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Industrial electroheating equipment — Test methods for direct arc furnaces

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National foreword

This British Standard is the UK implementation of EN 60676:2012. It is identical to IEC 60676:2011. It supersedes BS EN 60676:2002 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/27, Electroheating.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Industrial electroheating equipment - Test methods for direct arc furnaces
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Chauffage électrique industriel - Méthodes d'essai des fours à arc direct (CEI 60676:2011)

Industrielle Elektrowärmeanlagen - Prüfverfahren für Lichtbogen-Schmelzöfen (IEC 60676:2011)

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European Committee for Electrotechnical Standardization
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Foreword

The text of document 27/816/FDIS, future edition 3 of IEC 60676, prepared by IEC/TC 27 "Industrial electroheating" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60676:2012.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2012-09-13
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2014-12-13

This document supersedes EN 60676:2002.

EN 60676:2012 includes the following significant technical changes with respect to EN 60676:2002:

– Clause 1 (*Scope and object*) – types of furnaces are more clearly defined.

– Clause 2 (*Normative references*) and Clause 3 (*Terms and definitions*) have been updated and completed.

– New Clause 4 (*Features of the EAFsystem*) has been added; it mainly concentrates on the tests necessary for high-voltage / high-current electrical equipment in the installation.

– Clause 5 (*Type of tests and general conditions of their performance*) and Clause 6 (*Technical tests*) have been modified according to today's requirements for safe operation of an EAF.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60676:2011 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

[2] IEC 60146-1-1:2009 NOTE Harmonized as EN 60146-1-1:2010 (not modified).

[3] IEC 60683:2011 NOTE Harmonized as EN 60683:2012 (not modified).

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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

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 60398	1999	Industrial electroheating installations - General test methods	EN 60398	1999
IEC 60519-1	-	Safety in electroheating installations - Part 1: General requirements	EN 60519-1	-
IEC 60519-4	-	Safety in electroheat installations - Part 4: Particular requirements for arc furnace installations	EN 60519-4	-

CONTENTS

INDUSTRIAL ELECTROHEATING EQUIPMENT – TEST METHODS FOR DIRECT ARC FURNACES

1 Scope and object

This International Standard specifies test procedures, conditions and methods according to which the main parameters and the main operational characteristics of electric arc furnaces (EAF) operated either with alternating current (EAFac) or with direct current (EAFdc) with a capacity above 500 kg/heat are established.

The EAF technology is also applicable to furnaces, in which liquid metal is kept at high temperature or superheated to casting temperature (e.g. in a ladle furnace (LF), operated with alternating current).

Test methods for some special equipment, e.g. controlled rectifiers for EAFdc, are covered by IEC 60146-1-1.

Test methods for submerged arc furnaces (SAF) are covered by IEC 60683.

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 60398:1999, *Industrial electroheating installations – General test methods*

IEC 60519-1, *Safety in electroheating installations – Part 1: General requirements*

IEC 60519-4, *Safety in electroheat installations – Part 4: Particular requirements for arc furnace installations*

3 Terms and definitions

For the purposes of this document the terms and definitions given in IEC 60519-1:2010 and the following apply.

NOTE Refer to International Electrotechnical Vocabulary, IEC 600500, for general definitions. Terms relating to industrial electroheat are defined in IEC 60050-841.

3.1
active power
P
mean value of the instantaneous power p (in kW) taken under periodic conditions over one period of time T (in h):

$$P = \frac{1}{T}\int_0^T p\,dt$$

NOTE Active power instantaneous value (r.m.s.) measured at any time, including all phases.

