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IEEE Standard for Test Method for Energy Loss of Overhead Conductor

IEEE Power and Energy Society

Developed by the
Transmission and Distribution Committee

IEEE Std 2772™-2021

STANDARDS

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IEEE Power and Energy Society

Approved 25 March 2021

IEEE SA Standards Board

Abstract: A test method for energy loss of overhead conductors is defined and described in this standard.

Keywords: energy loss, IEEE 2772™, overhead conductor, test method

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When the IEEE SA Standards Board approved this standard on 25 March 2021, it had the following membership:

Introduction

This introduction is not part of IEEE Std 2772™-2021, IEEE Standard for Test Method for Energy Loss of Overhead Conductors.

This standard provides a test method to verify the energy loss of conductors under single laboratory conditions.

Contents

IEEE Standard for Test Method for Energy Loss of Overhead Conductor

1. Overview

1.1 Scope

This standard defines and describes a test method for energy loss of overhead conductors.

1.2 Purpose

This standard provides a basis for measuring the energy loss of overhead conductors under simulated actual conditions in laboratory. This standard provides technical support for reducing transmission loss and promotes technical progress of production enterprises.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).[1,2]

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).2

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

[1]The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.
[2]The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

ASTM B187/B187M, Standard Specification for Copper, Bus Bar, Rod, and Shapes and General Purpose Rod, Bar, and Shapes.

ASTM B236, Standard Specification for Aluminum Bars for Electrical Purposes (Bus Bars).

IEC 60060-1, High-voltage test techniques—Part 1: General definitions and test requirements.

IEC 61089, Round wire concentric lay overhead electrical stranded conductors.

IEC 61284, Overhead lines—Requirements and tests for fittings.

IEC 62219, Overhead electrical conductors—Formed wire, concentric lay, stranded conductors.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[3]

auxiliary test conductors: The connecting conductors at both terminals of the sample.

energy loss of conductors: Power loss per unit length of conductor (W/m) when a current passes under specific conditions.

non-stranded conductor: Conductor consisting of one or several parallel conductors that are non-stranded.

overhead conductor: Overhead conductor with air and insulator as insulation system, includes overhead bare wires and various types of bare busbars.

steady state temperature: The state under which the conductor temperature variation does not exceed 2 °C within 15 min, when test circuit is applied a constant current.

stranded conductor: Conductor consisting of a number of individual wires, all or some of which generally have a helical form.

4. Test equipment

Test equipment shall include current generator, horizontal tensile tester, and measuring devices of temperature, humidity, current, voltage, and power (or power factor).

Current generator and measuring devices of temperature, humidity, current, voltage, and power (power factor) can be integrated or separated.

The accuracy level of tension measurement of a horizontal tensile tester shall be no lower than class 1.0%.

The temperature measure meter shall employ thermal resistance or other suitable sensor, with a maximum permissible error not exceeding 0.5 °C.

Humidity shall be measured by using moisture sensitive resistance, moisture sensitive capacitor, or other suitable sensors with a maximum permissible error not exceeding ±5% relative humidity (RH).

[3] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.

AC current can be measured by a current transformer and ammeter with an accuracy level no lower than class 0.5.

DC current can be measured by a sensor and current test device with an accuracy level no lower than class 0.5

Voltage can be measured by a voltmeter with an accuracy level no lower than class 0.5.

Power factor can be measured by a power factor meter with an accuracy level no lower than class 0.5.

Power can be measured by a power meter with an accuracy level no lower than class 1.0.

5. Sample preparation

The customer shall confirm that incoming products are not used or processed until they have been inspected or otherwise verified as conforming to specified requirements.

If the sample is a stranded conductor, it shall comply with the requirements in accordance with IEC 61089 and IEC 62219. If the sample is a non-stranded conductor, it shall comply with the requirements in accordance with ASTM B187/B187M, ASTM B236, or the technical requirements provided by the customer.

Cut a conductor into two segments. One section will be used as a test sample, and the other section will be used as a standby test sample. The effective length of all test samples shall not be less than 100 times its diameter (or equivalent diameter) and shall not be less than 4 m.

The stranded conductor shall be equipped with the matching tensile clamps, which shall comply with the requirements in accordance with IEC 61284; the appropriate fittings shall be installed at both terminals of the non-stranded conductor and shall comply with the requirements in accordance with IEC 61284.

6. Test conditions

The test shall be carried out at an ambient temperature between 15 °C and 30 °C and an ambient humidity no greater than 80%. See Annex A.

All tests shall be carried out at ambient temperature unless otherwise stated in this standard.

The power quality of the test current shall comply with the requirements in accordance with IEC 60060-1.

The laboratory shall isolate current generators, transformers, and other equipment that may generate heat sources.

7. Test circuit layout

The layout test diagram of the stranded conductor energy loss is shown in Figure B.1. The tension clamps at both terminals are connected to the current generator through the auxiliary test conductor. The test auxiliary conductor shall use the annealed soft copper stranded wire of the equivalent section of the test sample. The wire is applied at both terminals of the sample to calculate the tension of 20% of the breaking force. During the test, the tension shall be stable.

The layout diagram of the non-stranded conductor energy consumption test is shown in Figure B.2. The auxiliary test conductor shall use the busbar of the equivalent section of the test sample.

The test circuit shall be arranged in a horizontal line into a test sphere, within 0.5 m from which the influence of magnetic sustenance is avoided. See Annex C. The test sphere layout is illustrated in Figure 1 and Figure 2.

