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Power transformers – Application guide

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS – APPLICATION GUIDE

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60076-8 has been prepared by IEC technical committee 14: Power transformers.

This first edition of IEC 60076-8 cancels and replaces IEC 60606 published in 1978. This edition constitutes a technical revision.

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

FDIS	Report on voting
14/260/FDIS	14/297/RVD

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

IEC 60076 consists of the following parts, under the general title: Power transformers.

Part 1: 1993, General
Part 2: 1993, Temperature rise
Part 3: 1980, Insulation levels and dielectric tests
Part 5: 1976, Ability to withstand short circuit
Part 8: 1997, Application guide

Annex A is for information only.

POWER TRANSFORMERS – APPLICATION GUIDE

1 General

1.1 *Scope and object*

This Standard applies to power transformers complying with the series of publications IEC 60076.

It is intended to provide information to users about:

- certain fundamental service characteristics of different transformer connections and magnetic circuit designs, with particular reference to zero-sequence phenomena;
- system fault currents in transformers with YNynd and similar connections;
- parallel operation of transformers, calculation of voltage drop or rise under load, and calculation of load loss for three-winding load combinations;
- selection of rated quantities and tapping quantities at the time of purchase, based on prospective loading cases;
- application of transformers of conventional design to convertor loading;
- measuring technique and accuracy in loss measurement.

Part of the information is of a general nature and applicable to all sizes of power transformers. Several chapters, however, deal with aspects and problems which are of the interest only for the specification and utilization of large high-voltage units.

The recommendations are not mandatory and do not in themselves constitute specification requirements.

Information concerning loadability of power transformers is given in IEC 60354, for oil-immersed transformers, and IEC 60905, for dry-type transformers.

Guidance for impulse testing of power transformers is given in IEC 60722.

1.2 *Normative references*

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(421):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 421: Power transformers and reactors*

IEC 60076: *Power transformers*

IEC 60076-1:1993, *Power transformers – Part 1: General*

IEC 60076-3:1980, *Power transformers – Part 3: Insulation levels and dielectric tests*

IEC 60289:1988, *Reactors*

IEC 60354:1991, *Loading guide for oil-immersed power transformers*

IEC 60722:1982, *Guide to the lightning impulse and switching impulse testing of power transformers and reactors*

IEC 60905:1987, *Loading guide for dry-type power transformers*

IEC 60909:1988, *Short-circuit current calculation in three-phase a.c. systems*

IEC 60909-1:1991, *Short-circuit current calculation in three-phase a.c. systems – Part 1: Factors for the calculation of short-circuit currents in three-phase a.c. systems according to IEC 60909 (1988)*

IEC 60909-2:1992, *Electrical equipment – Data for short-circuit current calculations in accordance with IEC 60909 (1988)*

IEC 61378-1: 1997, *Convertor transformers – Part 1: Transformers for industrial applications*

ISO 9001: 1994, *Quality systems – Model for quality assurance in design, development, production, installation and servicing*

2 Characteristic properties of different three-phase winding combinations and magnetic circuit designs

This chapter is an overview of the subject. Additional information is given in clause 4 on zero-sequence properties.

2.1 *Y-, D-, and Z-connected windings*

There are two principal three-phase connections of transformer windings: star (Y-connection) and delta (D-connection). For special purposes, particularly in small power transformers, another connection named zigzag or Z is also used. Historically, several other schemes have been in use (such as "truncated delta", "extended delta", "T-connection", "V-connection", etc.). While such connections are used in transformers for special applications, they no longer appear in common power transmission systems.

2.1.1 *Advantages of a Y-connected winding*

This type of winding:

- is more economical for a high-voltage winding;
- has a neutral point available;
- permits direct earthing or earthing through an impedance;
- permits reduced insulation level of the neutral (graded insulation);
- permits the winding taps and tapchanger to be located at the neutral end of each phase;
- permits single-phase loading with neutral current (see 2.2 and 4.8).