[IEC 60050-131:2002, 131-11-42, modified]

3.2
apparent power
S
power rating of the transformer, energizing the EAF (in MVA)

$$S = \sqrt{3}\, UI \qquad \text{(for three-phase EAF)}$$

where

U is the voltage, r.m.s., sinusoidal value [in kV]

I is the current, r.m.s. sinusoidal value [in KA]

[IEC 60050-131:2002, 131-11-41, modified]

3.3
arc furnace
furnace with a vessel, in which a metallic charge is heated mainly by electric arc using alternating current (EAFac) or direct current (EAFdc)

[IEC 60050-841:2004, 841-26-05, modified]

3.4
arc furnace transformer
transformer changing medium/high voltage electrical supply to low voltage and high current for an EAF

[IEC 60050-841:2004, 841-26-55, modified]

3.5
asymmetry factor
K
difference between maximum and minimum impedance of any phase, divided by the mean impedance of all three phases (in %)

NOTE Not applicable for EAFdc.

3.6
capacity (of EAF)
volume of liquid material, which can be produced in the EAF (in t)

NOTE Whether metric or short tonnes according to pre-requisites.

[IEC 60050-841:2004, 841-21-40, modified]

3.7
cold state (of EAF installation)
thermal state of EAF installation when the temperature of all parts equals the ambient temperature

3.8
electric arc furnace using alternating current
EAFac
furnace, in which electric arcs between the electrodes and the process material are formed, using three-phase alternating current

NOTE Ladle furnace (LF) is operated under the same conditions.

[IEC 60050-841:2004, 841-26-07, modified]

3.9
electric arc furnace using direct current
EAFdc
furnace, in which the direct current is induced via a bottom electrode (anode) to the material to be processed, forming arcs between the material and the electrode from top (cathode)

[IEC 60050-841:2004, 841-26-06, modified]

3.10
EAF electrode
part produced from high density graphite to transfer the electrical energy forming arcs between tip and charge material

NOTE In EAFdc, a bottom electrode (anode) is metallic or conductive material in the bottom of an EAF and arcs are formed between the charge material and the graphite electrode from top (cathode).

[IEC 60050-841:2004, 841-26-38, modified]

3.11
electrode clamp
metallic, water cooled equipment to hold the electrode and supply current for arcing to the electrode

[IEC 60050-841:2004, 841-26-39, modified]

3.12
heat
mass of liquid material which is tapped after one process from an EAF into a ladle (in t)

3.13
high-current line
assembly to conduct the high current between transformer secondary bushings and electrode(s) of an EAF

NOTE It consists of the bus bar system, cables and either a current tube system or current conducting electrode arm to the electrodes.

[IEC 60050-841:2004, 841-26-54, modified]

3.14
hot state (of EAF)
thermal state of an EAF in which the components and charge material are at a temperature above 600 °C and a steady-state temperature of the components is reached

3.15
medium/high-voltage switchgear
medium/high-voltage switchgear connecting the EAF transformer to the electrical supply by switching on/off under load

NOTE EAF circuit switchgear capable for up to 150 operations under load per day.

3.16
operational short circuit
short circuit due to direct contact of at least two electrodes in an EAFac with charge/liquid material

NOTE In EAFdc, short circuit is reached if the electrode from top is in contact with the charge/liquid material.

[IEC 60050-841:2004, 841-26-70, modified]

3.17
phase rotation
phase sequence of the electromagnetic field (counter clock wise seen from top of the furnace)

3.18
power factor
cos $\boldsymbol{\varphi}$
ratio of the active power to the apparent power measured on the primary side of the transformer

$$\cos \varphi = \frac{P}{S}$$

where

P is the active power [in MW]

S is the apparent power [in MVA]

NOTE In case of harmonics, power factor is determined according to IEC 60146-1-1.

3.19
power-on time (time p-on)
time (in min) between first arcing and tapping, in which the electrodes are under current

3.20
production rate
total quantity of metal (in t) tapped, divided by the tap-to-tap time (in h)

3.21
reactive power
$\boldsymbol{Q}$
total reactive electrical power (in MVAr) used in the system, measured on the primary side of the transformer

[IEC 60050-131:2002, 131-11-44, modified]

3.22
rectifier for direct current
device by means of which alternating current is transferred into direct current for EAFdc

3.23
reactor
reactor connected in series to the EAFac transformer to minimise impacts on the electrical supply created by the arcs and ensure arc stability during the process

3.24
shell
body of EAF made from steel and covered by a roof

[IEC 60050-841:2004, 841-26-20, modified]

3.25
smoothing choke (shunt reactor)
inductor smoothing electrical high frequency fluctuations in d.c. technology, due to changes in arc conditions

NOTE In case multiple rectifiers are coupled in the system, inductors can decrease the fluctuations as well.