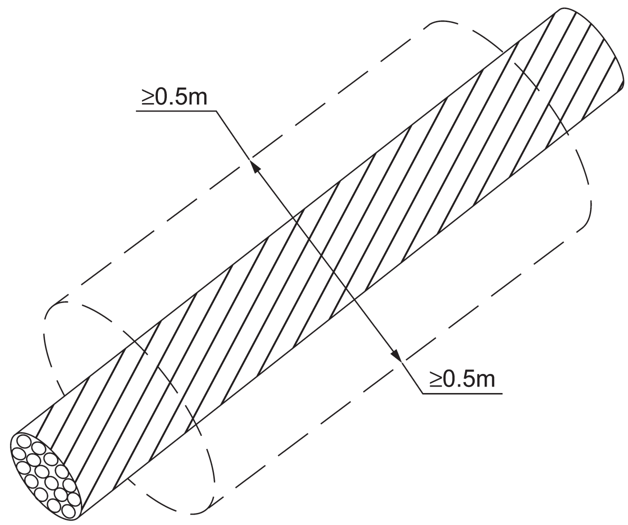


Figure 1—Stranded conductor layout of test sphere

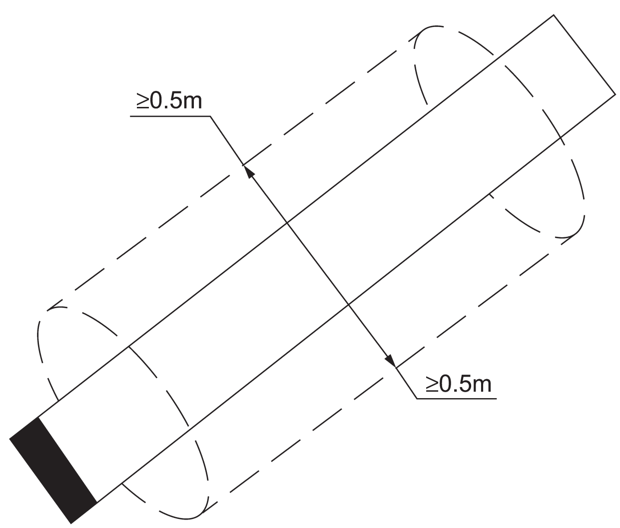


Figure 2—Non-standard conductor layout of test sphere

8. Test requirements

8.1 Temperature test

The temperature test shall be in accordance with the following:

a) Conductor temperature test: The conductor temperature measuring point is located at the midpoint of the conductor to be tested and 100 mm from the left and right sides of the midpoint. The temperature sensor shall be placed close to the conductor surface or placed inside the conductor. For the stranded conductor, the temperature sensor shall be placed in the outer strand of the wire and securely fixed; for non-stranded conductors, a small hole can be made on the surface, and the temperature sensor can be placed in the small hole and fixed tightly.

b) Ambient temperature test: The ambient temperature measurement point shall be no less than 1 m away from the conductor and at the same height as the conductor.

8.2 Current test

The current test shall be in accordance with the following:

a) AC current test: The current transformer selects the appropriate ratio. The sample is passed through the straight-through current transformer. The current meter is connected to the secondary side of the current transformer, and the test loop current value is obtained according to the current test device measurement reading and the transformer ratio.

b) DC current test: The current value of the test circuit is measured by a sensor and a current test device.

8.3 Potential measurement

At a distance of 500 mm from both terminals of the test sample, use a copper wire (diameter 0.8 mm ±0.2 mm) to tie 3~4 turns, or use another suitable clamp to make it in close contact with the conductor, and connect the voltmeter to the test circuit as shown in Figure B.1 and Figure B.2.

8.4 Power measurement

Power measurement can be divided into direct measurement and indirect measurement, as follows:

a) Direct measurement method. A power meter is employed to measure current, voltage, and power simultaneously.

b) Indirect measurement method. A power factor meter is employed to measure the power factor of the test circuit. The measured current, voltage, and power factor are multiplied to be the power value by means of following Equation (1).

$$P = UI\cos\phi \tag{1}$$

where

U is the measured voltage
I is the measured current
$\cos\varphi$ is the measured power factor. When measuring the dc test circuit, the power factor $\cos\varphi = 1$

The position of the voltage measuring point when measuring power (or power factor) is the same as in 8.3. The current is taken from the current measuring circuit of the current generating device.

9. Test procedure

Conduct the test procedure according to the following steps: distance measurement, heating process, constant temperature process, and cooling process. The conductor energy loss test shall be carried out three times; the cycling test flow diagram is shown in Figure 3.

9.1 Distance measurement

The test circuit is arranged according to the requirements of Clause 8, and the distance between the potential measurement points of the test piece is measured.

9.2 Heating process

When the conductor loading current is warmed up, it shall be in accordance with the following:

a) The value of current is applied to the test circuit, and the test current takes the current value at which the conductor is allowed to use the highest temperature or user specified temperature.

b) In order to shorten the test time, the initial applied current can be increased to accelerate the temperature rise, but it shall be not greater than 1.5 times of the test current value.

9.3 Constant temperature process

Monitor the conductor temperature variation to make sure it does not exceed 2 °C within 15 min.

When the sample temperature reaches a steady state, do the following:

a) For stranded conductors, keep the temperature constant for 30 min.

b) For non-stranded conductors, keep the temperature constant for 1 h.

c) During constant temperature, the time shall be re-timed when the measured temperature deviates from the set temperature by more than 2 °C.

d) Measure and record data every 5 min in the last 10 min of steady state. Average the values of three measurements to obtain the results.

