reduce the mechanical losses in other rotating parts, e.g. by partial dismantling or in the case of a water turbine, by preventing water in the runner chamber. Rotation of the runner in air produces a windage loss which should be determined either experimentally or from calculations.

7.2.2.2 Machine preparation for test

Electrically connect the test machine as a motor (on no-load) fed from a separate power source having a wide range of variable frequency. Any excitation shall be obtained from a separate source with a rapid and precise voltage control.

NOTE 1 The test machine may be driven by its normal prime mover, e.g. by Pelton turbine when the water supply to the runner can be cut off instantly.

NOTE 2 Excitation from a mechanically-coupled exciter is not recommended, but may be permitted when the value of the deviation of speed δ does not exceed 0,05. Losses in exciters coupled to the shaft of the test machine are to be taken into account.

The bearing temperatures shall be adjusted to the normal temperature at which the bearings operate with rated load, by adjusting the coolant flow.

The air temperature shall be adjusted, whenever possible, to the normal temperature at which the windage loss measurement is required by throttling the air coolant flow.

7.2.2.3 Testing preparation

Retardation tests shall be conducted as a series without interruption, whenever possible. It is recommended that the series start and finish with retardation tests of the test machine unexcited.

All tests shall be repeated several times at the preset rated values of open-circuit voltage or short-circuit current. The arithmetic mean value obtained from each series of measurements shall be assumed to be the appropriate loss value of that category of loss.

Select a value of δ (the per unit deviation of rotational speed from rated speed) which shall not be greater than 0,1 and may have to be less than this, depending on the characteristics of the machine.

7.2.2.4 Tests

Rapidly accelerate the test machine to a speed above n_N (1 + δ). Disconnect the machine from its supply source. Sufficient time delay shall separate the switching off of the supply and starting the measurements to allow electromagnetic transients to decay.

During deceleration to n_N (1 – δ) place the test machine in the required condition, according to the following tests:

When moment of inertia is known.

a) running unexcited;
b) running open-circuited, excited at rated voltage;
c) running with the armature terminals short-circuited, and the excitation set to give the rated armature current.

NOTE As an alternate, tests may be carried out at various values within limits of the order of 95 % to 105 % of either the rated voltage or rated short-circuit current.

Additional tests, when the moment of inertia is unknown, shall be conducted at the same values as determined in b) and c) according to either d) e) or f).

d) with the field suppressed, connect the test machine to a transformer previously set under no-load condition and excited to the preset values of current or open-circuit voltage;
e) with the field suppressed, connect the test machine to a transformer previously set under short-circuit;
f) with the field suppressed, simultaneously load the exciter or the auxiliary generator with a ballast resistance at a predetermined load.

Each retardation test shall be repeated at least twice.

7.2.2.5 Measurements

Measurements of voltage and current shall be taken at the instant when the test machine passes through rated speed, except in the case of an unexcited retardation test.

NOTE Excitation circuit power should be measured, if excitation is not provided by a separate source.

The measured values of open-circuit voltage or short-circuit current shall not differ from the preset values by more than ± 2 %. The calculated final value of the speed derivative in time for each of the tests shall be adjusted proportionally by the ratio of the square of the preset value to the measured value.

Highly accurate recording instruments shall be used either with continuous or with discrete recording of test values of speed and time.

For each test category, take sufficient measurements to accurately locate the points $n_N (1 + \delta)$ and $n_N (1 - \delta)$ as a function of time.

7.2.2.5.1 All tests

For all tests, record

n as a function of t (the armature circuit being short-circuited);

θ_w = winding temperatures (either directly or by resistance variation);

θ_a = inlet/outlet temperature of the primary cooling medium.

For the following tests record additionally:

where the numbered subscript denotes the specific test number.

7.2.2.5.2 Test 2

P_2 during initial operation at rated voltage (see 7.2.4.2.1);

U_2 open-circuit rated voltage.

7.2.2.5.3 Test 3 (for synchronous machines)

I_a armature current.

7.2.2.5.4 Test 4

P_4 transformer no-load loss;

U_4 open-circuit rated voltage.