3.26
specific electrical energy consumption
quotient of electrical energy consumed (in kWh) during melting and superheating of the metal (in t) tapped at a specified temperature

[IEC 60050-841:2004, 841-22-72, modified]

3.27
tap-to-tap time
t_{ttt}
time (in min) between end of tapping of previous heat and end of tapping of actual heat

4 Features of the EAF system

4.1 General

In the EAF ferrous metal (e.g. steel or liquid iron) or non-ferrous metal (e.g. copper, nickel or corundum etc.) can be produced. The EAF can be charged with solid or liquid material.

4.2 Electrical assembly of EAF

In the electrical assembly of an EAF the following equipment is included:

a) main circuit, i.e.:
   – medium/high voltage supply line including switchgear,
   – reactive power compensation (if applicable),
   – alternating current series reactor (if applicable),
   – EAF transformer,
   – high current bus bar system,
   – high current cables,
   – electrode arm system,
   – EAFdc: controlled rectifier and shunt reactor for direct current,
   – EAFac: three graphite electrodes from top,
   – EAFdc: specific electrode(s) in the bottom and graphite electrode(s) from top;
b) equipment to control all electrical parameters of the installation (i.e. boards, panels, desks, controls measuring and signalling devices etc.).

4.3 Furnace construction

The EAF consists of a vessel, covered by a roof, which can be opened for charging or maintenance.

The EAF is constructed from steel according to its nominal capacity. The bottom is lined with refractory to hold the liquid metal and slag. The side walls above the bottom are either lined with refractory or issued with water cooled side wall panels. The roof is either totally refractory clad or water cooled with a refractory centre piece around the electrodes.

The EAF capacity: according to the free volume of the furnace bottom and the specific density of the respective material to be molten in the EAF. The vessel: in horizontal position, metal surface below defined sill line, which allows the minimum amount of slag on top of the liquid material. Vessel lined according to design definitions.

NOTE Specific density of the respective material to be agreed upon between the supplier and user.

4.4 Water cooling

In specific cases electrical parts of the EAF shall be cooled by water.

NOTE In addition, cooling water is necessary to cool the vessel, roof and hydraulic system.

It shall be differentiated between the following cooling water circuits for the electrical equipment:

a) transformer, cooled by oil, which is indirectly cooled by water;
b) high current bus bar system including cables;
c) electrode arms;
d) semiconductor devices, cooled by special treated water, which is indirectly cooled by water.

5 Type of tests and general conditions of their performance

5.1 General

Tests shall be in accordance with the specifications given in IEC 60398.

During test procedures IEC 60519-1 and IEC 60519-4 shall be taken into account.

Tests shall be performed independently of the status of the SVC (Static Var Compensation) equipment.

Fluctuations in power supply should be minimal and symmetry of the three phases shall be maximized.

All measurement points are to be agreed upon between the supplier and user.

The type of measurement equipment as well as the layout and arrangement of the measurement points shall be shown in the test report.

5.2 List of tests during cold and hot state

The following tests with respect to the electrical equipment shall be conducted before the EAF is ready for operation and at regular intervals or following repair and modifications:

a) verification of electrical insulation of the high/medium voltage equipment and the high current lines (see 6.1.2),
b) cooling water system for transformer and high current system (see 6.2),
c) speed and motion of electrode system (see 6.3),
d) phase rotation test (see 6.7),
e) check of all safety devices and interlocks.

