

Power transformers — Application guide

ICS 29.180

National foreword

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The UK participation in its preparation was entrusted to Technical Committee PEL/14, Power transformers, which has the responsibility to:

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Summary of pages

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60076-8**

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**Transformateurs de puissance –
Guide d'application**

**Power transformers –
Application guide**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS – APPLICATION GUIDE

FOREWORD

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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.

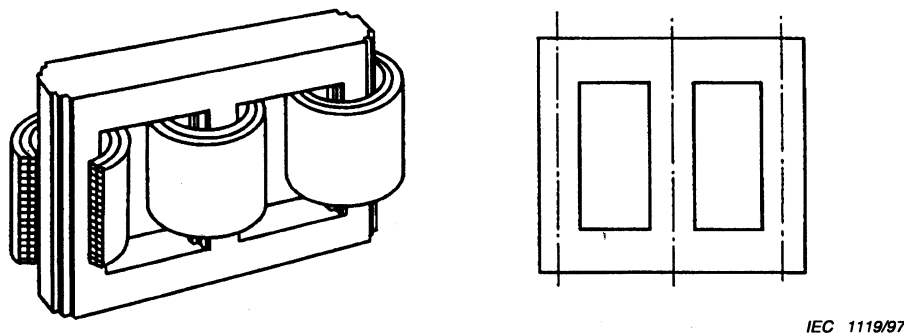
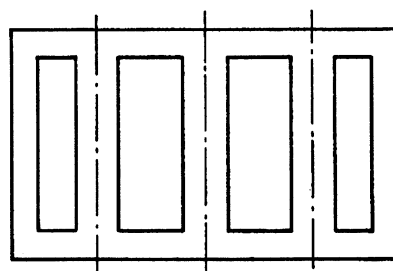
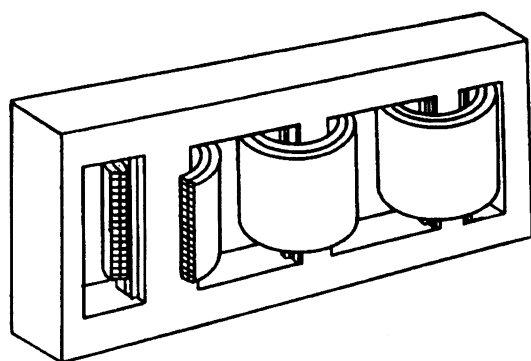


Figure 1 – Three-limb, core-form magnetic circuit

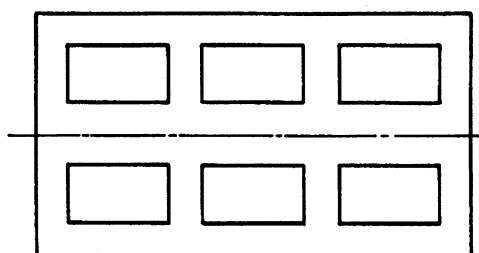
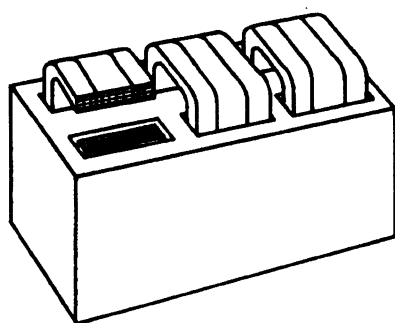
The five-limb, core-form magnetic circuit (see figure 2) has three limbs with windings and two unwound side limbs of lesser cross-section. The yokes connecting all five limbs also have a reduced cross-section in comparison with the wound limbs.