7.2.2.5.5 Test 5

P_5 transformer short-circuit loss;

I_a armature current.

7.2.2.5.6 Test 6

P_6 exciter or auxiliary generator load.

7.2.3 Determination of deceleration

This chord method requires the measurement of the time interval $(t_2 - t_1)$ during which the speed of the tested machine changes from $n_N (1 + \delta)$ to $n_N (1 - \delta)$, see Figure 1. The ratio of speed interval $2 \delta \, n_N$ to $(t_2 - t_1)$ is approximately the deceleration at rated speed:

$$\frac{2\delta n_N}{t_2 - t_1} \approx -\left.\frac{dn}{dt}\right|_{n = n_N}$$

where

δ is the per unit deviation of rotational speed from rated speed.

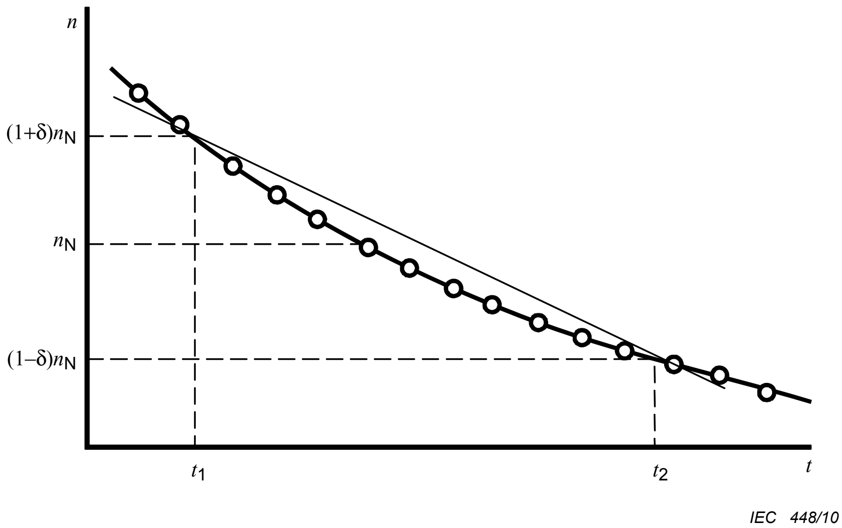

Figure 1 – Method of the chord

Determine the deceleration for the required tests and record as:

$$\left.\frac{dn}{dt}\right|_{t}$$

Where:

t is the number of the test according to 7.2.2.4.

NOTE According to the definition in 7.2.3 dn/dt is a negative value.

7.2.4 Determination of retardation constant

7.2.4.1 Known moment of inertia

When the moment of inertia of a machine rotating-part has been previously determined by either measurement (preferred) or by design calculation, the retardation constant is calculated from:

$$C = \frac{4\pi^2 J}{60^2} = 10{,}97 \times 10^{-3} J$$

where:

J is the moment of inertia, in kg·m^2.

7.2.4.2 Unknown moment of inertia

7.2.4.2.1 Operation as an unloaded motor

When the test machine is operated as an unloaded motor, the input power is equal to the sum of the mechanical loss P_{fw} and iron loss P_{Fe} (the armature circuit I^2R loss is ignored), then the retardation constant C is determined from the formula:

$$C = -\frac{P_{\mathrm{fw}} + P_{\mathrm{Fe}}}{n_{\mathrm{N}} \left.\frac{dn}{dt}\right|_{2}}$$

7.2.4.2.2 Retarded by open-circuited transformer

When the test machine is retarded by the transformer open-circuit loss, with the ohmic $I^{2}R$ loss according to the transformer open-circuit current ignored, then:

$$P_{\mathrm{fw}} + P_{\mathrm{Fe}} + P_{4} = -Cn_{\mathrm{N}} \left.\frac{dn}{dt}\right|_{4}$$

hence

$$C = -\frac{P_{4}}{n_{\mathrm{N}}\left\{\left.\frac{dn}{dt}\right|_{4} - \left.\frac{dn}{dt}\right|_{2}\right\}}$$