The following tests shall be made in hot state of the EAF:

f) short circuit during operation (see 6.4),
g) phase reactance symmetry (see 6.4.4),
h) specific electrical energy consumption (see 6.5),
i) specific production rate (see 6.5),
j) net power-on time (see 6.5.2),
k) power factor (see 6.5.2),

l) specific electrode consumption (see 6.6).

NOTE Additional tests are covered by commissioning and operation manuals issued by the supplier.

6 Technical tests

6.1 Electrical insulation of high-current system

6.1.1 General

Electrical insulation test shall be carried out on the EAF, empty in cold state without any cooling water in the system (water supply hoses disconnected) and electrodes in position.

EAFdc: transformer (controlled rectifier) and measurement systems on the secondary side shall be disconnected from the high current system.

6.1.2 Insulation resistance

Insulation shall be tested by means of a mega ohmmeter according to IEC 60398:1999, subclauses 7.1.2 and 7.1.3.

The tests shall be performed as follows:

– disconnect furnace transformer (EAFac) or rectifier (EAFdc) from the high current system,
– measure insulation between each phase and the EAF structure (earthed). The minimum value shall be 1 kΩ/V rated voltage.

The insulation test of the bottom electrode(s) shall be performed according to the commissioning or operation manual, issued by the supplier.

6.2 Cooling water system

Tests shall be carried out during normal production and EAF in hot state.

The following specific information of the cooling water is necessary in this respect:

– flow rate (in m^3/h),
– inlet and outlet pressure (in bar),
– maximum inlet and outlet temperature (in °C),
– quality (i.e. hardness, conductivity, etc.).

Cooling water composition, properties, pressure and inlet temperature shall be according to supplier’s recommendations.

Cooling water flow rate q (in m^3/h) shall be calculated according to the following formula:

$$q = \frac{Q_\mathrm{m}}{t} \qquad (1)$$

where

Q_m is the measured quantity of water [in m^3];
t is the time required for the test [in h].

6.3 Electrode motion speed

Electrode motion is measured using a stop watch for a defined distance in both directions (up and down). Each electrode arm issued with operational length of graphite electrode separately and in case of EAFac all three electrodes together.

NOTE Measurement is possible as well using an electric signal control.

6.4 Short-circuit test procedures

6.4.1 General

a) EAFac

Resistance [R] and reactance [X] of the high current system are determined by measuring the system current and voltage on the primary side of the transformer during short circuit. Values are converted to the high current system on the transformer secondary side according to transformer ratio and vector group.

For transformers with vector groups other than Dd0 (delta/delta without phase shift) the installation shall allow the measurement of the secondary currents with relevant instruments (i.e. Rogowski coils or current transformers).

b) EAFdc

Short circuit test shall be carried out to determine the rated and maximum current of the transformer and rectifier and to evaluate the losses of the high current system.

6.4.2 High current system: resistance and reactance of EAFac

Resistance (R) and reactance (X) values of the high current system are determined by means of a three phase short circuit condition (i.e. measurement of voltage and current in case three electrodes are dipped into the liquid metal at the same time) during normal operation with flat bath conditions (temperature above liquidus point).

Suitable alternative methods shall be agreed between the supplier and user in case the above-mentioned option is not possible due to certain preconditions.

6.4.3 Test procedures

Prior to tests, the EAF transformer shall be switched to suitable low tapping (reactor inserted, when installed) to ensure that the furnace current under the three-phase operational short circuit condition is as close as possible to the rated secondary current of the EAF transformer.

Tests shall be carried out under conditions close to rated current however avoiding damage at involved equipment (i.e. electrodes, transformer etc.).

Prior to the test, the three electrodes shall be adapted to the same length below the arm, to guarantee that the three arms are in the same position during the test. During the test the electrodes shall be dipped into the bath to reach a safe short circuit condition (stabilised fluctuation conditions and power factor reaches the short circuit value $<$ 0,25 inductive).

All tests shall be verified by a minimum of two tests. Impedance and asymmetry values are calculated for all tests and the arithmetic average value indicates the short circuit impedance.

