BS EN 60076-16:2011

BSI Standards Publication

Power transformers

Part 16: Transformers for wind turbines applications

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National foreword

This British Standard is the UK implementation of EN 60076-16:2011. It is identical to IEC 60076-16:2011.

The UK participation in its preparation was entrusted to Technical Committee PEL/14, Power transformers.

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

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Foreword

The text of document 14/690/FDIS, future edition 1 of IEC 60076-16, prepared by IEC/TC 14 "Power transformers", was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60076-16:2011.

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Endorsement notice

The text of the International Standard IEC 60076-16:2011 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:

IEC 60071-1:2006	NOTE	Harmonized as EN 60071-1:2006 (not modified).
IEC 60071-2:1996	NOTE	Harmonized as EN 60071-2:1997 (not modified).
IEC 60137:2008	NOTE	Harmonized as EN 60137:2008 (not modified).
IEC 60270:2000	NOTE	Harmonized as EN 60270:2001 (not modified).
IEC 62271-100:2008	NOTE	Harmonized as EN 62271-100:2009 (not modified).
IEC 62271-202:2006	NOTE	Harmonized as EN 62271-202:2007 (not modified).

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

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 60076-1	2011	Power transformers - Part 1: General	EN 60076-1	2011
IEC 60076-2	2011	Power transformers - Part 2: Temperature rise for liquid-immersed transformers	EN 60076-2	2011
IEC 60076-3 + corr. December	2000 2000	Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air	EN 60076-3	2001
IEC 60076-5	2006	Power transformers - Part 5: Ability to withstand short circuit	EN 60076-5	2006
IEC 60076-7	2005	Power transformers - Part 7: Loading guide for oil-immersed power transformers	-	-
IEC 60076-8	1997	Power transformers - Part 8: Application guide	-	-
IEC 60076-11	2004	Power transformers - Part 11: Dry-type transformers	EN 60076-11	2004
IEC 60076-12	2008	Power transformers - Part 12: Loading guide for dry-type power transformers	-	-
IEC 60076-13	2006	Power transformers - Part 13: Self-protected liquid-filled transformers	EN 60076-13	2006
IEC 61100	-	Classification of insulating liquids according to fire point and net calorific value	EN 61100	-
IEC 61378-1	2011	Convertor transformers - Part 1: Transformers for industrial applications	EN 61378-1	2011
IEC 61378-3	2006	Convertor transformers - Part 3: Application guide	-	-
IEC 61400-1	2005	Wind turbines - Part 1: Design requirements	EN 61400-1	2005
ISO 12944	Series	Paints and varnishes - Corrosion protection of steel structures by protective paint systems	-	-

CONTENTS

INTRODUCTION

This part of IEC 60076 is intended to specify the additional requirements for the transformers for installation in wind turbine applications.

Wind turbines use generator step-up transformers to connect the turbines to a network. These transformers can be installed in the nacelle or in the tower or outside close to the wind turbine.

This standard covers transformers for wind turbine applications or wind farms where the constraints on transformers exceed the requirement of the present IEC 60076 series. The constraints are not often known or recognized by the transformer manufacturers, wind turbine manufacturers and operators and as a result the level of reliability of these transformers can be lower than those used for conventional applications.

The transformers for wind turbine applications are not included in the present list of IEC 60076 standard series.

The purpose of this standard is help to obtain the same level of reliability as transformers for more common applications.

This standard deals particularly with the effects of repeated high frequency transient over-voltages, electrical, environmental, thermal, loading, installation and maintenance conditions that are specific for wind turbines or wind farms.

On site measurements, investigations and observations in wind turbines have detected risks for some different kind of installations:

– repeated high frequency transient over or under voltages in the range of kHz;
– over and under frequency due to turbine control;
– values of over voltage;
– over voltage or under voltage coming from LV side;
– high level of transient over voltages due to switching;
– presence of partial discharge around the transformer;
– harmonic contents current and voltage;
– overloading under ambient conditions;
– fast transient overload;
– clearances not in compliance with the minimum prescribed;
– installation conditions and connections;
– restricted conditions of cooling;
– water droplets;
– humidity levels that exceed the maximum permissible values;
– salt and dust pollution and extreme climatic conditions;
– high levels of vibration;
– mechanical stresses.

Therefore it is necessary to take into account in the design of the transformer the constraints of this application, or to define some protective devices to protect the transformer. Additional or improved routine, type or special tests for these transformers have to be specified to be in compliance with the constraints on the network.

POWER TRANSFORMERS –

Part 16: Transformers for wind turbine applications

1 Scope

This part of IEC 60076 applies to dry-type and liquid-immersed transformers for rated power 100 kVA up to 10 000 kVA for wind turbine applications having a winding with highest voltage for equipment up to and including 36 kV and at least one winding operating at a voltage greater than 1,1 kV.

Transformers covered by this standard comply with the relevant requirements prescribed in the IEC 60076 standards.

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 60076-1:2011, *Power transformers – Part 1: General*

IEC 60076-2:2011, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60076-3:2000, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-5:2006, *Power transformers – Part 5: Ability to withstand short circuit*

IEC 60076-7:2005, *Power transformers – Part 7: Loading guide for oil-immersed power transformers*

IEC 60076-8:1997, *Power transformers – Application guide*

IEC 60076-11:2004, *Power transformers – Part 11: Dry-type transformers*

IEC 60076-12:2008, *Power transformers – Part 12: Loading guide for dry-type power transformers*

IEC 60076-13:2006, *Power transformers – Part 13: Self-protected liquid-filled transformers*

IEC 61100, *Classification of insulating liquids according to fire-point and net calorific value*

IEC 61378-1:2011, *Converter transformers – Part 1: Transformers for industrial applications*

IEC 61378-3:2006, *Converter transformers – Part 3: Application guide*

IEC 61400-1:2005, *Wind turbines – Part 1: Design requirements*

ISO 12944 (all parts), *Paints and varnishes – Corrosion protection of steel structures by protective paint systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
wind turbine transformer
generator step up transformer connecting the wind turbine to the power collection network of the wind farm

3.2
tower
part of the supporting structure of wind turbine on top of which the nacelle with generator and other equipments are located

3.3
nacelle
housing that contains the drive-train and other elements on top of a horizontal-axis wind turbine tower

4 Service conditions

4.1 Normal service conditions

Unless otherwise stated in this standard, the service conditions in IEC 60076-11 and IEC 60076-1 apply.

4.2 Altitude

IEC 60076 series applies.

4.3 Temperature of cooling air

The installation of transformers inside an enclosure without active cooling systems increases the transformer temperature.

The purchaser shall specify the maximum cooling air temperatures if they are different from those stated in IEC 60076-2.

The transformer shall be designed according to real ambient temperatures and installation real conditions as described by the purchaser at enquiry stage.

Clause A.1 provides considerations for transformers installed in a naturally ventilated area like at the rear of the nacelle or in a separate enclosure installed outside the tower and equipped with air inlet and outlet.

In case of transformer installed in the tower or in an enclosure where natural ventilation is not provided the formula in A.1 is not applicable. For transformers operating under these conditions, the effects of air inlet and outlet, cooling conditions, efficiency of air cooling and ventilation shall be considered.

The purchaser shall prescribe the air ambient temperature and air flow inside the tower at the enquiry stage. If no temperature or air flow is specified, an internal ambient temperature inside the tower of 10 K higher than external temperature shall be assumed and not limited air circulation around the transformers.