7.2.4.2.3 Retarded by short-circuited transformer

When the test machine is retarded by the transformer short-circuit loss, with the iron loss corresponding to magnetic flux in the short-circuited transformer ignored, then

$$P_{\mathrm{fw}} + P_{\mathrm{sc}} + P_{5} = -Cn_{\mathrm{N}} \left.\frac{dn}{dt}\right|_{5}$$

hence

$$C = -\frac{P_{5}}{n_{\mathrm{N}}\left\{\left.\frac{dn}{dt}\right|_{5} - \left.\frac{dn}{dt}\right|_{3}\right\}}$$

7.2.4.2.4 Retardation by exciter or auxiliary generator

When the test machine is retarded by the exciter or auxiliary generator loaded with a ballast resistance, the retardation losses consist only of the test machine mechanical loss P_{fw} and the measured load P_{6} (with allowance for efficiency of the exciter or auxiliary generator which can be determined by calculations). Then:

$$P_{\mathrm{fw}} + P_{6} = -Cn_{\mathrm{N}} \left.\frac{dn}{dt}\right|_{6}$$

hence

$$C = -\frac{P_{6}}{n_{\mathrm{N}}\left\{\left.\frac{dn}{dt}\right|_{6} - \left.\frac{dn}{dt}\right|_{1}\right\}}$$

7.2.5 Determination of losses

7.2.5.1 General

The tested loss P_{t} which retards the machine is:

$$P_{\mathrm{t}} = -Cn_{\mathrm{N}} \left.\frac{dn}{dt}\right|_{t}$$

Where:

n_N is rated speed, in $\min^{-1}$;

P_t is tested loss, in W;

C is retardation constant according to 7.2.4;

$\left.\frac{dn}{dt}\right|t$ is the deceleration from test t, where t is the specific test number according to 7.2.2.4.

7.2.5.2 Friction and windage loss

The friction and windage (mechanical) loss P_{fw} of the test machine are:

$$P_{fw} = -Cn_N \left.\frac{dn}{dt}\right|1$$

7.2.5.3 Iron loss

The iron loss P_{Fe} is:

$$P_{Fe} = -Cn_N \left.\frac{dn}{dt}\right|2 - P_{fw}$$

NOTE Excitation should be provided by a separate source according to 7.2.2.2.

7.2.5.4 Short-circuit loss

The short-circuit loss P_{sc} is:

$$P_{sc} = -Cn_N \left.\frac{dn}{dt}\right|3 - P_{fw}$$

NOTE Excitation should be provided by a separate source according to 7.2.2.2.

7.2.5.5 Separation of additional and short-circuit losses

The sum of the I^2R loss and the additional loss in the armature circuit is determined as the difference of losses measured in the third and first test. Separation of this sum into components, if required, is done by subtracting from it the I^2R loss in the armature circuit calculated from the armature circuit resistance corresponding to the test temperature.

7.2.5.6 Measurement of losses in bearings

Losses in common bearings should be stated separately, whether or not such bearings are supplied with the machine.

The losses in bearings and thrust bearings shall be subtracted from the total sum of the mechanical losses. If the tested machine uses direct-flow cooling of the bearings, these losses are distributed between the tested machine and any other coupled to it mechanically, such as turbine, in proportion to the masses of their rotating parts. If there is no direct-flow cooling, the distribution of bearing losses shall be determined from empirical formulae.

7.3 Calorimetric method

7.3.1 General

The calorimetric method may be used to determine the efficiency of large electrical rotating machinery:

a) either by the determination of the total loss on load, or

b) by the determination of the segregated losses.

In the calorimetric method losses are determined from the product of the amount of coolant and its temperature rise, and the heat dissipated in the surrounding media.

Calorimetric losses of the machine consist of:

– losses inside the reference surface P_{irs},
– losses outside the reference surface P_{ers} (for example external bearings, excitation equipment, external motors for water-cooling pumps).

The loss inside the reference surface P_{irs} is determined from:

$$P_{irs} = P_{irs,1} + P_{irs,2}$$

where:

$P_{irs,1}$ is the loss measured calorimetrically;

$P_{irs,2}$ is the loss dissipated through the “reference surface” by conduction, convection, radiation, leakage, etc.