Measurement on primary side

I_{1A}, I_{1B}, I_{1C}	U_{1A}, U_{1B}, U_{1C}	P_{1A}, P_{1B}, P_{1C}
	U_{1AB}, U_{1AC}, U_{1BC}	P_{1AB}, P_{1AC} P_{1BC}

Calculations of primary values

$$\sum P = P_{1A} + P_{1B} + P_{1C} \quad \text{or} \quad \sum P = P_{1AB} + P_{1BC} \quad \text{according to Figure 1} \tag{2}$$

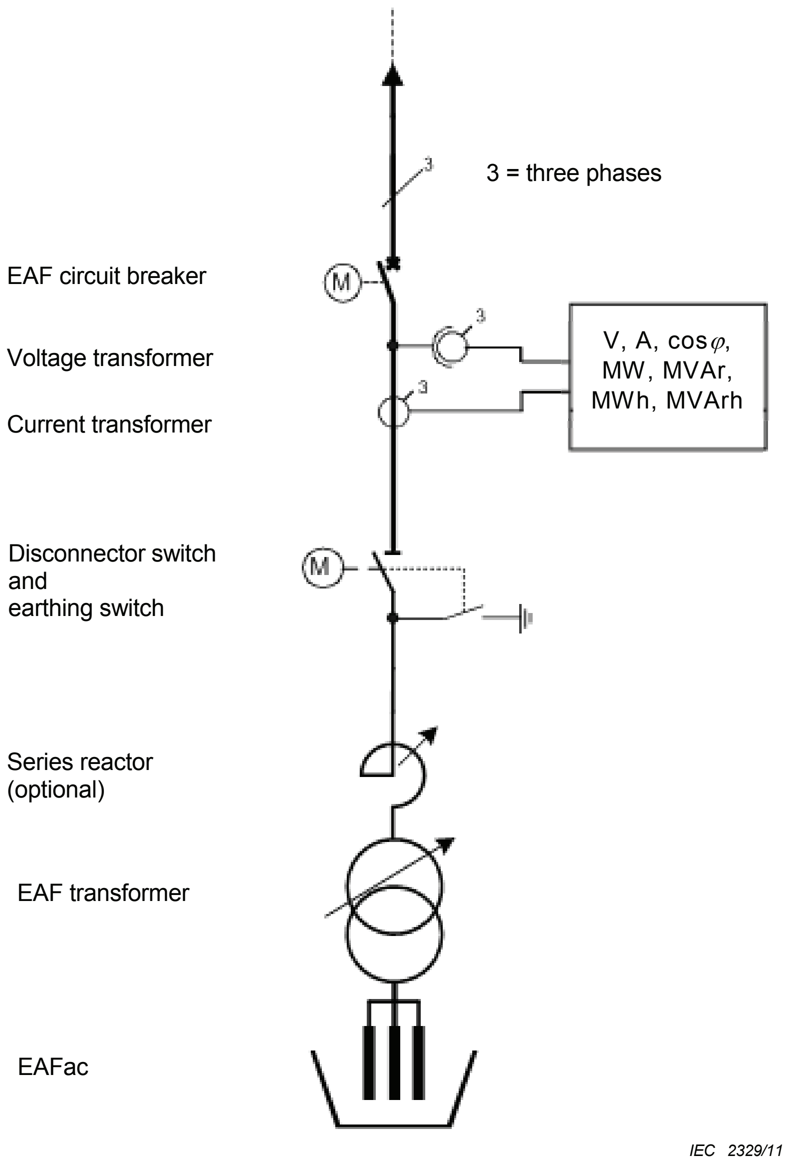

Figure 1 – Wiring diagram for measuring electrical data of the high current system to determine the resistance and reactance values