The effect of external direct solar radiation is not taken into account at the design stage. This can increase the temperature of transformers parts and therefore information should be given by purchaser at enquiry time.

4.4 Content of harmonic currents in the transformer

At the enquiry stage the purchaser shall specify the magnitude and frequency of all harmonic currents supplied to the transformer. The manufacturer shall take the losses caused by these harmonic currents into account in the transformer design to prevent that the winding and liquid temperature rises exceed the permissible limits.

A method to calculate the impact of the harmonic currents on the design of the transformer is given in A.2.

The transformer shall be designed to take into account the increased rating required due to the harmonic currents. The temperature rise test shall be carried out with the equivalent rated power due to the harmonics defined in A.2. The result of the test shall be in compliance with temperature limits guaranteed for the transformer and related to the transformer insulation thermal class.

4.5 Wave-shape of supply voltage

Within the prescribed value of U_m a transformer shall be capable of continuous service at full load without damage under conditions of 'overfluxing' where the ratio of voltage over frequency exceeds the corresponding ratio at rated voltage and rated frequency according to IEC 60076-1.

The wind turbine manufacturer shall state at enquiry stage the maximum ratio between the voltage and the frequency. The transformer manufacturer shall take into account this value in the design of the transformer.

The purchaser shall specify in the inquiry the magnitude and frequency of any harmonic voltages present in the supply. A method to calculate the impact of the voltage harmonics on the design of the transformer is given in A.3.

4.6 Transient over and under voltages

The risk of failures of a wind turbine transformer is higher due to the fact of repeated transient over and under voltages on each side on transformer.

Several solutions are available to increase the reliability of the transformer against these fast transient interactions:

– to evaluate the insulation level of the transformer and if necessary apply one or more of the following solutions. This can be done by modeling or measuring the system by high frequency resonance analysis. The resonance frequency test is a special test. The test method shall be agreed between manufacturer and purchaser. One method is described in A.4;
– to install standard protection technique such as surge arresters (HV, LV), or RC circuit or surge capacitor.

The choice of the lists 2 or 3 in Table 1 shall be the responsibility of the system engineer based on specific insulation co-ordination (IEC 60071-1 and -2) and risk assessment.

The list 3 covers transformers with increased ability to withstand repeated transient over voltages and increases the reliability of the transformer.

Table 1 – Insulation levels

Highest voltage for equipment U_m (rms) kV	Rated short duration separated source AC withstand voltage (RMS) kV	Rated lightning impulse withstand voltage (peak value) in kV	
		List 2	List 3
≤ 1,1	3	-	20
3,6	10	40	50
7,2	20	60	75
12	28	75	95
17,5	38	95	125
24	50	125	150
36	70	170	200

High frequency steep surges can be generated by switching operation on LV or HV side. These surges are transferred by cables to the terminals of the transformer. Transformers have different values of resonance frequency. See A.4.

If the high frequency steep surges generated by switching operation on LV and HV side coincide with the internal frequency of the winding, the result of these surges can resonate with the winding internal frequencies and cause higher electric stresses than the dielectric withstand strength of the windings

NOTE For U_m ≤ 1,1 kV a.c. withstand voltage should have higher value as 10 kV.

4.7 Humidity and salinity

An abnormal level of humidity and salinity can lead to failures of dry type transformers and problems on open type bushings of liquid-immersed transformers or dry type transformers in enclosures.

The standard pollution levels for open type bushing for liquid-immersed transformers are defined in IEC 60815 series. There are also simulated rain tests defined in IEC 60137.

According to IEC 60076-11, the relative humidity in the test chamber shall be maintained above 93 % for environmental class E2 transformers. Salinity shall be such as the conductivity of the water in E2 test shall be in the range of 0,5 to1,5 S/m.

If a dry type transformer shall operate under more severe conditions than corresponding to class E2 without a protective enclosure against humidity and salinity, the capability of the transformer design shall be demonstrated by the test according to class E3 described in 7.4.5 in this standard.

IEC 61400-1 states that relative humidity up to 95 % shall be taken into account as a normal environmental condition.

Higher values of humidity and salinity shall be given at enquiry stage.

4.8 Special electrical and environmental conditions around the transformer

IEC 60076-3 recommends general minimum clearances between transformer live parts and conductive parts of the wind turbine.

Any part of the wind turbine made of insulation material becomes conductive when moistened with rain water, salt water or other conductive liquids. Partial discharges in the surroundings of the transformer can decrease the dielectric strength of the air.

Therefore the clearances between these wind turbine parts and the live parts of the transformer shall not be less than the clearances recommended in IEC 60076-3.

The transformer manufacturer shall indicate the required minimum clearances on the outline drawing of the transformer and it is the responsibility of the purchaser to follow up that these requirements will be met.

4.9 Level of vibration

Vibrations of the structure where the transformer is to be installed shall be taken into account when designing the transformer and special consideration shall be given in the stress transferred to connection terminals.

The purchaser shall specify vibration spectrum at the enquiry stage. The procedure of vibration test if any should be agreed at enquiry stage between purchaser and manufacturer.

4.10 Provision for unusual service conditions for transformers for wind turbine applications

Provision for unusual service conditions are indicated in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers.

4.11 Transportation and storage conditions

Transportation and storage conditions are indicated in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers.

Storage conditions shall be included in maintenance and operation manuals and shall be taken into account by the purchaser.

4.12 Corrosion protection

Depending on the kind of the installation, the purchaser should choose a protection class defined in ISO 12944 or otherwise agreed between purchaser and manufacturer.

5 Electrical characteristics

5.1 Rated power

The rated power shall be in accordance with 5.1 of IEC 60076-1.

The rated power S_r of the transformer is based on the fundamental frequency of the voltage U_1 and of the current I_1. The rated power of a three phase transformer is therefore:

$$S_r = \sqrt{3} \times U_1 \times I_1$$

The temperature rise and the cooling requirements of the transformer shall be determined after allowance is made for any increased losses due to harmonics.

5.2 Highest voltage for equipment

The highest voltage for equipment shall be chosen in accordance with Clause 5 of IEC 60076-3:2000.

The wind turbine designer shall inform the transformer manufacturer of peak voltages, frequencies and durations of any transient and repeated over voltages (see also Table 1 of this standard).

Information about insulation coordination is described in IEC 60071-1 and IEC 60071-2.

5.3 Tappings

The requirements in Clause 5 of IEC 60076-1:2011 apply.

The preferred tapping range if any is either:

- +5 % to –5 % in steps of 2,5 %,

or

- +5 % to –5 % in steps of 5 %.

Tapping selection shall be made by means of off-circuit bolted links or an off-circuit tap changer.

5.4 Connection group

Unless otherwise specified by the purchaser, transformer connections shall be Dyn with clock hour figure 5 or 11 in accordance with Clause 7 of IEC 60076-1:2011.

5.5 Dimensioning of neutral terminal

The neutral terminal shall be capable of carrying full phase rated current unless otherwise specified by the purchaser.

5.6 Short circuit impedance

For general purpose the impedance voltage shall be in accordance with IEC 60076-5.

For auxiliary windings when the combined impedance voltage of the tertiary winding and the system result in short circuit current levels for which the transformer cannot feasibly or economically be designed to withstand, the manufacturer and the purchaser shall mutually agree on the maximum allowed over current. In this case, provision should be made by the purchaser to limit the over current to the maximum value determined by the manufacturer and stated on the rating plate.