2.1.2 *Advantages of a D-connected winding*

This type of winding:

- is more economical for a high-current, low-voltage winding;
- in combination with a star-connected winding, reduces the zero-sequence impedance in that winding.

2.1.3 *Advantages of a Z-connected winding*

This type of winding:

- permits neutral current loading with inherently low zero-sequence impedance. (It is used for earthing transformers to create an artificial neutral terminal of a system);
- reduces voltage unbalance in systems where the load is not equally distributed between the phases.

2.2 *Characteristic properties of combinations of winding connections*

The notation of winding connections for the whole transformer follows the conventions in IEC 60076-1, clause 6.

This subclause is a summary of the neutral current behaviour in different winding combinations. Such conditions are referred to as having "zero-sequence components" of current and voltage. This concept is dealt with further in clauses 4 and 5.

The statements are also valid for three-phase banks of single-phase transformers connected together externally.

2.2.1 *YNyn and YNauto*

Zero-sequence current may be transformed between the windings under ampere-turn balance, meeting low short-circuit impedance in the transformer. System transformers with such connections may in addition be provided with delta equalizer winding (see 4.7.2 and 4.8).

2.2.2 *YNy and Yyn*

Zero-sequence current in the winding with earthed neutral does not have balancing ampere-turns in the opposite winding, where the neutral is not connected to earth. It therefore constitutes a magnetizing current for the iron core and is controlled by a zero-sequence magnetizing impedance. This impedance is high or very high, depending on the design of the magnetic circuit (see 2.3). The symmetry of the phase-to-neutral voltages will be affected and there may be limitations for the allowable zero-sequence current caused by stray-flux heating (see 4.8).

2.2.3 *YNd, Dyn, YNyd (loadable tertiary) or YNy + d (non-loadable delta equalizer winding)*

Zero-sequence current in the star winding with earthed neutral causes compensating circulating current to flow in the delta winding. The impedance is low, approximately equal to the positive-sequence short-circuit impedance between the windings.

If there are two star windings with earthed neutrals (including the case of auto-connection with common neutral), there is a three-winding loading case for zero-sequence current. This is dealt with in 4.3.2 and 4.7.2, and in clause 5.

2.2.4 *Yzn or ZNy*

Zero-sequence current in the zigzag winding produces an inherent ampere-turn balance between the two halves of the winding on each limb, and provides a low short-circuit impedance.

2.2.5 *Three-phase banks of large single-phase units – use of delta connected tertiary windings*

In some countries, transformers for high-voltage system interconnection are traditionally made as banks of single-phase units. The cost, mass, and loss of such a bank is larger than for a corresponding three-phase transformer (as long as it can be made). The advantage of the bank concept is the relatively low cost of providing a spare fourth unit as a strategic reserve. It may also be that a corresponding three-phase unit would exceed the transport mass limitation.

The three single-phase transformers provide independent magnetic circuits, representing high magnetizing impedance for a zero-sequence voltage component.

It may be necessary to provide a delta equalizer winding function in the bank, or there may be a need for auxiliary power at relatively low-voltage from a tertiary winding. This can be achieved by external busbar connection from unit to unit in the station. The external connection represents an additional risk of earth fault or short circuit on the combined tertiary winding of the bank.

2.3 *Different magnetic circuit designs*

The most common magnetic circuit design for a three-phase transformer is the three-limb core-form (see figure 1). Three parallel, vertical limbs are connected at the top and bottom by horizontal yokes.