9.4 Cooling process

The cooling process of the test shall be in accordance with the following:

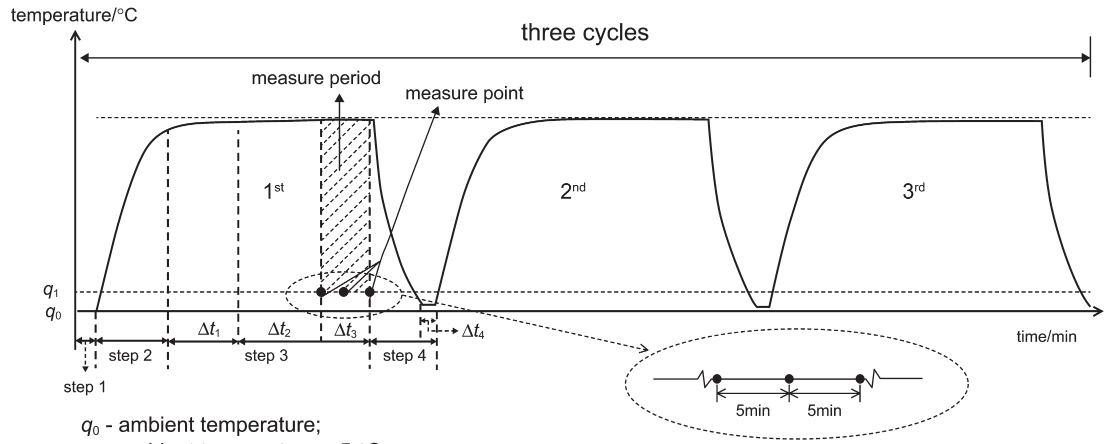
a) At the end of the constant temperature process, the current is shut off and the conductor is allowed to cool to within +5 °C ambient temperature.

b) Allow forced cooling. During the forced cooling of the conductor, the temperature of the entire conductor shall be uniformly cooled.

c) When the conductor temperature is cooled to within +5 °C of ambient temperature, cooling shall be stopped, and the conductor shall be allowed to stand at ambient temperature for not less than 5 min before another test is started.

9.5 Cycling test

The conductor energy loss test shall be carried out three times. The cycling test process is shown in Figure 3.



q_0 - ambient temperature;
q_1 - ambient temperature + 5 °C;
step 1 - distance measurement;
step 2 - heating process;
step 3 - constant temperature process, Δt_1 is 15 min to inspect the conductor temperature variation, Δt_2 is 30 min for stranded conductors to keep the temperature steady, or 1 h for non-stranded conductors to keep the temperature steady, Δt_3 is last 10 min to measure and record data;
step 4 - cooling process, $\Delta t_4$1 is not less than 5 min.

Figure 3—Flow diagram of conductor energy loss consumption test

10. Results and calculation

The calculation equation of energy loss of conductor is shown in Equation (2).

$$P_c = \frac{P}{l} \tag{2}$$

where

P_c is energy loss of conductor in W/m
P is the measured value of power in W
l is the distance between the potential measurement points in m

Average the results of three tests to determine the test report data.

The relative deviation of each test data from its average shall not exceed 5%; otherwise, the whole process shall be resampled and retested.

11. Report

The test report shall include conductor specifications/models, the laboratory ambient temperature (temperature and humidity), test current, current type (dc or ac), current frequency, voltage, power (or power factor), wire temperature, and wind speed.

Annex A

(informative)

Effects of air humidity on temperature distribution surrounding overhead lines

A.1 Thermodynamic properties of humidity

The amount of moisture in the atmosphere is always changing. Thermal parameters of humid air, e.g., density, heat capacity, thermal conductivity, dynamic viscosity, etc., are affected by the moisture content, thus affecting the heat conduction and convection process of overhead lines.

The specific humidity of air is defined as the mass of water vapor in 1°kg of dry air.

$$d = 622\frac{\varphi p_s(t)}{p_{ma} - \varphi p_s(t)} \tag{A.1}$$

where

d is the moisture content of air
φ is the percentage of relative humidity of air
t is the temperature of air in °C
$p_s(t)$ is the pressure of saturated vapor

The pressure of saturated vapor can be defined as:

$$p_s(t) = e^{7.23\times10^{-7}t^3 - 2.71\times10^{-4}t^2 + 7.2\times10^{-2}t + 6.42} \tag{A.2}$$

The density, specific heat capacity, thermal conductivity, and dynamic viscosity of the moisture in air can be defined by the following equations:

$$\rho_{ma} = \frac{p_{ma}(1 + 0.001d)}{R_{da}T(1 + 0.001606d)} \tag{A.3}$$

$$c_{p,ma} = \frac{c_{p,da}}{1 + d}\left(1 + d\frac{c_{p,v}}{c_{p,da}}\right) \tag{A.4}$$

$$\lambda_{ma} = \frac{\lambda_{da}}{1 + d\dfrac{M_{da}}{M_v}A_{da,v}} + \frac{d\lambda_v}{d + \dfrac{M_v}{M_{da}}A_{v,da}} \tag{A.5}$$

$$\mu_{ma} = \frac{M_{da}^{-1/2}\mu_{da} + dM_v^{-1/2}\mu_v}{M_{da}^{-1/2} + M_v^{-1/2}} \tag{A.6}$$

where

ρ_{da} is the density of dry air in kg/m^3
ρ_{ma} is the density of humid air in kg/m^3

$c_{p,da}$ is the thermal capacity of dry air in J/K
$c_{p,ma}$ is the thermal capacity of humid air in J/K
λ_{da} is the thermal conductivity of dry air in W/(m·K)
λ_{ma} is the thermal conductivity of humid air in W/(m K)
μ_{da} is the dynamic viscosity of dry air in Pa·s
μ_{ma} is the dynamic viscosity of humid air in Pa s

Equation (A.3) through Equation (A.6) indicate that the density, thermal conductivity, and dynamic viscosity of the moisture in air decreases with the increasing moisture content, but the thermal capacity increases. This effect is more pronounced at high temperatures.