5.7 Insulation levels for high voltage and low voltage windings

The selected insulation level for the high voltage and low voltage windings shall be in accordance with Table 1 of this standard.

5.8 Temperature rise guaranteed at rated conditions

The design of the transformer shall be in accordance with the operating conditions (harmonic contents, ambient temperature) stated by the purchaser at the enquiry stage.

The guaranteed temperature rise shall take into account the additional losses due to harmonics if specified, which increase eddy losses and stray losses in the windings and structural/frame parts.

If no harmonics are specified at the design stage but the actual real load current in service contains harmonics, the load on the transformer may need to be reduced to prevent the transformer temperature rises exceed the guaranteed limits.

Examples of calculations of the impact of harmonic currents are given in A.2.

5.9 Overload capability

The loading guides for liquid-immersed transformers in IEC 60076-7 and for dry type transformers in IEC 60076-12 shall apply.

5.10 Inrush current

Due to frequent energizing of the transformers during wind farm operation, transformers are frequently exposed to mechanical and thermal effects of inrush currents.

Frequency of energisation (number of energisation per year) shall be given at enquiry stage. Unless otherwise specified, switching is done on the HV (grid) side. The method of switching and synchronization shall be described in case of generator side energisation.

System inrush current limitations (maximum value, duration) shall be given at enquiry stage by the purchaser.

5.11 Ability to withstand short circuit

Transformers shall fulfill the requirements in IEC 60076-5. If the purchaser requires a test to demonstrate this fulfillment, this test shall be stated in the contract.

5.12 Operation with forced cooling

When additional cooling by means of fans or pumps is provided, the nominal power rating with and without forced cooling shall be subject to agreement between purchaser and manufacturer.

The rating plate shall indicate both the power rating without forced cooling and the maximum power rating with forced cooling.

NOTE In case of forced cooling, the back-to-back method to carry out the temperature rise test for the transformer is preferred and is subject to agreement between manufacturer and purchaser at enquiry stage. Temperatures measured by the back-to-back tests correspond more closely to those obtained in practice during normal operation.

6 Rating plate

See IEC 60076-1 and IEC 60076-11.

7 Tests

7.1 List and classification of tests (routine, type and special tests)

See IEC 60076-1 and IEC 60076-11.

7.2 Routine tests

Tests described in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers apply.

NOTE Impulse test for all transformers type and partial discharge tests for liquid-immersed transformers can be justified on each unit by agreement between purchaser and manufacturer at enquiry stage. See IEC 60076-13 for this kind of test cycle for partial discharge test on liquid-immersed transformers.

7.3 Type tests

Tests described in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers shall apply.

Partial discharge for liquid-immersed transformers less 72,5 kV are not defined in IEC 60076-3 and consequently test condition of IEC 60076-13 shall apply.

NOTE Chopped wave test can be a part of type testing by agreement between purchaser and manufacturer at enquiry stage.

7.4 Special tests

7.4.1 General

Special tests shall be defined at enquiry stage by the purchaser.

7.4.2 Chopped wave test

The extension of the lightning impulse test to include impulses chopped on the tail as a special test is recommended after agreement at enquiry stage.

The peak value of the chopped impulse shall be 110 % of the specified full wave impulse (BIL).

Clause 14 of IEC 60076-3:2000 shall apply.

7.4.3 Electrical resonance frequency test

The method is described in A.4.

7.4.4 Climatic tests

IEC 60076-11 shall apply for dry type transformers.

7.4.5 Environmental test E3

The transformer shall be placed in a test chamber in which temperature and humidity are kept under control.

The volume of the chamber shall be at least five times that of the rectangular box circumscribing the transformer. The clearances from any part of the transformer to walls, ceiling and spraying nozzles shall be not less than the smallest phase-to-phase clearance between live parts of the transformer (see IEC 60076-3) and not less than 150 mm according to 26.3.1 of IEC 60076-11:2004.

The temperature of the air in the test chamber shall be such as to ensure condensation on the transformer.

The humidity in the chamber shall be maintained above 95 %. This may be achieved by periodically or continuously atomizing a suitable amount of water.

The conductivity of the water shall be in the range of 3,6 S/m to 4 S/m.

The position of the mechanical atomizers shall be chosen in such a way that the transformer is not directly sprayed.

The transformer shall be kept in air having a relative humidity above 95 % for not less than 6 h, without being energized.

Within 5 min thereafter, the transformer shall be submitted to a test with induced voltage as follows:

a) transformers with windings intended for connection to a system which are solidly earthed or earthed through a low impedance shall be energised at a voltage of 1,1 times the rated voltage for a period of 15 min;
b) transformers with windings intended for connection to systems which are isolated or earthed through considerable impedance shall be submitted to a test with induced voltage for 3 successive periods of 5 min. During the test, each high voltage terminal in turn shall be connected to earth and a voltage of 1,1 times the rated voltage shall be applied between the other terminals and earth. The three-phase test can be replaced by single-phase tests with the two non-earthed phase terminals being interconnected.

Preferably the dielectric test should be performed in test chamber.

During the voltage application, no flash over shall occur, and visual inspection shall not show any serious tracking.

If no information in respect of test condition a) or b) is available, test b) should be performed.

7.4.6 Fire behavior test

IEC 60076-11 shall apply for dry type transformers.

Liquids for immersed transformers are described in IEC 61100.

Annex A
(informative)

Calculation method and tables

A.1 Cooling of transformer in a naturally ventilated room

A.1.1 Assumptions

The room is cooled by naturally air circulation therefore:

Q_{AF} is the heat dissipation by forced air circulation (kW)

$$Q_{AF} = 0 \quad \text{(A.1)}$$

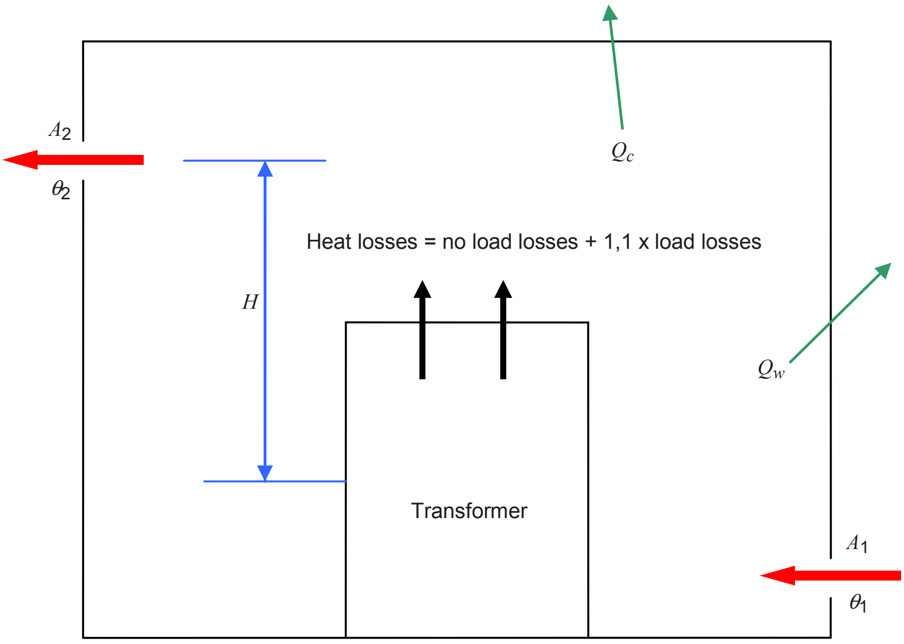
Q_C, Q_W are losses dissipated respectively through ceiling and the walls (kW)

$$Q_C = Q_W = 0 \quad \text{(A.2)}$$

In case of harmonics in load current special considerations shall be taken into account according A.2 or the transformer shall to be derated.