Short-circuit test electrode A and B dipped

$$R_{1AB} = \frac{4\sum P}{(I_{1A} + I_{1B})^2} \qquad Z_{1AB} = \frac{2U_{1AB}}{I_{1A} + I_{1B}} \qquad X_{1AB} = \sqrt{Z_{1AB}^2 - R_{1AB}^2} \tag{3}$$

Short-circuit test electrode B and C dipped

$$R_{1BC} = \frac{4\sum P}{(I_{1B} + I_{1C})^2} \qquad Z_{1BC} = \frac{2U_{1BC}}{I_{1B} + I_{1C}} \qquad X_{1BC} = \sqrt{Z_{1BC}^2 - R_{1BC}^2} \tag{4}$$

Short-circuit test electrode A and C dipped

$$R_{1AC} = \frac{4\sum P}{(I_{1A}+I_{1C})^2} \qquad Z_{1AC} = \frac{2U_{1AC}}{I_{1A}+I_{1C}} \qquad X_{1AC} = \sqrt{Z_{1AC}^2 - R_{1AC}^2} \tag{5}$$

NOTE 1 In case U_{1A}, U_{1B} and U_{1C} are measured instead of U_{1AB}, U_{1AC} and U_{1BC}, the phase-phase voltages can be calculated via the vector diagrams of the three single-phase short-circuit tests.

Common analyses for the three single-phase short-circuit tests:

$$R_{1A} = \frac{R_{1AB}+R_{1AC}-R_{1BC}}{2} \qquad R_{1B} = \frac{R_{1AB}+R_{1BC}-R_{1AC}}{2} \qquad R_{1C} = \frac{R_{1BC}+R_{1AC}-R_{1AB}}{2} \tag{6}$$

$$X_{1A} = \frac{X_{1AB}+X_{1AC}-X_{1BC}}{2} \qquad X_{1B} = \frac{X_{1AB}+X_{1BC}-X_{1AC}}{2} \qquad X_{1C} = \frac{X_{1BC}+X_{1AC}-X_{1AB}}{2} \tag{7}$$

$$Z_{1A} = \sqrt{R_{1A}^2 + X_{1A}^2} \qquad Z_{1B} = \sqrt{R_{1B}^2 + X_{1B}^2} \qquad Z_{1C} = \sqrt{R_{1C}^2 + X_{1C}^2} \tag{8}$$

EAF transformer voltage ratio, resistance and reactance

$$k_T = \frac{U_1}{U_2} \tag{9}$$

$$R_{T2A} \approx R_{T2B} \approx R_{T2C} \approx R_{2Tm} = \frac{P_{CuT}}{3\,I_{2T}^2} \tag{10}$$

$$X_{2TA} \approx X_{2TB} \approx X_{2TC} \approx X_{2Tm} = \sqrt{\left(\frac{U_{2T}^2 u_{kT}}{100 S_T}\right)^2 - R_{2Tm}^2} \tag{11}$$

High-current line (secondary voltage) for EAF transformers with vector group Dd0 or Yy0

$$R_A \approx \frac{R_{1A}}{k_T^2} - R_{2Tm} \qquad R_B \approx \frac{R_{1B}}{k_T^2} - R_{2Tm} \qquad R_C \approx \frac{R_{1C}}{k_T^2} - R_{2Tm} \tag{12}$$

$$X_A \approx \frac{X_{1A}}{k_T^2} - X_{2Tm} \qquad X_B \approx \frac{X_{1B}}{k_T^2} - X_{2Tm} \qquad X_C \approx \frac{X_{1C}}{k_T^2} - X_{2Tm} \tag{13}$$

$$Z_A = \sqrt{R_A^2 + X_A^2} \qquad Z_B = \sqrt{R_B^2 + X_B^2} \qquad Z_C = \sqrt{R_C^2 + X_C^2} \tag{14}$$

Analysis of three single-phase short-circuit tests for calculating mean values of impedance and reactance according to Figure 1.