A.2 Simulation model

The overhead line model for this simulation is LGJ 240/30, as shown in Figure A.1.

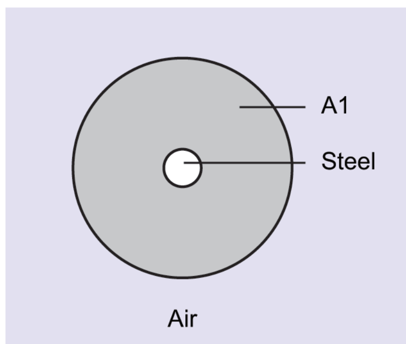


Figure A.1—LGJ 240/30 overhead line model

The main heat source of an overhead line is joule heating when the load current flows through the conductor, and the main heat transfer ways are conduction, convection, and radiation. The governing equations are as follows:

$$\rho(\vec{u}\cdot\nabla)\vec{u} = \nabla\cdot[-p\vec{I}+\mu(\nabla\vec{u}+(\nabla\vec{u})^T)-\frac{2}{3}\mu(\nabla\cdot\vec{u})\vec{I})]+\vec{F} \tag{A.7}$$

$$\nabla\cdot(\rho\vec{u}) = 0 \tag{A.8}$$

$$\rho C_p\vec{u}\cdot\nabla T = \nabla\cdot(k\nabla T)+Q \tag{A.9}$$

where

ρ is the density of the heat transfer medium, kg/m^3
u is the velocity field of air, m/s
p is the pressure of air, Pa
μ is the dynamic viscosity of air, Pa·s
F is the volume force vector, N
C_p is the heat capacity of the heat transfer medium, J/(kg·K)
T is the temperature, K
k is the thermal conductivity of the heat transfer medium, W/(m·K)

Q is the heat source, W/m^3

Equation (A.7) and Equation (A.8) are for the thermal convection process of air, and Equation (A.9) is for the heat conduction processes of the overhead line and air. In the air domain, the heat source is zero; in the overhead line domain, the air source is defined as:

$$Q = I^2 R / S \tag{A.10}$$

where

Q is the heat source, W/m^3
R is the ac line resistance of the overhead line, Ω/m
S is the sectional area of the conductor, m^2
I is the load current, which is set to 550 A in this standard

All the objects in nature with a temperature above absolute zero are always radiating heat, which can be described by Equation (A.11).

$$-\vec{n} \cdot (-k \nabla T) = \varepsilon\sigma({T_{amb}}^4 - T^4) \tag{A.11}$$

where

σ is the Avogadro Boltzmann constant
ε is the radiation ratio, which is set to 0.23 in this standard
T_{amb} is the ambient temperature, which is set to 40 °C in this standard

Table A.1 lists some basic thermodynamic properties of dry air, steel and aluminum, and the thermodynamic properties of the moisture in air can be calculated by Equation (A.1), Equation (A.2), Equation (A.3), Equation (A.4), Equation (A.5), and Equation (A.6).

Table A.1—Thermodynamic properties of dry air, steel, and aluminum

Material	Density kg/m^3	Capacity J/(kg·K)	Conductivity W/(m·K)	Viscosity Pa·s
Dry air	$\rho(p, T)$	$C_p(T)$	$\lambda(T)$	$\mu(T)$
Steel	7850	460	50	—
Aluminum	2700	880	121	—

where

$c_p(T)$ is $1047.63657 - 0.372589265 \times T + 9.45304214\text{e}-4 \times T^2 - 6.02409443\text{e}-7 \times T^3 + 1.2858961\text{e}-10 \times T^4$

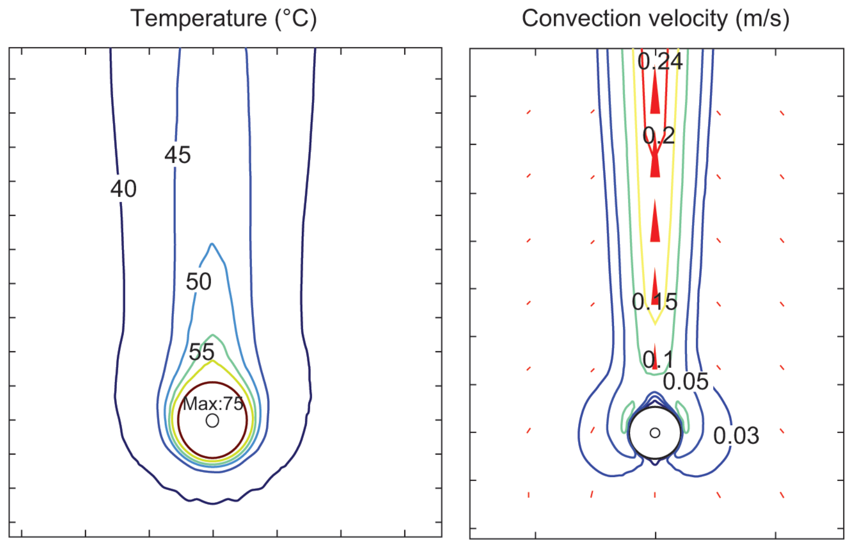
$\lambda(T)$ is $-0.00227583562 + 1.15480022\text{e}-4 \times T - 7.90252856\text{e}-8 \times T^2 + 4.11702505\text{e}-11 \times T^3 - 7.43864331\text{e}-15 \times T^4$