The heat dissipation through ceiling and the walls is generally low. This quantity is depending on the heat transfer coefficients of the materials of the walls and ceiling, the surface area of ceiling and the walls and difference between indoor and outdoor temperatures.

See following Figure A.1:



Key

A_1	Air inlet effective cross section (m^2)
A_2	Air outlet effective cross section (m^2)
θ_1 , θ_2	Air temperatures of inlet and outlet (°C)
H	Difference in height between mid outlet surface and mid height of transformer (m)
Q_c, Q_w	Losses dissipated respectively through ceiling and the walls (kW)

Figure A.1 – Heat dissipation in a natural ventilated room

A.1.2 Data for the calculation of ventilation

Transformer produces losses that are dissipated in the room. This subclause gives the calculation of these losses.

$\Delta\theta_a$ is the air temperature rise (K):

$$\Delta\theta_a = \theta_2 - \theta_1 \text{ approximate value = 15 K} \quad \text{(A.3)}$$

NLL is the transformer no load losses (kW);

LL are the transformer nominal load losses at reference temperature (kW);

HL are the transformer heat losses in the room (kW);

Heat losses = No load losses $+$ 1,1 $\times$ Load losses:

$$HL = NLL + 1{,}1 \times LL \text{ (kW)} \quad \text{(A.4)}$$

NOTE Value 15 K indicated above is common empirical value from the experience of the manufacturers.

A.1.3 Output

Losses produces by the transformers should be dissipated outside the room. This annex allows to give the surface of the air inlet.

A_1 is the air inlet effective cross section (m^2);

A_2 is the air outlet effective cross section (m^2):

$$A_2 \;/\; A_1 > 1{,}1 \text{ (minimum 10 \% more)} \quad \text{(A.5)}$$

Q_{tot} is the heat dissipation in the transformer's room (kW):

$$Q_{tot} = Q_{nac} + Q_{wc} + Q_{AF} \text{ (kW)} \quad \text{(A.6)}$$

Q_{nac} is the dissipation by natural air circulation (kW):

$$Q_{nac} = 0{,}1 \times A_1 \times \sqrt{H\,\Delta\theta_a{}^3} \text{ (kW)} \quad \text{(A.7)}$$

$\Delta\theta_a$ is the air temperature rise (K);

Q_{wc} is the heat dissipation through the walls and ceiling (kW):

$$Q_{wc} = Q_w + Q_c = 0 \text{ (see assumption)} \quad \text{(A.8)}$$

Q_{AF} is the heat dissipation by forced air circulation (kW);

$Q_{AF} = 0$ (see assumption).

To assure a good ventilation of the room:

$$HL = Q_{nac} + Q_{wc} \text{ (kW)} \quad \text{(A.9)}$$

The required air inlet section A_1 is then given by:

$$A_1 = \frac{HL}{0{,}1\sqrt{H\;\Delta\theta_a{}^3}} \text{ (m}^2\text{)} \quad \text{(A.10)}$$

Calculation of air outlet section A_2:

See formula (A.5).

A.1.4 Numerical application for a 1 000 kVA transformer

In this example, harmonics are not considered.

$$NLL = \quad 2{,}3 \text{ kW}$$

$$LL = \quad 11 \text{ kW}$$

The heat losses HL in the room are:

$$HL = NLL + 1{,}1 \times LL \quad = \quad 2{,}3 + 1{,}1 \times 11 = 14{,}4 \text{ kW}$$

$$H = \quad 4{,}6 \text{ m}$$

Finally it comes:

$$A_1 = \frac{14{,}4}{0{,}1 \times \sqrt{4{,}6 \times 15^3}} = 1{,}155 \text{ m}^2$$

The effective cross section of the air inlet shall be at least of 1,155 m^2 to assure a correct cooling of the transformer in its naturally ventilated room.

Calculation of air outlet section A_2:

$$A_2 \text{ minimum} = 1{,}1 \times 1{,}155 = 1{,}271 \text{ (m}^2\text{)}$$

The effect of transformer installed in a natural ventilated room is increasing temperature rises of the transformer by approximately half of air increased temperature between inlet and outlet (IEC 62271-202).

A.2 Determination of the power rating of a transformer loaded with non-sinusoidal currents

A.2.1 Transformer load losses

The transformer losses are of two types:

– direct losses (Ohmic losses) = $I^2 \times R$ (W); (A.10)

– additional losses υ are equal to eddy losses + stray losses.

The stray losses and eddy losses definitions are as in IEC 60076-8 and IEC 61378-1. Two frequencies method for separating stray losses and eddy losses by measurement is stated in IEC 61378-3.

A.2.2 Eddy losses (e_i)

Losses due to electromagnetic flux in the winding.

e_i are eddy losses per unit for considered winding.

A.2.3 Load losses (Ll)

Load losses (Ll) for a considered winding at the reference temperature.

$$Ll = R \times I^2 \times (1 + e_i) \text{ (W)} \qquad \text{(A.11)}$$

A.2.4 Stray losses (s_i)

Losses due to electromagnetic flux in clamps, cover, tank and other metallic parts.

A.2.5 Total load losses (Tl)

The transformer total load losses Tl are given by:

$$Tl = R_1 \times I_1^2 \times (1 + e_1) + R_2 \times I_2^2 \times (1 + e_2) + S_i \text{ (W)} \quad \text{(A.12)}$$

A.2.6 Harmonics

The losses of a transformer loaded with non sinusoidal currents depend on the frequency of each harmonic present in the current and its RMS value.

The total losses of the transformer at rated current change when the current contains harmonic content instead of a simple sinusoidal shape.

A transformer designed without special care concerning harmonic content of its current must be derated.

Harmonic components are represented by a periodic wave having a frequency that is an integral multiple of the fundamental frequency.

Harmonics are designated by their harmonic number or multiple of the fundamental frequency.

Harmonic with a frequency of 250 Hz is called the 5th harmonic (5 times the fundamental harmonic) with a fundamental frequency of 50 Hz for example.

Harmonics superimpose themselves on the fundamental wave form, distorting it and changing its magnitude.

Harmonic currents are generated when a non linear load is connected to the secondary of the transformer (examples: convertors, electronic equipment).

The problems caused by harmonic currents are: increased losses and overheating in the transformer, eddy losses are of most and stray losses are of the less concern when harmonic currents are present.

The eddy losses increase with the square of the frequency.

Due to these physical reasons (increased losses and overheating) the harmonic spectrum must be known before designing or sent to the transformer manufacturer to determine the ability to withstand such harmonics.

A.2.7 Eddy losses due to harmonic currents

A.2.7.1 RMS current calculation: I_{rms}

The root mean square (RMS) of current I_{rms} supplying a non sinusoidal load is:

$$I_{rms} = \sqrt{\sum_{h=1}^{h=n} I_h^2} \text{ (A)} \quad \text{(A.13)}$$

where

h is the current harmonic order;

I_h is the magnitude of the harmonic h (A).