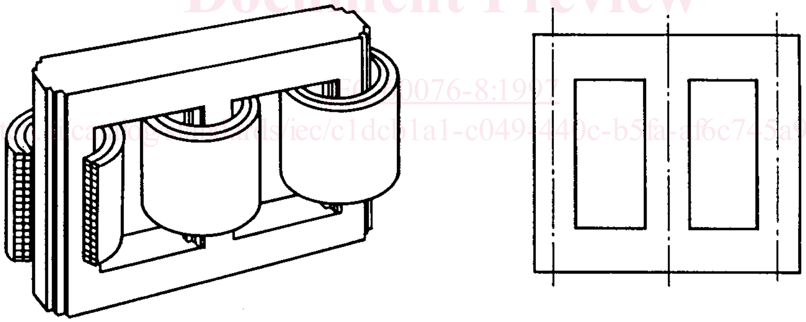
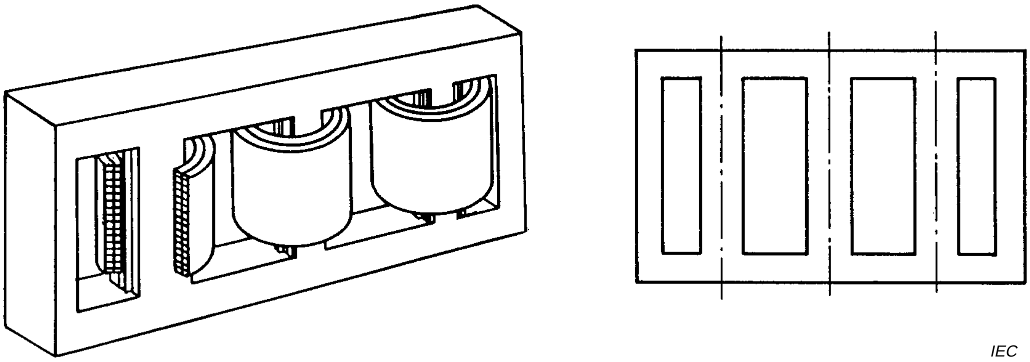


Figure 1 – Three-limb, core-form magnetic circuit

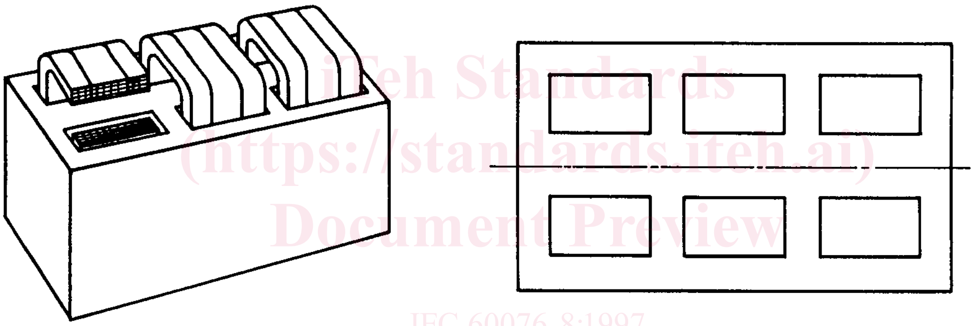
The five-limb, core-form magnetic circuit (see figure 2) has three limbs with windings and two unwound side limbs of lesser cross-section. The yokes connecting all five limbs also have a reduced cross-section in comparison with the wound limbs.