The "reference surface" is a surface completely surrounding the machine such that all losses produced inside it (P_{irs}), and not measured calorimetrically, are dissipated through it to the outside (see Figure 2).

The excitation equipment may or may not be inside the reference surface. When outside the reference surface the excitation equipment losses should be determined separately either by measurement or by calculation.

NOTE $P_{irs,2}$ may be negative and therefore subtracted when heat from surrounding ambient flows into the reference surface.

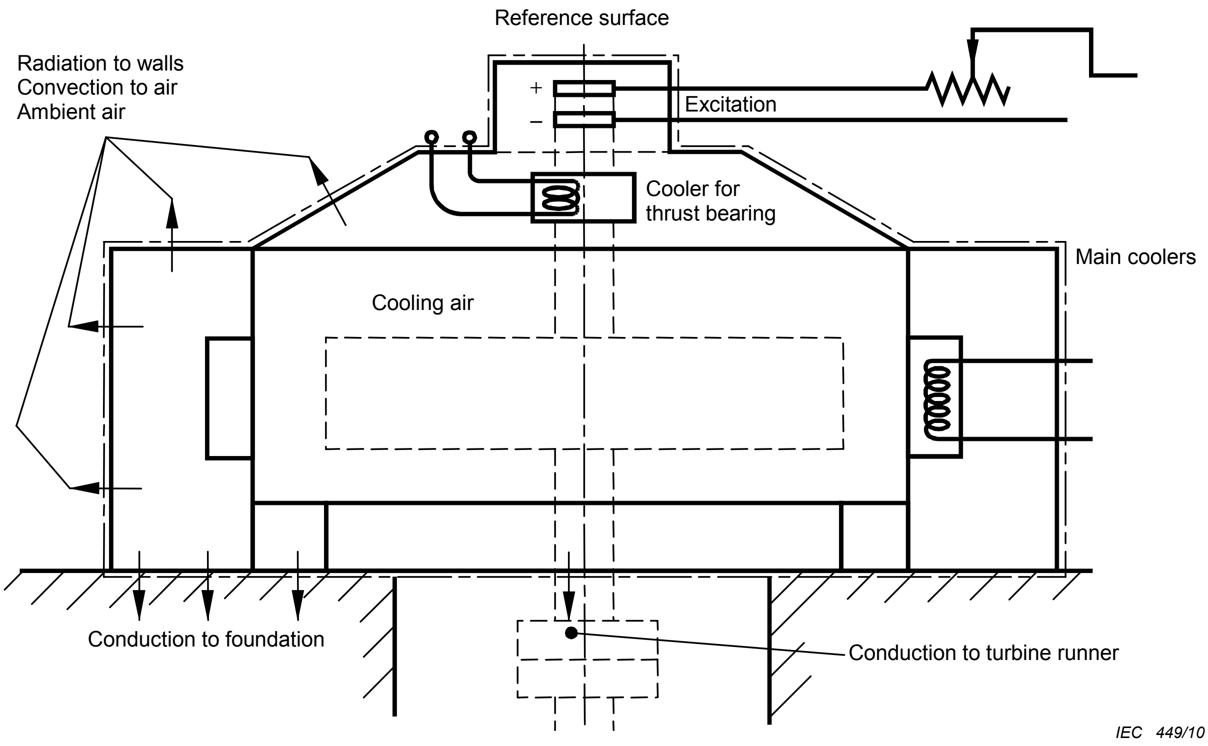

Figure 2 – Reference surface

7.3.2 Calorimetric instrumentation

7.3.2.1 Flowmeters

The volume rate of flow of fluids is best measured by volumetric or velocity type flowmeters. Other measuring methods with the same or greater accuracy may be used.

Install the flowmeters in accordance with manufacturer's instructions (straight sections up and downstream, position, etc.). It is recommended to control the flow of the cooling fluid by operating a valve placed downstream from the flowmeter.

Care should be taken that no air bubbles be present in the water.

The flowmeters shall be calibrated before and after the measurements in conditions similar to those prevailing during the test measurements.

In the case of volumetric measurements, the time shall be measured by means of an electrical timing device. The measuring time shall be at least 5 min during at least 2 intervals. The average values shall be recorded.