A.2.7.2 Eddy losses calculation

The eddy current losses at a particular harmonic are given by:

$$P_h = P_f \times r_h^2 \times h^2 \quad \text{(W)} \tag{A.14}$$

where

P_f are the eddy losses at the fundamental frequency f with the RMS of rated current I_r (W);

P_h are the eddy losses at harmonic h (W);

r_h is the ratio of the magnitude of the current of harmonic of order h over the fundamental current:

$$r_h = \frac{I_h}{I_1} \tag{A.15}$$

The total eddy losses (P_{EL}) are given by the sum of the eddy losses for each individual harmonics.

$$P_{EL} = P_f \sum_{h=1}^{h=n} r_h^2 \times h^2 \quad \text{(W)} \tag{A.16}$$

A.2.7.3 Stray losses

The stray losses at a particular harmonic h vary according to 6.2 of IEC 61378-1:2011 and Annex A.

$$SL_{ih} = r_h^2 \times h^{0,8}$$

where

r_h is the ratio of the magnitude of the current of harmonic of order h over the fundamental current.

<u>Example:</u>

Harmonic h = 5

Magnitude = 25,8 %

$SL_{i5} = 0{,}258^2 \times 5^{0{,}8} = 0{,}241\,2$

A.2.8 Harmonic eddy loss factor: *K* factor

The K factor is the ratio between total eddy losses due to all harmonic currents referred to eddy losses at fundamental current I_1.

The eddy losses increase by K time its sinusoidal value when the transformer is loaded with non sinusoidal currents.

$$K \text{ factor} = \frac{P_{\mathrm{EL}}}{P_{\mathrm{f}}} \tag{A.17}$$

A.2.9 Transformer total losses Ttl s in service with non sinusoidal current

Ttl s = no load losses (Nll) + total load losses with non sinusoidal current (Lls)

$$Ttl\text{ s} = Nll + \left[\left(Ih_1^2 \times R_1 \times I_1^2\right) \times \left(k_1 \times \left(1 + e_1\right)\right)\right] + \left[\left(Ih_2^2 \times R_2 \times I_2^2\right) \times \left(k_2 \times \left(1 + e_2\right)\right)\right] + S_i \tag{A.18}$$

A.2.10 Top oil temperature rise with non sinusoidal currents TO_{i} for liquid-immersed transformers

See IEC 60076-7 for top oil temperature rise calculation:

$$TO_{\mathrm{i}} = TO_{\mathrm{rx}} (Ttl\text{ s} / Ttl)^{0,8} \tag{A.19}$$

where

TO_{i} is the top oil temperature rise with non sinusoidal currents;

TO_{r} is the top oil temperature rise at rated current.

A.2.11 De-rating of the transformer

De-rating of the transformer shall be approximately as follows:

SrE = permissible loading for the transformer:

$$SrE = Sr \times (Ttl / Ttl\text{ s})^{0,5} \tag{A.20}$$

Sr is the nominal load of the transformer (kVA).

The derating factor of transformer is $(Ttl / Ttl\text{ s})^{0,5}$.

A.2.12 Calculation examples of harmonic effects for liquid-immersed and dry type transformers

A.2.12.1 Equivalent currents due to harmonic contents

This example is for design purpose and to demonstrate the influence of the transformer design especially regarding the importance of quantity of the eddy losses. Eddy losses are depending on the design of the windings (dimension, raw material, impedance).

The magnitude of the harmonic is given according to IEC 61378 series to enhancement factors.

Two examples are given in the following Tables A.1 and A.2. Table A.1 is for a liquid-immersed transformer and Table A.2 is for a dry type transformer.

In the first table: RMS current is increased by 3,82 % above fundamental current, resulting in eddy losses increased by a K factor of 3,808 and stray losses by a factor of 1,308.

In the second table: RMS current is increased by 4,6 % above fundamental current, resulting in eddy losses increased by a K factor of 5,96 and stray losses by a factor of 1,41.

A.2.12.2 Example for a liquid-immersed transformer

A.2.12.2.1 Calculation of the permissible loading for the transformer

Table A.1 – Impact of harmonics content on liquid-immersed transformer losses

Harmonic order (h)	Magnitude (%)	I_h/I_1	$(I_h/I_1)^2$ enhancement factor	Eddy losses enhancement factor	Stray losses enhancement factor
1	100	1	1	1,000	1,000 0
5	25,8	0,258	0,066 56	1,664	0,241 2
7	8,3	0,083	0,006 89	0,338	0,032 7
11	5,2	0,052	0,002 70	0,327	0,018 4
13	3,3	0,033	0,001 09	0,184	0,008 5
17	1,5	0,015	0,000 23	0,065	0,002 2
19	1,4	0,014	0,000 20	0,071	0,002 1
23	0,9	0,009	0,000 08	0,043	0,001 0
25	0,8	0,008	0,000 06	0,040	0,000 8
29	0,7	0,007	0,000 05	0,041	0,000 7
31	0,6	0,006	0,000 04	0,035	0,000 6
		Σ	1,077 9	3,808	1,308

RMS current	**1,038 2**	
THD	**27,91 %**	THD is the total harmonic distortion rate (%)

THD according to IEC60076-1:2011,3.13.2

$$I_r^2 = \sqrt{\sum_{h=1}^{h=n} I_h^2}$$

$$I_r^2 = 1{,}077\ 9$$

$$K \quad \text{factor} = \frac{P_{\text{EL}}}{P_{\text{f}}} = 3{,}808$$

This calculation below is done with the coefficient calculated in Table A.1.

Rated power = 1 000 kVA

No load losses = 1 100 W

Load losses at 75 °C = 10 456 W

Frequency = 50 Hz

Rated top oil temperature rise = 60 K

Mean winding temperature rise = 65 K

Low voltage winding

Calculated losses at fundamental current

I^2R losses at 75 °C = 4 000 W

Eddy losses (4 %) = 160 W

Total losses at 75 °C = 4 000 + 160 = 4 160 W

LV winding gradient = 18 K

Stray losses = 320 W

Calculated losses in service with non sinusoidal currents

I^2R losses = 4 000 × (1,038 2)^2 = 4 312 W

Eddy losses = 160 × 3,808 = 609 W

Total LV winding losses = 4 312 + 609 = 4 921 W

Calculated LV winding gradient = 18 × (4 921/4 160)$^{0,5 \times 1,6}$ = 20,6 K

Total in service stray losses = 320 × 1,308 = 419 W

High voltage winding

Calculated losses at fundamental current

I^2R losses at 75 °C= 5 300 W

Eddy losses (12 %) = 636 W

Total losses at 75 °C = 5 300 + 636 = 5 936 W

HV winding gradient = 17 K

Stray losses = 40 W

Calculated losses in service with non sinusoidal currents

I^2R losses = 5 300 × (1,038 2)^2 = 5 710 W

Eddy losses = 636 × 3,808 = 2 421 W

Total HV winding losses = 5 710 + 2 421 = 8 131 W

Calculated HV winding gradient = 17 × (8 131/5 936)$^{0,5 \times 1,6}$ = 21,9 K

Total in service stray losses = 40 × 1,308 = 52 W

Transformer total losses (Ttl) at fundamental current

Ttl = no load losses (NLl) + total load losses (Ll)

Ttl = 1 100 + 4 000 + 160 + 320 + 5 300 + 636 + 40 = 11 556 W

Transformer Total losses Ttl s in service with non sinusoidal current

Ttl s = 1 100 + 4 312 + 609 + 419 + 5 710 + 2 421 + 52 = 14 623 W

pu increased top oil temperature rise with non sinusoidal currents

TOi / Tor = $(14\,623/11\,556)^{0,8}$ = 1,21 (+21 %)

Derating of the transformer shall be approximately:

Permissible loading for the transformer = Rated power × $(11\,556/14\,623)^{0,5}$

Permissible loading for the transformer = Rated power × 0,89

Derating of the transformer shall be approximately 11 %.