$\mu(T)$ is $-8.38278\text{e}-7 + 8.35717342\text{e}-8 \times T - 7.69429583\text{e}-11 \times T^2 + 4.6437266\text{e}-14 \times T^3 - 1.06585607\text{e}-17 \times T^4$

A.3 Simulation results

Figure A.2 shows the temperature distribution surrounding the overhead line and the convection velocity of air when the air humidity is 40%. The maximum temperature is located on the conductor surface, which is

~75 °C. Air surrounding and above the overhead line is heated in the vertical direction, whose temperature gradient is shown in Figure A.2(a). The air flow is also induced by the temperature distribution and the maximum convection velocity reaches 0.24 m/s, which is shown in Figure A.2(b). The air convection causes the isotherms to be intensive underneath the overhead line but sparse above it, building a high temperature region straight upward.



(a) Contour lines of temperature **(b) Contour lines of convection velocity**

Figure A.2—Temperature and convection velocity distributions

Figure A.3 shows the dynamic change of temperature on the conductor surface when the air humidity is 20%, 40%, 60%, and 80%, respectively. The temperature goes up gradually with time at first, then stabilizes slowly until the heat accumulation and dissipation process is balanced. When the air humidity is increased from 20% to 80%, the heat dissipation process is weakened, raising the surface temperature of the overhead line by ~8%.

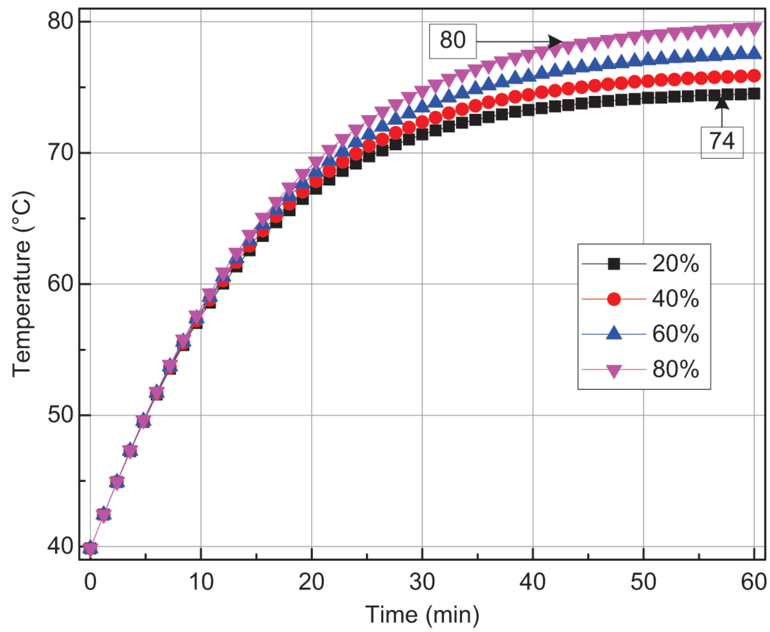


Figure A.3—Dynamic change of temperature on the conductor surface

The relative environment humidity less than 80% is conducive to the natural convection and heat dissipation on the conductor surface. Therefore, the requirement of relative humidity in IEC 60060-1 is also applicable to the energy loss test of the overhead conductor.

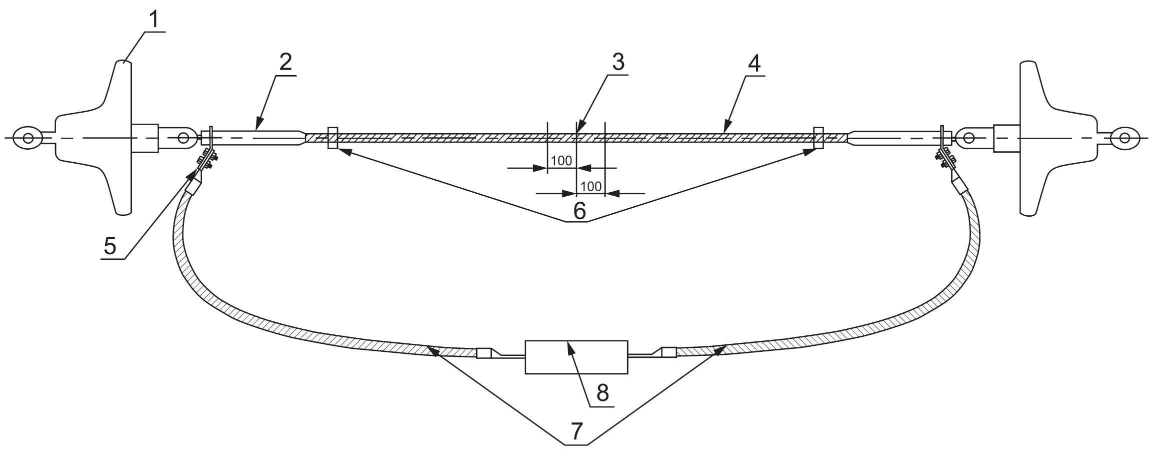
Annex B

(normative)

Test arrangement of conductor

B.1 Test arrangement of the stranded conductor

The test arrangement of the stranded conductor energy consumption is shown in Figure B.1.