When measurement is made with a direct-reading flowmeter, 20 readings shall be recorded and an average value determined.

Provisions shall be made to measure both water pressure and temperature at the flowmeter.

7.3.2.2 Thermal detectors

Thermal measurements shall be made preferably by platinum resistance temperature detectors placed directly in the liquid coolant, and positioned in-line with each other so as to obtain direct readings for determination of the temperature rise of the liquid coolant (water, oil).

NOTE Thermocouples are permitted, but their improper use could increase the uncertainty. Thermal detectors placed in oil-filled thermometric pockets are also permitted but add additional uncertainty.

The thermal instruments shall be calibrated before and after the tests.

Recording instruments shall be used.

Where possible, water pipes should be insulated from the reference surface and well behind the measuring point to avoid heat transfer to the outside.

Equalizing baffle shall be installed in order to obtain homogeneous flow.

7.3.2.3 Coolers

Calorimetric measurements should be performed separately on every cooling circuit. With a single-medium coolant, one or more calorimeters are needed for the bearing oil, and one calorimeter for the cooling water of air- or gas-coolers. The use of two primary coolants, for example, hydrogen and pure water, requires one or several calorimeters depending upon the connection of the coolers and the scope of measurement.

Figure 3 shows four gas-to-water coolers connected in parallel.

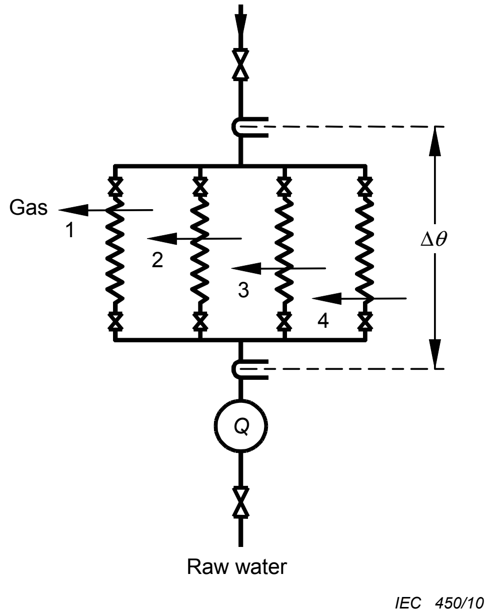

Figure 3 – Four coolers connected in parallel, single calorimeter, single coolant

NOTE The result is independent of the distribution of water in the paralleled coolers, of the gas distribution, and of the distribution of losses in the partial gas flows 1 to 4.

Figure 4 shows a series connection of coolers for use with two-fluid cooling.

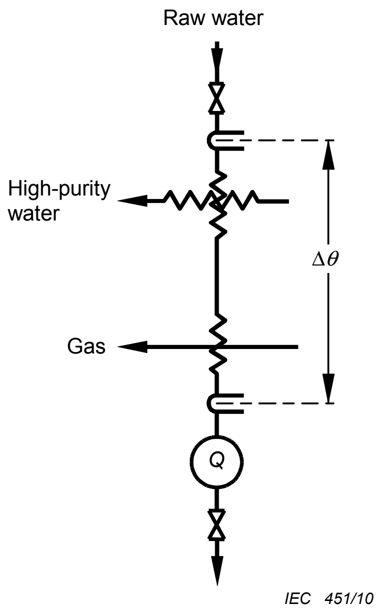

Figure 4 – Series connected coolers, two coolants

For both cases the total of the dissipated losses is determined from the measurement of the volume rate of flow of the cooling water Q, and by measuring the total temperature rise $\Delta\theta$.

7.3.2.4 Pipe layout and connections

It is advisable to establish the measuring paths for oil and water flow measurements, and the temperature measuring points, when planning the pipe layout, as additions or changes to the installation at a later date are not only costly but can also result in contamination of the bearing oil and high-purity water circuits.

Flowmeter installation shall allow for free pipe lengths between slide valve and flowmeter having the following minimum values as shown in Figure 5: The straight length of inlet piping between flowmeter and S1 is ≥ 10 times and between flowmeter and S2 is ≥ 5 times the nominal diameter of pipe.