A.2.12.2.2 Conclusion

The 1 000 kVA transformer taken as an example is not appropriate for the service described and

- transformer shall be designed with reduced winding temperatures and top oil temperature rises,

or

- purchaser has to select a transformer with a higher rated power (e.g. 1 000/0,89 kVA),

or

- the transformer rated power is not adequate for such load profile and the user shall reduce transformer loading by a factor of 0,89.

NOTE In the case where the (ohmic and eddy) losses are known in both LV and HV windings, then the specific losses of the considered winding should be considered for an accuracy value of derating based on winding hot spot.

A.2.12.3 Example for a dry type transformer

A.2.12.3.1 Calculation of the permissible loading of the transformer

Table A.2 – Impact of harmonics content on dry type transformers losses

Harmonic order (h)	Magnitude (%)	I_h/I_1	$(I_h/I_1)^2$ enhancement factor	Eddy losses enhancement factor	Stray losses enhancement factor
1	100	1	1	1,000	1,000 0
5	26,2	0,262	0,068 64	1,716	0,248 8
7	11,0	0,110	0,012 10	0,593	0,057 4
11	8,1	0,081	0,006 56	0,794	0,044 7
13	5,8	0,058	0,003 36	0,569	0,026 2
17	4,2	0,042	0,001 76	0,510	0,017 0
19	2,6	0,026	0,000 68	0,244	0,007 1
23	1,9	0,019	0,000 36	0,191	0,004 4
25	1,6	0,016	0,000 26	0,160	0,003 4
29	1,2	0,012	0,000 14	0,121	0,002 1
31	0,8	0,008	0,000 06	0,062	0,001 0
		Σ	1,093 9	5,960	1,412
	RMS current	**1,046**			
	THD	**30,65 %**	THD is the total harmonic distortion rate (%)		

THD according to IEC 60076-1:2011, 3.13.2

Calculation of the equivalent current

$$I_r^2 = \sqrt{\sum_{h=1}^{h=n} I_h^{\,2}}$$

$$I_r^2 = 1{,}093\ 9$$

K factor = $\dfrac{P_{\mathrm{EL}}}{P_{\mathrm{f}}}$ = 5,960

Rated power = 1 000 kVA

No load losses = 2 300 W

Load losses at 120 °C = 11 000 W

Frequency = 50 Hz

Mean winding temperature rise = 100 K

Low voltage winding

Calculated losses at fundamental current

I^2R losses at 120 °C = 4 100 W

Eddy losses (2,9 %) = 120 W

Total losses at 120 °C = 4 100+120 = 4 220 W

LV winding gradient = 100 K

Stray losses = 320 W

Calculated losses in service with non sinusoidal currents

I^2R losses = 4 100 × (1,046)^2 = 4 485 W

Eddy losses = 120 × 5,959 = 715 W

Total LV winding losses = 4 485 + 715 = 5 200 W

Calculated LV winding gradient = 100 × (5 200 / 4 220)$^{0,5 \times 1,6}$ = 118,1 K

Total in service stray losses = 320 × 1,412 = 452 W

High voltage winding

Calculated losses at fundamental current

I^2R losses at 120 °C= 6 000 W

Eddy losses (7,5 %) = 450 W

Total losses at 120 °C = 6 000 + 450 = 6 450 W

HV winding gradient = 100 K

Calculated losses in service with non sinusoidal currents

I^2R losses = 6 000 × (1,046)^2 = 6 563 W

Eddy losses = 450 × 5,959 = 2 682 W

Total HV winding losses = 6 563 + 2 682 = 9 245 W

Calculated HV winding gradient = 100 × (9 245/6 450)$^{0,5 \times 1,6}$ = 133,4 K

Transformer total losses (Ttl) at fundamental current

Ttl = no load losses (Nll) + total load losses (Ll)

Ttl = 2 300 + 4 100 + 123 + 320 + 6 000 + 450 = 13 293 W

Transformer total losses Ttl s in service with non sinusoidal currents

Ttl s = 2 300 + 4 485 + 715 + 452 + 6 563 + 2 682 = 17 197 W

Derating of transformer shall be approximately:

Permissible loading for the transformer = Rated power × (13 293 /17 197)^{0,5}

Permissible loading for the transformer = Rated power × 0,88

Derating of transformer shall be approximately 12 %.

A.2.12.3.2 Conclusion

The 1 000 kVA transformer taken as example is not appropriate for the service described and

- transformer shall be designed with reduced winding temperatures,

or

- purchaser has to select a transformer with a higher rated power (eg 1 000/0,88 kVA),

or

- the transformer rated power is not adequate for such load profile and the user shall reduce transformer loading by a factor of 0,88.

A.3 Effects of voltage harmonics

The effect of this voltage distortion leads to an increasing of:

- magnetic flux density;
- no load losses;
- no load current;
- noise level;
- magnetic core temperature;

Bh: Flux density corresponding to harmonic h	(T)
Bn: Flux density at nominal voltage	(T)
Vh: Voltage harmonic components	(V)
V1: Rated voltage.	(V)

Table A.3 – Example of voltage harmonic order

Harmonic order (h)	Magnitude (%)	Vh/V1	(Vh/V1)²	Bh/Bn	(Bh/Bn)²
1	100	1	1	1	1
2	4	0,04	0,001 6	0,02	0,000 4
3	16	0,16	0,025 6	0,053 333	0,002 844 44
4	6	0,06	0,003 6	0,015	0,000 225
5	20	0,2	0,04	0,04	0,001 6
6	2	0,02	0,000 4	0,003 333	$1,1111 \times 10^{-5}$
7	11	0,11	0,012 1	0,015 714	0,000 246 94
8	2	0,02	0,000 4	0,002 5	0,000 006 25
9	5,8	0,058	0,003 36	0,006 444	$4,1531 \times 10^{-5}$
10	4,2	0,042	0,001 76	0,004 2	0,000 017 64
11	2,6	0,026	0,000 68	0,002 364	$5,5868 \times 10^{-6}$
13	1,9	0,019	0,000 36	0,001 462	$2,1361 \times 10^{-6}$
15	1,6	0,016	0,000 26	0,001 067	$1,1378 \times 10^{-6}$
29	1,2	0,012	0,000 14	0,000 414	$1,7122 \times 10^{-7}$
31	0,8	0,008	0,000 06	0,000 258	$6,6597 \times 10^{-8}$
		Σ	1,090 3		1,005 402 014

RMS voltage	**1,044**
THD (voltage)	**30,05 %**
RMS flux density	**1,003**
THD (flux density)	**7,35 %**

THD according to IEC60076-1:2011, 3.13.2.

RMS voltage is the square root of the sum of (Vh/V1)².

RMS flux density is the square root of the sum of (Bh/Bn)².