$$R_{1,\text{mean}} = \frac{1}{3}\left(\frac{P_{1A}}{I_A^2} + \frac{P_{1B}}{I_B^2} + \frac{P_{1C}}{I_C^2}\right) \tag{15}$$

$$X_{1,\text{mean}} = \frac{1}{3}\left[\sqrt{\left(\frac{U_{1A}}{I_{1A}}\right)^2 - \left(\frac{P_{1A}}{I_{1A}^2}\right)^2} + \sqrt{\left(\frac{U_{1B}}{I_{1B}}\right)^2 - \left(\frac{P_{1B}}{I_{1B}^2}\right)^2} + \sqrt{\left(\frac{U_{1C}}{I_{1C}}\right)^2 - \left(\frac{P_{1C}}{I_{1C}^2}\right)^2}\right] \quad (16)$$

$$Z_{1,\text{mean}} = \sqrt{R_{1,\text{mean}}^2 + X_{1,\text{mean}}^2} \quad (17)$$

Analysis of three-phase short-circuit tests for calculating mean values of impedance and reactance

$$U_{1\,\text{phase-ground, mean}} = \frac{U_{1AB} + U_{1AC} + U_{1BC}}{3\sqrt{3}} \quad (18)$$

$$I_{1,\text{mean}} = \frac{I_{1A} + I_{1B} + I_{1C}}{3} \quad (19)$$

$$Z_{1,\text{mean}} = \frac{U_{1\text{phase-ground, mean}}}{I_{1,\text{mean}}} \qquad R_{1,\text{mean}} = \frac{P_{1AB} + P_{1BC}}{3 \cdot I_{1,\text{mean}}^2} \qquad X_{1,\text{mean}} = \sqrt{Z_{1,\text{mean}}^2 - R_{1,\text{mean}}^2} \quad (20)$$

In these formulae: test conditions: (1) primary side; (2) secondary side; (A, B, C) phases:

I_{1A}, I_{1B}, I_{1C} is the current per phase;
U_{1A}, U_{1B}, U_{1C} is the voltage per phase;
P_{1A}, P_{1B}, P_{1C} is the power per phase;
R_{1A}, R_{1B}, R_{1C} is the resistance per phase;
X_{1A}, X_{1B}, X_{1C} is the reactance per phase;
Z_{1A}, Z_{1B}, Z_{1C} is the impedance per phase;
k_T is the voltage ratio of the transformer for the tap of the test;
P_{CuT} is the transformer load losses at rated capacity;
I_{2T} is the rated secondary transformer current;
U_{2T} is the rated secondary transformer voltage;
S_T is the rated apparent power of the transformer;
u_{kT} is the rated percentage impedance voltage of the transformer;
R_{2TA}, R_{2TB}, R_{2TC} is the secondary phase resistances of the transformer;
R_{2Tm} is the mean secondary phase resistance of the transformer;
X_{2TA}, X_{2TB}, X_{2TC} is the secondary phase reactance of the transformer;
X_{2Tm} is the mean secondary phase reactance of the transformer;
R_A, R_B, R_C is the resistance per phase;
X_A, X_B, X_C is the reactance per phase;
Z_A, Z_B, Z_C Is the impedance per phase.

NOTE 2 Data concerning the EAF transformer may include the reactor. Special care is necessary in case the reactor is saturated during the test.

NOTE 3 In calculations of characteristics for taps other than those used in the short-circuit test, be aware of different values of the transformer reactance on each tap.

The adopted phase resistance/reactance of the high-current line is the arithmetic mean value of resistance / reactance determined during two or more tests.

6.4.4 Asymmetry factor

The asymmetry factor (K) (in %) is calculated on basis of the value per phase impedances Z_{1A}, Z_{1B}, Z_{1C} by the following formula:

$$K_{as-z} = \frac{Z_{max} - Z_{min}}{Z_m} 100 \quad (21)$$

where

Z_{max} is the maximum impedance per phase;

Z_{min} is the minimum impedance per phase;

Z_m is the arithmetic mean value of impedance of all three phases.