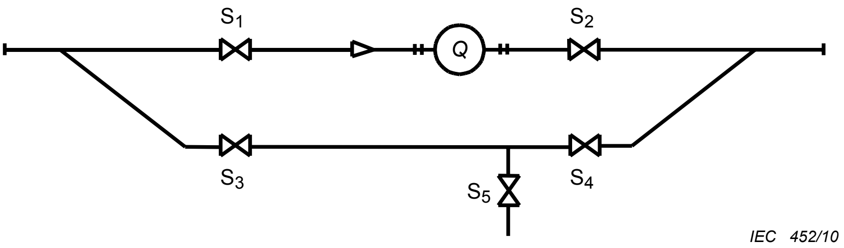

Figure 5 – Bypass piping

To permit flowmeter installation and removal without interrupting operation, a bypass piping arrangement, as shown in Figure 5, permits flowmeter isolation. A small valve S5 is required to verify that no cooling water bypasses the flowmeter (Q), i.e. that the slide valves S3 and S4 are tightly closed.

To obtain an easily measurable temperature, a valve placed downstream from the flowmeter should be used to control the flow of water.

When the temperature rise of the cooling medium is either too small or it is not permissible to change the volume rate of flow (for example bearing oil), bypass calorimetry shall be used which makes possible a larger temperature difference $\Delta\theta$ for improved uncertainty. The parallel piping, with a throttling device, (as shown in Figure 6) permits measuring a fraction of the coolant flow.

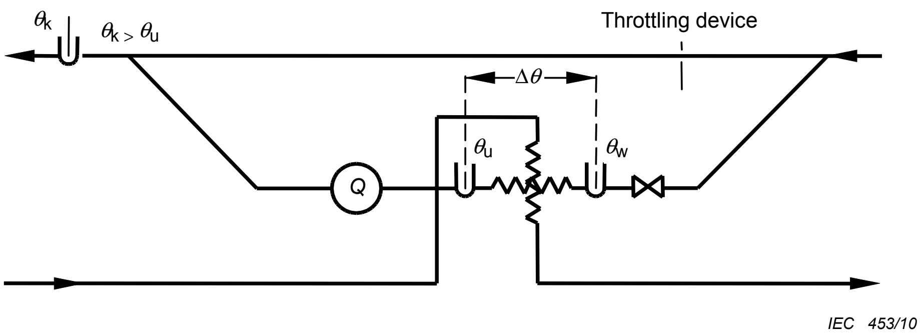

Figure 6 – Parallel piping

Key

Q Flowmeter

θ_w Temperature of hot coolant

θ_u Temperature to which the partial coolant flow within the bypass is cooled down

θ_k Mixed temperature of θ_u and θ_w

To improve measuring accuracy, the bearing and its cooling piping should be insulated, if possible.

7.3.3 Test procedure

The test machine shall be completely assembled as for normal operation.

During testing the test machine temperature and the coolant temperature shall be kept as close to normal operating conditions as possible.

Following assembly of the machine, determine the area of the reference surface. Divide the surface into 10 to 15 approximately equal area segments and attach thermal detectors to each segment. Install sufficient thermal detectors in the ambient air to determine the most accurate average temperature rise.

The calorimetric method may be used to determine the following losses:

a) Friction and windage loss (with rotor unexcited).

b) Active iron loss (at no-load usually at U_N and 1,05 U_N).

c) Stator-winding and additional-load losses (with stator-winding short-circuited usually at I_N and 0,7 I_N).

d) Total losses (usually between 0,5 and 1,0 load at rated and unity power-factor) for determination of efficiency.

When determining the efficiency by adding separate losses it is essential that the measurements should be made at the same cooling-medium temperature.

Operate the machine under the selected test condition until thermal equilibrium is maintained. With respect to coolant temperature thermal equilibrium is reached, when the temperature of the coolant does not vary by more than a gradient of 1 K per hour.

NOTE For guidance, the duration of the test will vary depending on the method of measuring the losses, and is likely to be 10 h to15 h for determination of losses at full load, and 15 h to 30 h for determination of losses at no-load.