IEC 1120/97

Figure 2 – Five-limb, core-form magnetic circuit

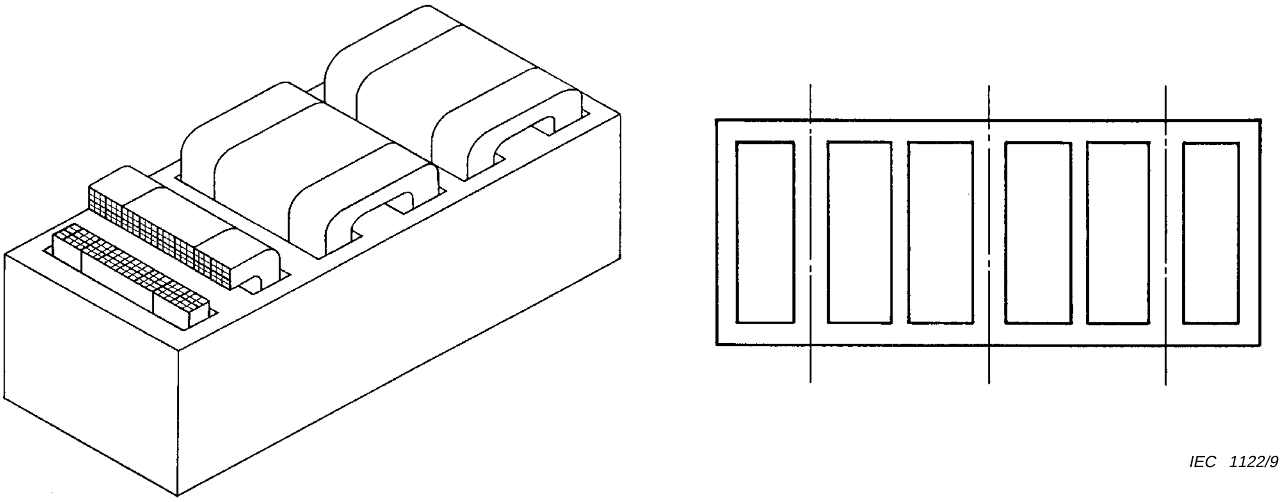
The conventional shell-form three-phase design has a frame with the three wound limbs horizontal and having a common centre line (see figure 3). The core-steel limbs inside the windings have an essentially rectangular cross-section and the adjoining parts of the magnetic circuit surround the windings like a shell.



IEC 1121/97

Figure 3 – Three-phase conventional shell-form magnetic circuit

A new three-phase shell-form magnetic circuit is the seven-limb core, in which the wound limbs are oriented in a different way (see figure 4).



IEC 1122/97

Figure 4 – Three-phase seven-limb shell-form magnetic circuit

The principal difference between the designs, to be discussed here, lies in their behaviour when subjected to an asymmetrical three-phase set of voltages having a non-zero sum i.e. having a zero-sequence component.

This condition may also be described as starting from a zero-sequence current without balancing ampere-turns in any other winding. Such a current appears as a magnetizing current for the magnetic circuit and is controlled by a magnetizing impedance, across which a zero-sequence voltage drop is developed.

The usual types of magnetic circuits behave as follows.

2.3.1 *Three-limb core-form magnetic circuit*

In the three-limb core-form transformer, positive and negative sequence flux components in the wound limbs (which have a zero sum at every instant) cancel out via the yokes, but the residual zero-sequence flux has to find a return path from yoke to yoke outside the excited winding. This external yoke leakage flux sees high reluctance and, for a given amount of flux (a given applied zero-sequence voltage), a considerable magnetomotive force (high magnetizing current) is required. In terms of the electrical circuit, the phenomenon therefore represents a relatively low zero-sequence (magnetizing) impedance. This impedance varies in a non-linear way with the magnitude of the zero-sequence component.

Conversely, uncompensated zero-sequence current constitutes a magnetizing current which is controlled by the zero-sequence magnetizing impedance. The result is a superposed asymmetry of the phase-to-neutral voltages, the zero-sequence voltage component.

The zero-sequence yoke leakage flux induces circulating and eddy currents in the clamping structure and the tank, generating extra stray losses in these components. There could also be increased eddy losses in the windings caused by the abnormal stray flux. There are limitations to the magnitude of any long duration neutral current which is allowable in service. This is considered in 4.8.

2.3.2 *Five-limb core-form, or shell-form magnetic circuit*

In a five-limb core-form, or a shell-form transformer, there are return paths available for the zero-sequence flux through unwound parts of the magnetic circuit (side limbs of five-limb core, outside parts of the shell frame plus, and for the seven-limb shell-form core, the two unwound inter-winding limbs). The zero-sequence flux sees low magnetic reluctance equivalent to a very high magnetizing impedance, similar to that of normal positive-sequence voltage. This applies up to a limit, where the unwound parts of the magnetic circuit reach saturation. Above that, the impedance falls off, resulting in peaked, distorted current.