The consequences of this high voltage distortion (THD <5 % is considered being practically sinusoidal) are not high as flux density is much less distorted than voltage.

Magnetic flux density is time integral of voltage and thus each harmonic flux density component is inversely relative to the harmonic order. The increase in RMS flux value is close to zero, therefore no correction is needed for the measured no load losses in regard to voltage harmonics.

The following parameters are also related to the design of the transformer under non sinusoidal voltage:

- no load current (especially under presence of DC component);
- noise level, (especially under presence of DC and second harmonics);
- magnetic core temperature (especially under presence of DC and second harmonics).

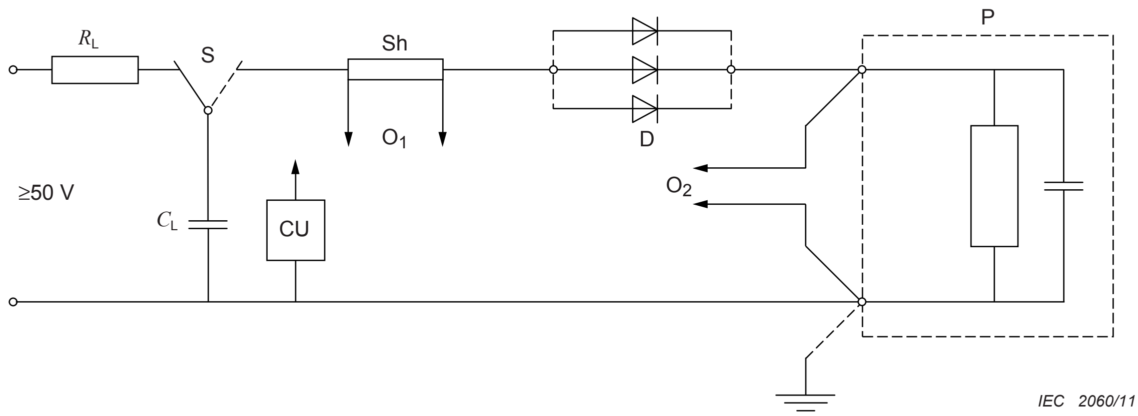
NOTE The harmonic frequency flux density components increase only eddy current part no load losses. With grain oriented core materials this part is approximately 50 % of total no load losses. The second part, hysteresis losses part, also approximately 50 % is influenced only by an increase in hysteresis loop area and peak flux density reached, which both in practical cases are not influenced.

A.4 Electrical resonance frequency measurement

A.4.1 Method of measurement

In order to determine the resonance natural frequency of a winding of a transformer, in a frequency range between 50 Hz and some 100 kHz, the measurement using the principle by capacitor current injection will be used. This method is also described in Annex F of IEC 62271-100:2008. During the measurement the other windings shall be short circuited.

The general diagram of current injection device, given by IEC 62271-100 is given in Figure A.2 below.



Key

R_L	Charging resistor
S	Switching relais
C_L	Source capacitance
Sh	Current measuring shunt
O_1	Cathode-ray oscillograph, trace 1 recording magnitude and linearity of the current and checking the diode operation
O_2	Cathode-ray oscillograph, trace 2 recording the response of the circuit
D	Parallel connection of up to 100 fast silicon switching diodes
P	Circuit the prospective TRV of which is to be measured
CU	Control unit to provide the sequence of operation

Figure A.2 – Schematic diagram of power frequency current injection apparatus

NOTE Other method like frequency sweep with respective continuous impedance measurements can be used. During the measurement other windings of transformer shall be short circuited.

A.4.2 Measurement of the resonance frequency of a transformer winding

The principle consists in discharging a capacitor in the winding of the transformer and to analyse the visual winding voltage response.

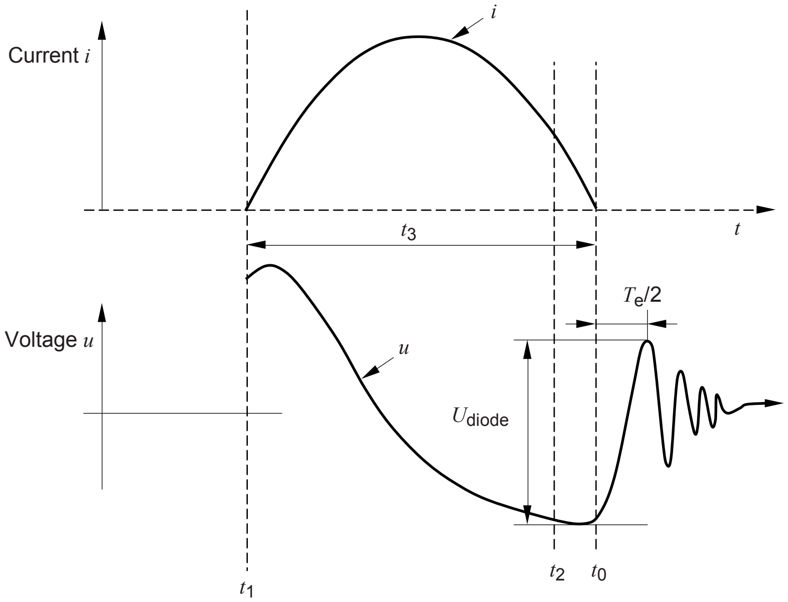
The capacitance discharge is followed by a dumped oscillation, as no energy is feeded.

The frequency of this oscillation is the frequency of resonance of the transformer.

he following Figure A.3 shows the waveforms of current i and voltage u after the time where the current passes through 0 after switching the switching relay S.

The transient recovery voltage (TRV) is starting and the dumped oscillation is illustrated.

The first half cycle Te/2 of the TRV gives the frequency of resonance of the switched winding of the transformer.



Key

t_0	Time where current passes trough zero (beginning of the TRV oscillation)
t_1	Instant of switching of relays S
t_2	Tripping of the cathode-ray oscillograph
t_3	Duration of current through diode D
u	Voltage curve across the terminals of the circuit P
i	Waveform of the injected current
U_{diode}	Maximum voltage stressing of the diodes
$T_e/2$	Duration of half-cycle of TRV

Figure A.3 – Switched transformer winding voltage responses with capacitor injection

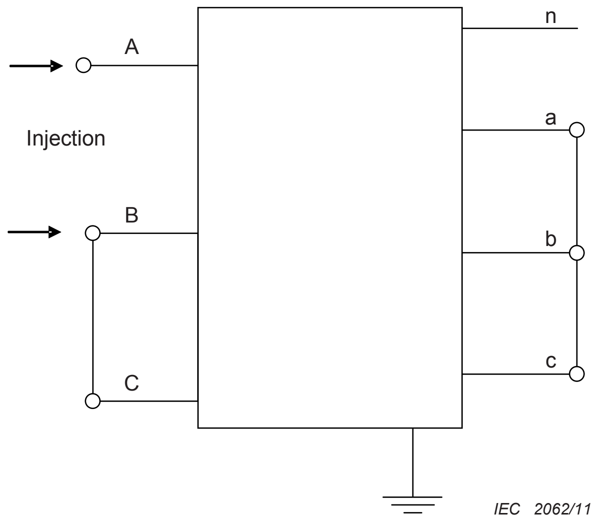
A.4.3 Practical aspects of the injection measurement method

A.4.3.1 Injection test figures

This measurement is carried out in single phase supply for three phase transformers.

Below is described a scheme to measure phase A.