1-Insulator

2-Tension clamp

3-Temperature measurement point

4-Stranded conductor

5-Clamp flow guide plate

6-Potential measurement point

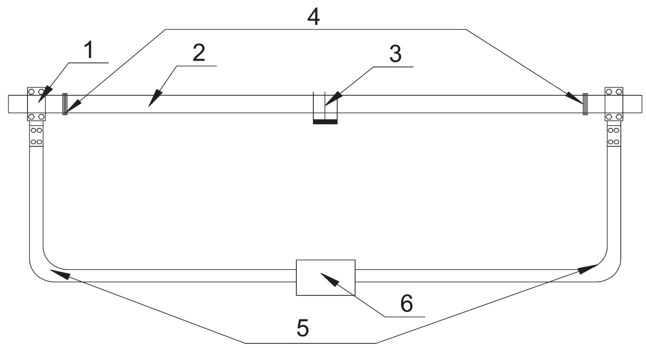
7-Auxiliary test conductor

8-Current generating device

Figure B.1—Schematic diagram of the energy consumption test of stranded conductors

B.2 Test arrangement of the non-stranded conductor

The test arrangement of the non-stranded conductor energy consumption is shown in Figure B.2.



1-Busbar fittings

2-Non-twisted conductors

3-Temperature measuring points

4-Potential measuring points

5-Test auxiliary conductors

6-Current generating device

Figure B.2—Schematic diagram of the energy consumption test of non-stranded conductors

Annex C

(informative)

Influence of surrounding magnetic substances on the result of conductor energy consumption test

The influence of the magnetic substance on the conductor energy consumption test results in the test area and the relationship between the influence and the distance are analyzed by simulation.

In the research, the Maxwell electromagnetic finite element analysis software was used to model and simulate the wire and surrounding magnetic substances in the energy consumption test, so as to obtain the magnetic field lines distribution and loss around the wire under the influence of the magnetic substance.

In the simulation, the diameter of the wire is set to 20 mm, and the length of the wire axis is set to 20 mm × 100 according to the energy consumption test requirements. For the surrounding magnetic materials, as shown in Figure C.1, in the energy consumption test, the surrounding magnetic materials are usually drainage copper bars and other auxiliary equipment. In this study, in order to reduce the calculation cost, the surrounding magnetic substance is equivalent to a cube with a side length of 100 mm. Figure C.2, Figure C.3, Figure C.4, Figure C.5, Figure C.6, and Figure C.7 show the distribution of magnetic field lines around the wire when the magnetic substance is at different distances from the wire.