Following temperature stability, record:

- Average flowmeter values for each calorimeter circuit: Q; p and θ .
- Temperature-rise values for each calorimeter circuit: θ_n and θ_{n+1} .
- Reference surface area.
- Average reference surface temperatures: $\theta_{rs.}$

7.3.4 Determination of losses

7.3.4.1 Test losses

Test losses of the machine consist of the losses inside the reference surface P_{irs} and the losses outside the reference surface P_{ers}, as defined in 7.3.1.

NOTE Losses in bearings inside the reference surface are included in the loss P_{irs}. If possible, they should be measured separately.

7.3.4.2 Coolant loss $P_{irs,1}$

For each operating condition, and when temperature stability has been achieved, the loss (in kW) dissipated by each coolant circuit is:

$$P_{irs,1} = c_p \cdot Q \cdot \rho \cdot \Delta\theta$$

where

Q is the volume rate of flow of the coolant, (m^3/s),

$\Delta\theta$ is the temperature rise ($\theta_{n+1} - \theta_n$) of the coolant in K from the total temperature rise $\Delta\theta$ (Figure 3),

c_p is the specific heat capacity of the cooling medium in kJ/(kg K) at pressure p,

ρ is the density of the coolant in kg/m^3 at the temperature at the point of flow measurement.

In case of water as a coolant both c_p and ρ are determined from Figure 7.