In case of injection between A and B (then B and C connected together) with LV phases (a, b, c) short circuited and LV neutral not connected, the following way of injection given in Figure A.4 will be used:



Key

A,B,C High voltage terminals

a,b,c Low voltage terminals

n Is neutral terminal

Figure A.4 – HV Injection test figure

With the 3 LV phases short circuited, 3 different ways of HV injection should be considered:

- HV phases B and C connected together and LV neutral connected to the ground of transformer. This case shall be used when the LV neutral is earthed during operation and gives the value of phase A.
- HV phases B and C connected together and connected to ground and LV neutral connected to the ground of transformer. This case is valid to see the difference in case of high voltage system ground fault and gives the value of phase A.
- HV phases B and C connected together and LV neutral not connected. This case shall be used when the LV neutral is not earthed during operation. Figure A.4 shows this kind of measurement configuration and gives the value of phase A.

For measurement of the other phases, rotation of the same sequences should be applied.

A.4.3.2 Example of measurement system

Figure A.5 is showing a practical measurement system with devices such as:

– battery supply, capacitors, driving diode, winding of transformer to be measured at the bushings;

– S1 and S2, current and voltage measuring and waveform visualisation devices;

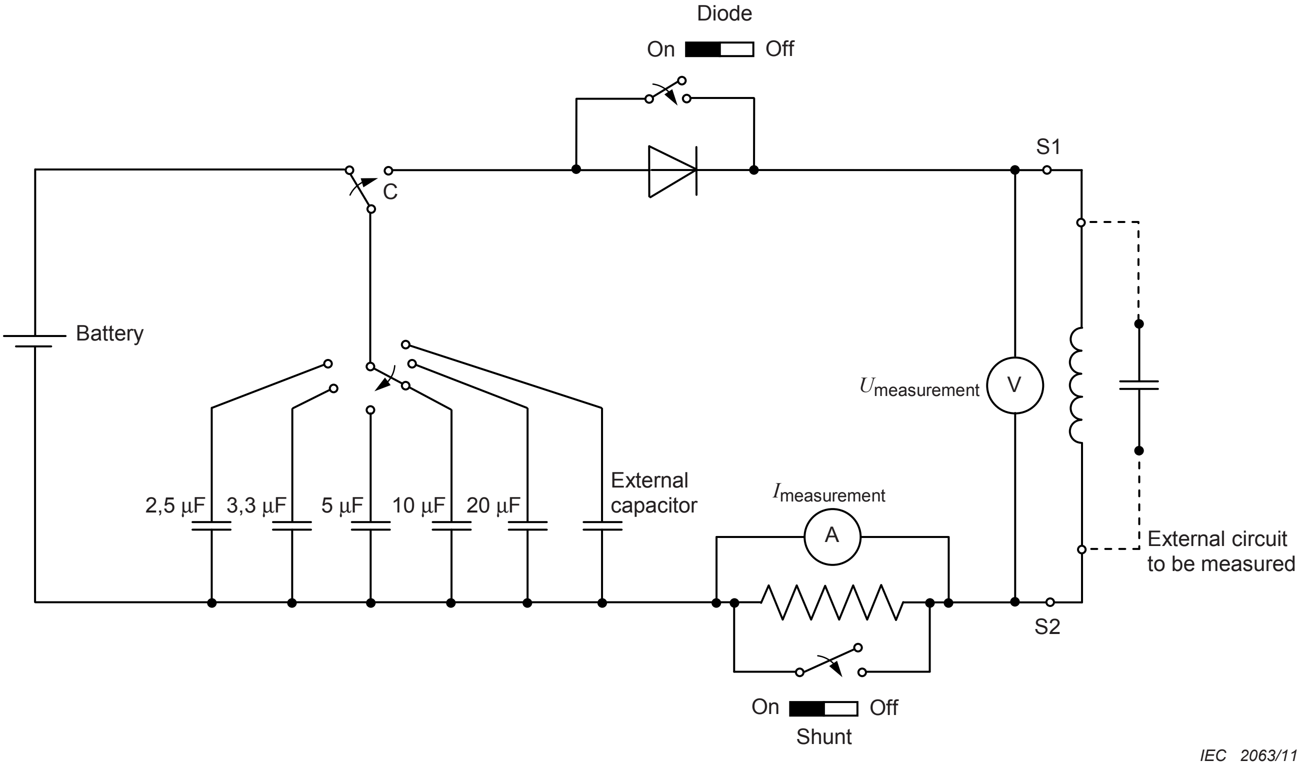


Figure A.5 – Example of measurement device

The recommendations are as follows:

– contact C with no bounces required;

– some diodes with reduced recovery time may be used and mounted in parallel;

– supply of the voltage visualisation device (oscilloscope) by battery or with an insulation transformer.

A.5 Table of symbols

Symbol	Meaning	Units
θ_1	Air inlet temperature	°C
θ_2	Air outlet temperature	°C
$\Delta\theta_a$	Air temperature rise between outlet and inlet	K
υ	Additional losses	W
A_1	Air inlet effective cross section	m^2
A_2	Air outlet effective cross section	m^2
AF	Air forced cooling	-
Bh	Flux density corresponding to harmonic *h*	T
Bn	Flux density at nominal voltage	T
E2 , E3	Environmental classes	-

Symbol	Meaning	Units
e_i	Eddy losses per unit for considered winding	-
f	Frequency	Hz
h	Current harmonic order	-
H	Difference in height between mid outlet surface and mid height of the transformer	m
HL	Heat losses of transformer	kW
HV	High voltage	kV
I	Load current circulating in the considered winding (see A.2)	A
I_{rms}	RMS current	A
I_1	Fundamental current	A
Ih	Magnitude of the harmonic h current	A
I_r	Rated current	A
K factor	Ratio between total eddy losses due to all harmonic currents referred to eddy losses at fundamental current	-
LL	Transformer nominal load losses at reference temperature	kW
Ll	Load losses for a considered winding at reference temperature	W
Lls	Transformer total load losses with non sinusoidal current	W
LV	Low voltage	V
NLL	Transformer no-load losses	kW
P_{EL}	Total eddy losses for each individual harmonics	W
P_f	Eddy losses at fundamental frequency with rated current	W
Ph	Eddy losses at harmonic h	W
Q_{AF}	Heat dissipation by forced air circulation	kW
Q_c, Q_w	Losses dissipated respectively through ceiling and the walls	kW
Q_{nac}	Dissipation power by natural air circulation	kW
Q_{tot}	Heat dissipation power in the transformer's room	kW
Q_{wc}	Heat dissipation through the walls and ceiling	kW
R, R_1, R_2	Winding resistance	Ω
rh	Ratio of magnitude of current harmonic h over fundamental current	-
S_i	Stray losses	W
SL_{ih}	Stray losses for harmonic of order h referred to stray losses at fundamental current I_1	-
Sr	Nominal load of the transformer	kVA
SrE	Permissible loading for the transformer	kVA
THD	Total harmonic distortion rate	%
Tl	Transformer total load losses	W
TOi	Top oil temperature rise with non sinusoidal currents	K
Tor	Top oil temperature rise with rated current	K

Symbol	Meaning	Units
Ttl	Transformer total losses at fundamental current	W
Ttls	Transformer total losses in service with non sinusoidal current	W
U_m	Highest voltage for equipment	kV
V1	Rated voltage	kV
Vh	Voltage harmonic at order *n* expressed per unit	V

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BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

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