IEC 1120/97

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

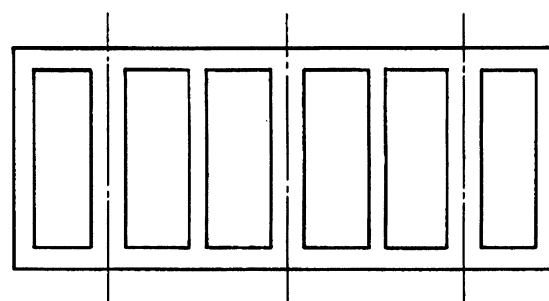
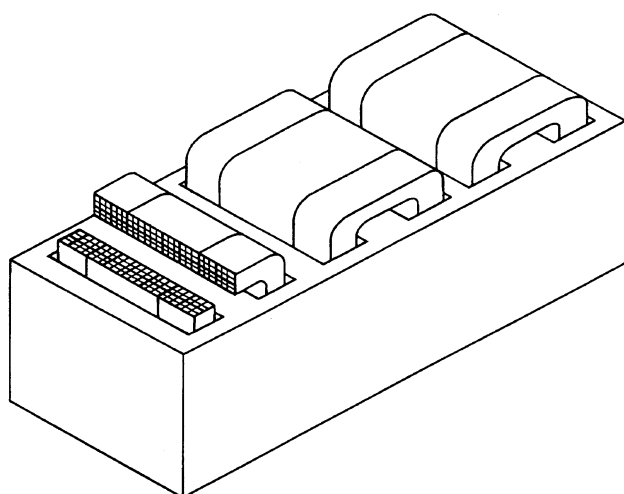
The conventional shell-form three-phase design has a frame with the three wound limbs horizontal and having a common centre line (see figure 3). The core-steel limbs inside the windings have an essentially rectangular cross-section and the adjoining parts of the magnetic circuit surround the windings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

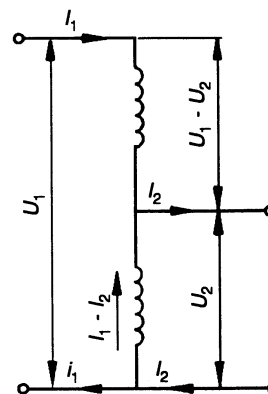
3.1 By definition, an auto-connected transformer is a transformer in which at least two windings have a common part (see 3.1.2 of IEC 60076-1).

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 $\alpha \times S$. 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:

$$((420 - 240)/420) \times 300 = 129 \text{ MVA}$$

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

$$(129 + 129 + 100)/2 = 179 \text{ MVA}$$

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.

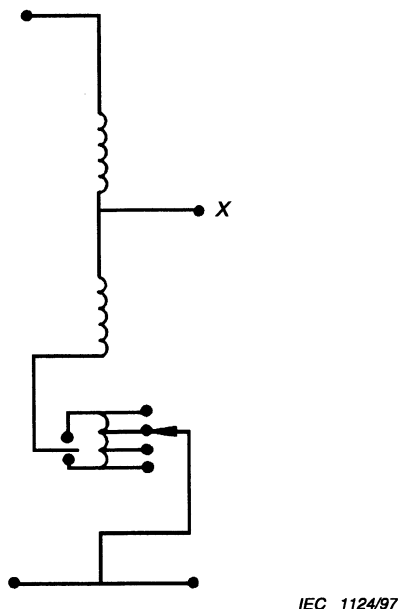
The series winding of an auto-transformer sometimes presents design difficulties for the insulation across the winding. It is assumed that the X-terminal, the low-voltage side-line terminal, stays at low potential at the incidence of a transient overvoltage on the high-voltage side-line terminal. The 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