A three-phase bank of single-phase transformers reacts similarly. The magnetic circuits are separate and independent at any applied service voltage.

Due to the phenomena described above, it is customary to provide such transformers or transformer banks with a delta-connected stabilizing winding (see clause 4).

3 Characteristic properties and application of auto-connected transformers

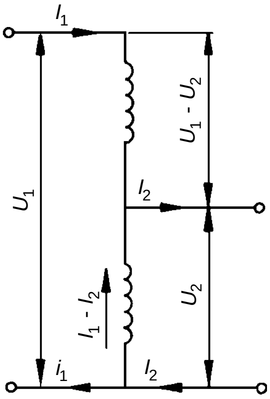
3.1 By definition, an auto-connected transformer is a transformer in which at least two windings have a common part (see 3.1.2 of IEC 60076-1).

The single line diagram of an auto-transformer is shown in figure 5. The high-voltage side of the transformer (identified with U_1, I_1 in the figure) consists of the common winding together with the series winding. The low-voltage side (U_2, I_2) consists of the common winding alone. The high- and low-voltage systems are electrically connected.

$$U_1 I_1 = U_2 I_2 = S$$

$$\frac{U_1 - U_2}{U_1} = \frac{I_2 - I_1}{I_2} = \alpha$$

$$(U_1 - U_2) I_1 = U_2 (I_2 - I_1) = \alpha S$$



IEC 1123/97

Figure 5 – Auto-connected transformer, single-line diagram

3.2 *The reduction factor or auto-factor, α*

The auto-transformer is physically smaller and has lower losses than a separate winding transformer for the same throughput power. The relative saving is greater the closer the transformation ratio is to unity. The two windings (series and common) represent the same equivalent power ratings or, expressed in other terms, balancing ampere-turns. The relations shown in figure 5 immediately explain the reduction factor, α, of the auto-connection. If *S* is the rated power of the auto-connected windings, noted on the rating plate, then the transformer is similar, with regard to physical size and mass, to a separate winding transformer having rated power α × *S*. This is often referred to with expressions such as intrinsic rated power or equivalent two-winding rating.

Example

An auto-connected transformer 420/240 kV, 300 MVA, is comparable with a separate winding transformer having a rated power of:

((420 – 240)/420) × 300 = 129 MVA

If the transformer in addition is provided with a non-auto-connected tertiary winding of 100 MVA rated power (YNauto d 300/300/100 MVA), then its equivalent two-winding rating will be

(129 + 129 + 100)/2 = 179 MVA

3.3 *Short-circuit impedance and leakage flux effects*

The short-circuit impedance of a transformer may be described physically in terms of the reactive power in the leakage field. This in turn depends on the physical size and geometry of the windings.

For an auto-transformer with its reduced dimensions, the reactive power in the leakage field is naturally smaller than for a separate winding transformer with the same rated power. Its impedance, expressed as a percentage, will then be correspondingly lower. The auto-connection factor, α, is also a benchmark for the percentage impedance.

However, it may also be observed that if the percentage impedance of an auto-transformer is specified with an elevated value (with a view to limiting fault-current amplitudes in the secondary-side system) then this transformer will, from a design point of view, be a physically small unit with a quite large leakage field. This will be reflected as higher additional losses (winding eddy loss as well as stray field loss in mechanical parts) and possibly even saturation effects due to leakage flux circulating in part through the magnetic circuit. Such effects would restrict the loadability of the unit above rated conditions, but this is not revealed by standard tests.

The transformer loading guide, IEC 60354, takes these phenomena into account when separating between large and medium power transformers. Auto-transformers are to be classified according to their equivalent power rating, and the corresponding percentage impedance, instead of by the rating-plate figures.