The impedances shall be measured during the short circuit test as close as possible to the rated secondary current, corresponding to the power rating of the transformer on the primary side. Resistance (R) values not to be considered due to large influences by the electrode dimensions and material.

NOTE Asymmetry (in %) can be derived by measuring the phase reactance (X) according to the following formula:

$$K_{as-x} = \frac{X_{max} - X_{min}}{X_m} 100 \quad (22)$$

where

X_{max} is the maximum reactance per phase;

X_{min} is the minimum reactance per phase;

X_m is the arithmetic mean value of reactance of all three phases.

The arithmetic mean value of minimum two measurements represents the test result.

6.5 Main characteristics of EAF during production

6.5.1 General

The following characteristics shall be measured and/or calculated:

- specific electrical energy consumption [in kWh/t],
- production rate [in t/h],
- power factor (in cos φ),
- power-on time [in min],
- tap-to-tap time [in min].

6.5.2 Test procedures

The tests shall be carried out during five consecutive heats under normal operation (fume extraction and cleaning systems, if any, in operation). The arithmetic mean value of each test value represents the test result.

Bulk density and main characteristics of the charge material shall be defined between the supplier and user.

The following values are measured and/or calculated:

a) Specific electrical energy consumption (in kWh/t): electrical energy consumed for the heat divided by the mass of liquid metal (in t) tapped at a specific temperature:

$$e_{\mathrm{p}} = \frac{E_{\mathrm{pt}} - E_0}{G} \tag{23}$$

where

E_{pt} is the energy reading following tapping [in kWh];

E_0 is the energy reading prior to test [in kWh];

G is the mass of liquid metal tapped [in t].

NOTE Since e_{p} is affected by the tapping temperature, power-off time, oxygen consumption etc., the correction for e_p should be according to a formula defined and agreed between the supplier and the user.

b) Specific production rate p (in t/h) during time t_{ttt}:

$$p = \frac{G}{t_{\mathrm{ttt}}} \tag{24}$$

where

G is the mass of liquid metal tapped [in t];

t_{ttt} is the tap-to-tap time [in h].

c) Power factor cos φ during agreed time of process steps:

$$\cos\varphi = \frac{E_{\mathrm{pt}} - E_0}{\sqrt{(E_{\mathrm{pt}} - E_0)^2 + (E_{\mathrm{Qt}} - E_{\mathrm{Q0}})^2}} \tag{25}$$

where

E_{Qt} is the energy reactive after test period [in kVArh];

E_{Q0} is the energy reactive prior to test [in kVArh].

NOTE Energy measurements are made by means of a suitable and verified three phase meter connected to the primary side of the transformer.

d) Power-on time: the time measured under which the electrodes are under current.

e) Tap-to-Tap time: operation time measured under specified conditions.

6.6 Electrode consumption

Electrode consumption per mass of liquid metal (in kg/t) is measured during five consecutive test heats. Electrode quality shall be defined and agreed between the supplier and user.

Any electrode breakage or unspecific losses during the test period shall be deducted.

$$g_{\mathrm{el}} = \frac{G_{\mathrm{el}}}{G} \tag{26}$$

where

g_{el} is the electrode consumption per mass of metal tapped [in kg/t];

G_{el} is the electrode consumption during test heats [in kg];

G is the mass of total tapped material during the test heats [t].

6.7 Phase rotation

Phase rotation shall be measured by a phase sequence meter on the secondary side of the transformer as close as possible to the electrodes. Phase rotation shall be anti clock wise.

Improper phase rotation loosens the electrode nippling and thus could initiate electrode breakage.

6.8 EAF – Rated capacity

Shell, refractory lined and in hot state. Charge material (metallic and additives) and proceedings (melt down, submerged arc heating, deslagging, tapping etc.) shall be according to supplier's recommendations. Reaching final temperature and composition the heat is tapped. The final mass of metal in the ladle shall reach at least the EAF rated capacity.

In case of an EAF using a bottom tapping system, a liquid heel inside the EAF shall be considered.

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