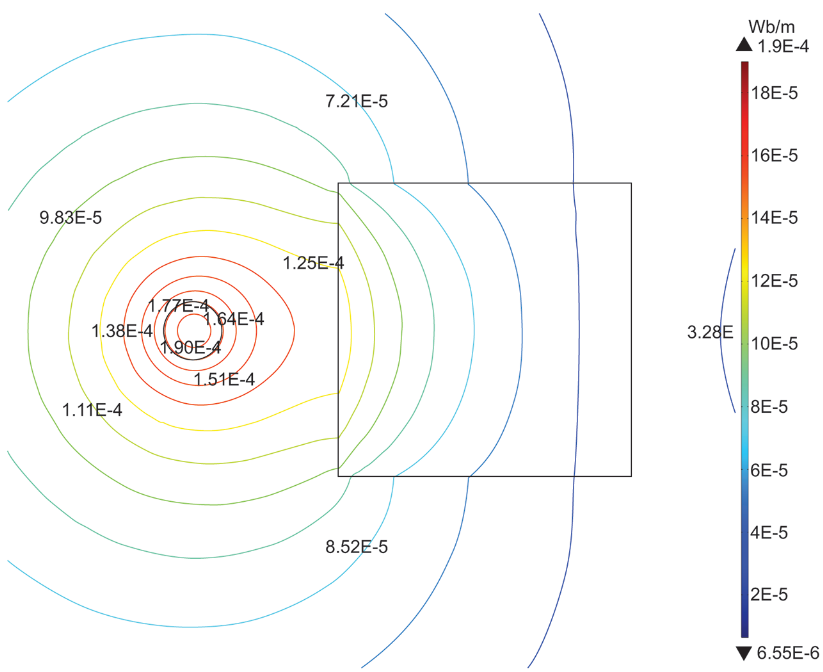


Figure C.1—Distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.1 m

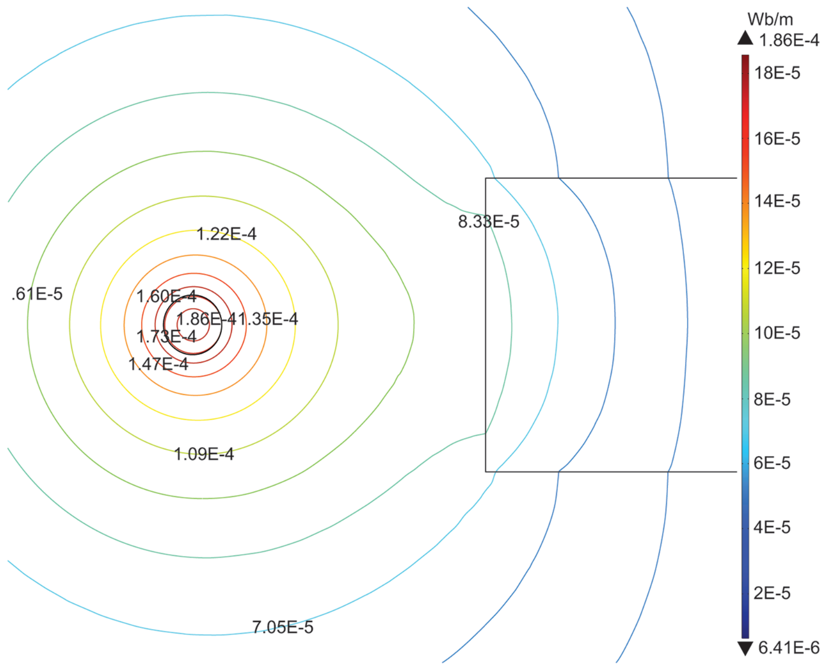


Figure C.2—Distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.15 m

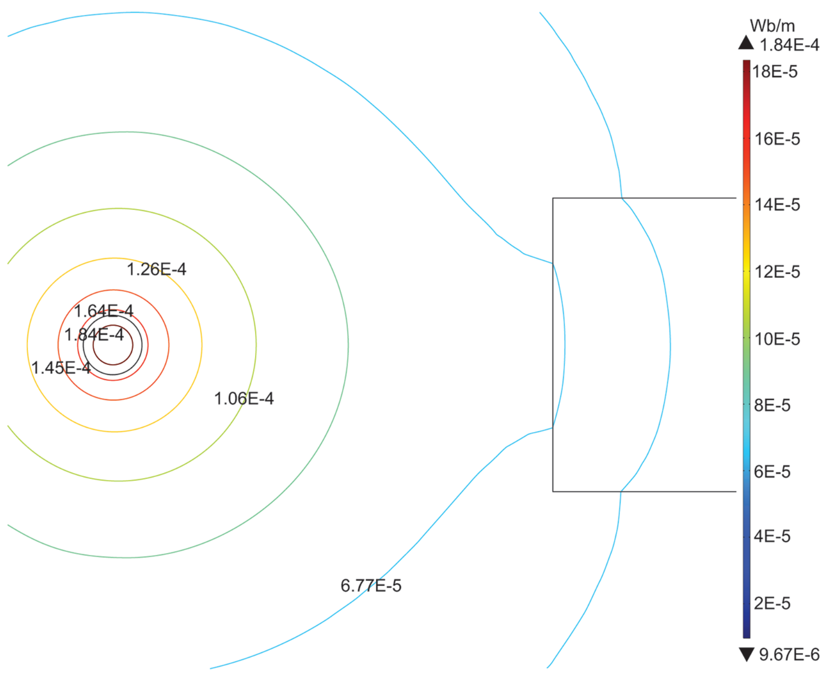


Figure C.3—The distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.2 m

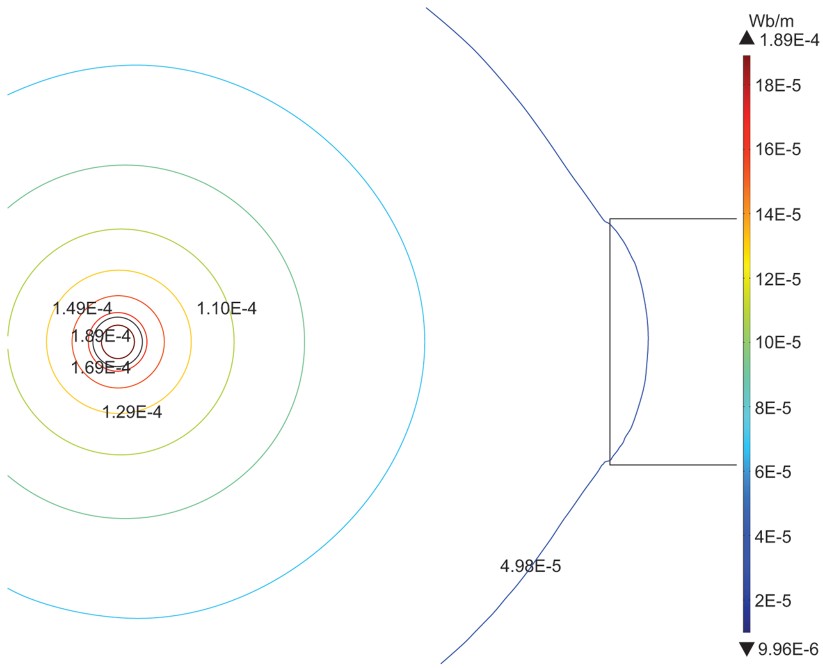


Figure C.4—The distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.25 m

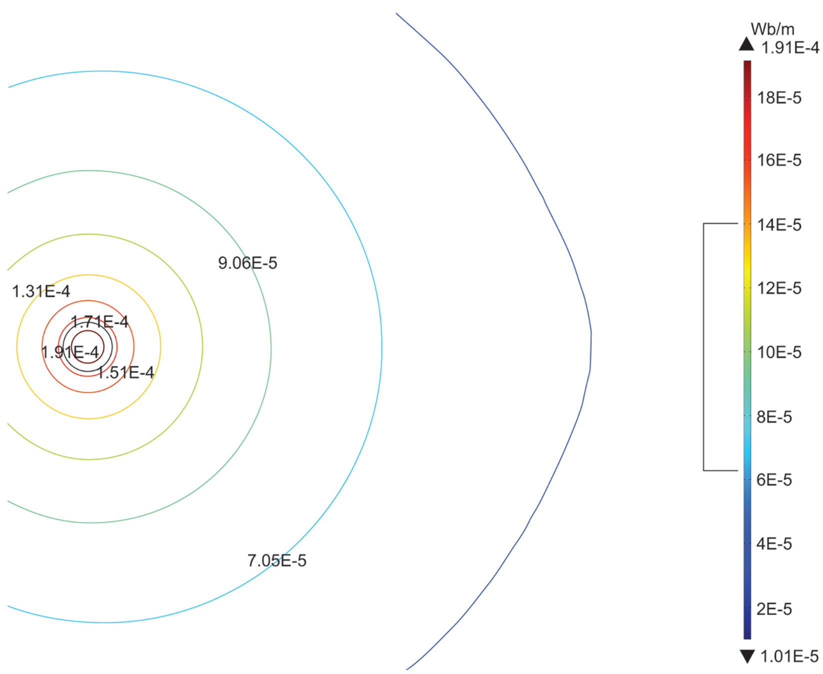


Figure C.5—Distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.3 m

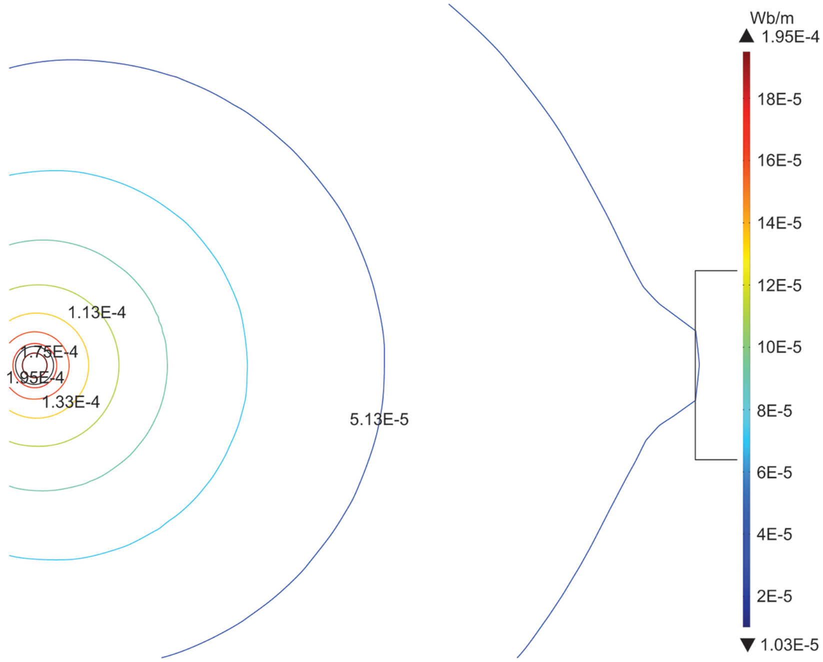


Figure C.6—Distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.4 m

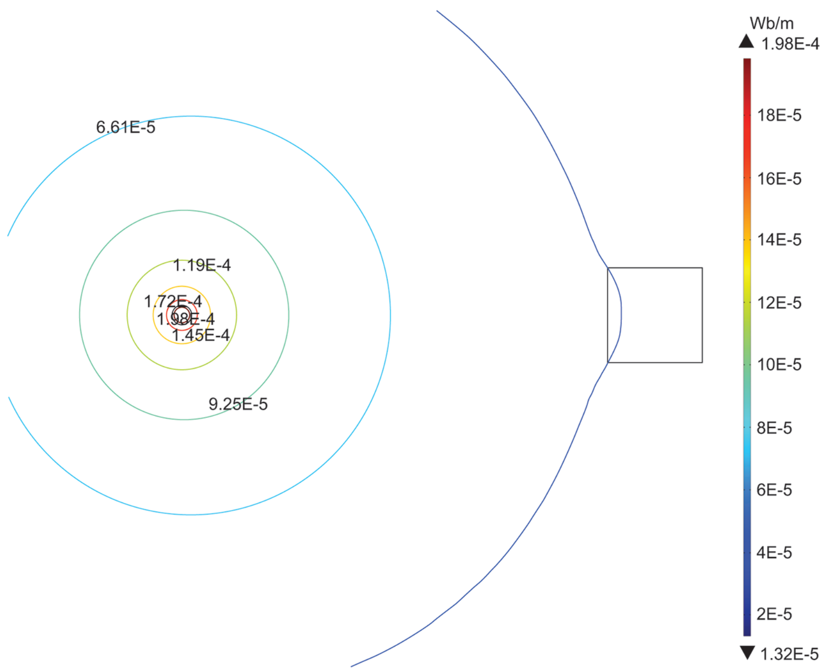


Figure C.7—Distribution of magnetic field lines when the distance between the magnetic object and the center of the wire is 0.5 m

In addition, through the finite element simulation software, the energy consumption at different distances between the magnetic object and the center of the wire is analyzed. The analysis results are shown in Table C.1.

Table C.1—The loss of magnetic objects at different distances from the center of the wire

Distance (m)	0.1	0.15	0.2	0.25	0.3	0.4	0.5
Energy consumption (W)	4.42	4.39	4.38	4.36	4.35	4.35	4.35

Based on the calculation results of finite element simulation analysis, we can obtain the following conclusions.

a) When conducting the energy consumption test, the surrounding magnetic substances will affect the distribution of the magnetic lines of force around the wire.

b) The influence of the surrounding magnetic substance on the energy consumption test result is inversely proportional to the distance of the surrounding magnetic substance from the wire.

c) For the research case (wire diameter 20 mm, equivalent magnetic object 100 mm × 100 mm), when the distance of the magnetic object from the wire exceeds 0.3 m, the impact on the magnetic field and energy consumption around the wire can be considered negligible.

In summary, it can be considered that within 0.5 m from the test area, other magnetic substances shall be avoided as much as possible to avoid affecting the test is reasonable.

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