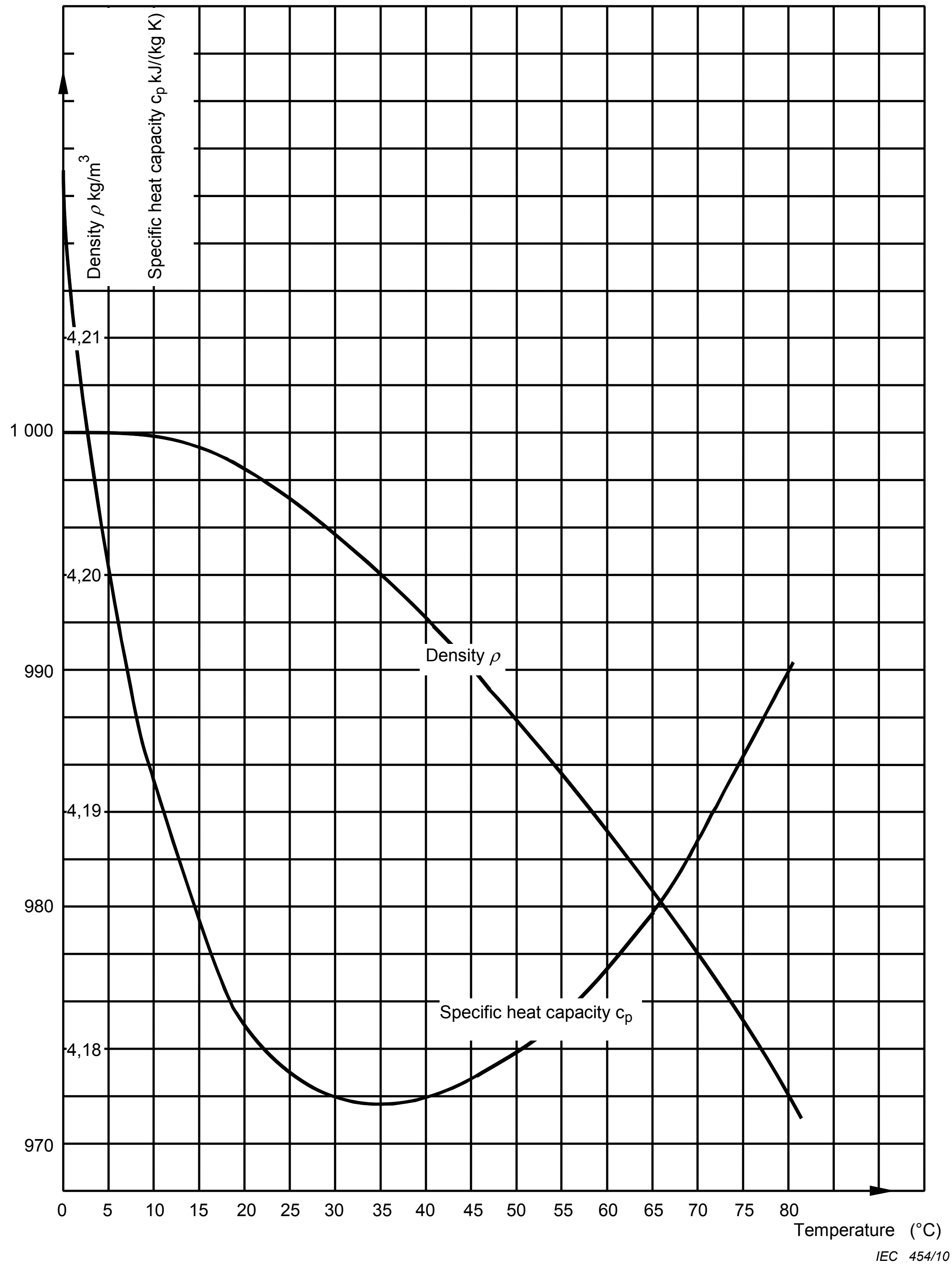

Figure 7 – Characteristics of pure water as a function of temperature

Where there is any doubt as to the accuracy of the factors employed for c_p and ρ, particularly if the cooling water contains salts, it will be necessary for c_p and ρ to be measured.

The temperature measurement includes the difference in temperature due to losses in the coolers and associated pipe-work between measuring points which is assumed to be 1 K for a pressure drop of 4,2 MN/m^2. The loss corresponding to the pressure drop shall be subtracted from the total losses.

NOTE Bearing losses could be measured using oil as a cooling medium, but there is less uncertainty when measuring on the water side of an oil-to-water heat exchanger because the thermal characteristics of water are better known.

7.3.4.3 Reference-surface loss $P_{irs,2}$

This loss constitutes a small part of the total losses and consists of:

– the losses, dissipated in the foundations and in the shaft by conduction; (usually negligible and very difficult to measure),

– the losses dissipated through the “reference surface” by conduction, convection, radiation, leakage, etc.

The $P_{irs,2}$ loss should be minimized by suitable insulation of the reference surface or portions of the machine. This procedure is suited to locations where it is difficult to suppress external air current or to maintain relatively constant ambient temperature conditions.

In practice, by conducting the tests in such a way that the loss $P_{irs,2}$ is less than 2,5 % of the loss P_{irs} measured at full load, and less than 5 % of the loss P_{irs} determined by the method of separate loss measurements, only the losses dissipated at the surface of the machine need to be taken into consideration. This loss $P_{irs,2}$ may be obtained from the formula:

NOTE $P_{irs,2}$ may be negative when heat flows into the reference surface and must in this case be subtracted.

$$P_{irs,2} = h \times A \times \Delta\theta$$

where:

$\Delta\theta$ is the temperature difference between the average reference surface temperature and the ambient-air temperature;

A is the area of the reference surface;

h is the heat transfer coefficient for losses dissipated from surfaces in contact with air as follows:

For forced-air convection:

– for external surfaces:

$$h = 11 + 3\,v \text{ [W/(m}^2\cdot\text{K)]},$$

where v is the velocity of ambient air in m/s,

– for surfaces entirely within the machine's external surface:

$$h = 5 + 3\,v \text{ [W/(m}^2\cdot\text{K)]},$$

where v is the velocity of cooling air in m/s.

For natural convection:

The loss dissipated by the surface is generally between 10 W and 20 W/(m^2 • K). A reasonable assumption being 15 W/(m^2 • K) when the air currents over the transfer surfaces have been eliminated.

7.3.4.4 External loss, P_{ers}

The loss P_{ers} (which is evaluated separately) consists mainly of the following:

– losses in the rheostat in the main excitation circuit, in voltage regulation, shunt and excitation circuits independent of the exciter,

– losses in the exciter and the slip-rings when their cooling circuits are independent of that of the main machine,

– losses by friction in the bearings, when they are wholly or partly outside the reference surface.