3.4 *System restrictions, insulation co-ordination*

The direct electrical connection between the primary and secondary (three-phase) systems implies that they will have a common neutral point and that the three-phase connection of the auto-transformer is in star. In practice, the systems will normally be effectively earthed and the neutral point of the auto-transformer will usually be specified with reduced insulation level.

- If the transformer neutral is to be directly earthed, the necessary insulation level is very low (see 5.5.2 of IEC 60076-3).
- It may alternatively be foreseen that not all neutrals of several transformers in a station will be directly earthed. This is in order to reduce the prospective earth fault currents. The unearthed neutrals will, however, usually be provided with a surge arrester for protection against transient impulses. The specified arrester rated voltage and the insulation level of the neutral will be co-ordinated with the power frequency voltage appearing at the unearthed neutral during a system earth fault.
- In extra-high-voltage systems with long overhead lines, the possibility of successful single-pole reclosing may be improved by specially tuned reactor earthing. This requires a relatively high insulation of the transformer neutral, which is connected via the tuning reactor to earth.

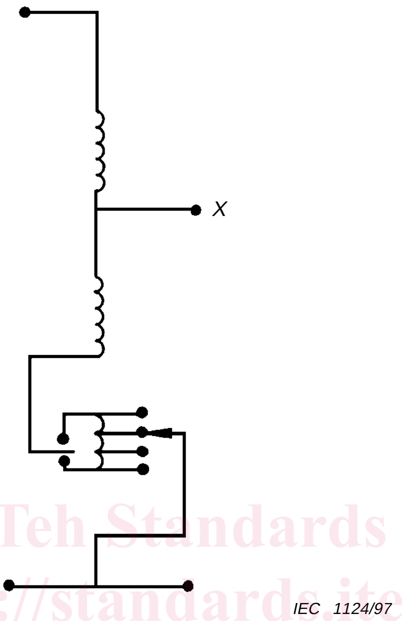
The series winding of an auto-transformer sometimes presents design difficulties for the insulation across the winding. It is assumed that the X-terminal, the low-voltage side-line terminal, stays at low potential at the incidence of a transient overvoltage on the high-voltage side-line terminal. The stress corresponding to the whole impulse insulation level of the high-voltage side will therefore be distributed along the series winding only. This represents a correspondingly higher turn-to-turn voltage, compared with an overvoltage across the low-voltage side, distributed along the common winding.

3.5 *Voltage regulation in system-interconnection autotransformers*

Variation of the voltage ratio in an auto-connected transformer may be arranged in different ways. Some of these follow the underlying principles of 5.1 of IEC 60076-1. Others do not because the number of effective turns is changed in both windings simultaneously.

The tapping turns will be either at the neutral terminal or at the joint between the common and the series windings (common point) (see figure 6).

3.5.1 *Tapping turns at the neutral*



Regulation at the neutral simultaneously increases or decreases the number of turns in both the high-voltage and low-voltage windings but the ratio between the windings changes. This type of regulation will be insufficient in the sense that it requires many regulating turns for the specified range of variation of ratio. Therefore, the volts per turn in the transformer will vary considerably across the tapping range (variable flux). The phenomenon gets more pronounced the closer the ratio of the transformer approaches unity (low α value). This has to be covered by a corresponding over-dimensioning of the magnetic circuit. It will also result in unequal voltages per step.

The obvious advantage of regulation in the neutral is that the tapping winding and the tap-changer will be close to neutral potential and require only low insulation level to earth.

Figure 6 – Tapping turns at the common neutral

3.5.2 *Tapping turns at the X-terminal*

Regulation arranged at the auto-interconnection in the transformer (the low-voltage side-line terminal) requires the tapping winding and tapchanger to be designed with the insulation level of the X-terminal. They will be directly exposed to steep-front voltage transients from lightning or switching surges. Figure 7 shows a number of different arrangements.