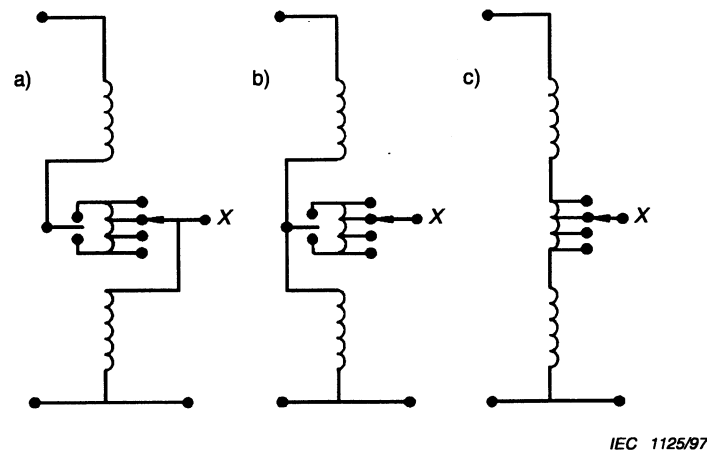
Regulation at the neutral simultaneously increases or decreases the number of turns in both the high-voltage and low-voltage windings but the ratio between the windings changes. This type of regulation will be insufficient in the sense that it requires many regulating turns for the specified range of 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.



- a) The number of turns in the common winding remains unchanged. This is a logical choice if the low-voltage system voltage remains relatively constant while the high-voltage system voltage is more variable.
- b) This alternative is the opposite to a). The number of turns facing the high-voltage system voltage remains constant, while the effective number of turns of the low-voltage side varies.
- c) The number of turns is constant on the high-voltage side, but for a specific number of reconnected turns, the ratio varies more than in case b). Case b) on the other hand permits plus-minus utilization of the tapping winding by reversing it as indicated in the figure.

Figure 7 – Tapping turns at the lower voltage terminal

4 Zero-sequence properties – neutral load current and earth fault conditions, magnetic saturation and inrush current

This clause outlines the characteristics of three-phase transformers and banks of single-phase transformers with regard to asymmetrical three-phase service conditions.

There are differences depending on the geometry of the magnetic circuit and on the combination of three-phase connections of the windings.

The asymmetrical conditions comprise transient disturbances as well as asymmetries during continuous service, giving rise to:

- temporary loss of symmetry of three-phase voltages and, consequently, of the symmetry of magnetization of the core;
- temporary or permanent asymmetry of load currents, particularly current in the neutral, which will affect the voltage stability, leakage flux and core magnetization.

4.1 Introduction of the symmetrical components of a three-phase system

A short explanation of the conventional analytical method called symmetrical components, which is frequently referred to in power system analysis, is given in 4.1.1. For further information on this method and its application, see textbooks on power system analysis.

A further explanation regarding the practical aspects of earthing of the system through transformer neutrals is given in 4.1.2.

4.1.1 *Principles and terminology of symmetrical components of voltage and current*

The method, as conventionally applied, presupposes synchronous and sinusoidal voltages and currents, linked by circuit elements in the form of constant impedance or admittance, with equal value for the three phases. These assumptions imply that all circuit equations are linear, and that changes of variables by linear transformations are possible. One such transformation is that of symmetrical components.

In the general asymmetrical case, the three individual phase voltages or phase current have unequal amplitudes and are not spaced equally in time (not 120 electrical degrees apart). The sum of the momentary values may be different from zero. The phasor picture is an asymmetrical star. The vectorial sum of the three phasors does not necessarily form a closed triangle (non-zero sum).

It is however always possible to replace the original three asymmetrical variables by a combination of the following three symmetrical components:

- a positive sequence component having a fully symmetrical, ordinary set of three-phase voltages or currents;
- a negative sequence component having another symmetrical set, but with opposite phase sequence;
- a zero sequence component having the same phasor value in all three phases with no phase rotation.

The two first components each have zero sum at every instant. The third component represents the residual, non-zero sum of the original variables, with one-third appearing in each phase.

The advantage of the method of symmetrical components for calculation of voltages and currents is that the original system of three coupled equations with three unknown variables is replaced by three separate, single-phase equations with one unknown, one for each component. Each equation makes use of the relevant impedance or admittance parameters for the respective component.

The solution of the equations for the separate symmetrical components are then superposed back, phase by phase, to obtain the phase voltages or currents of the real system.

The algorithms for transformation of the original phase quantities into symmetrical components and back again can be found in appropriate textbooks.

4.1.2 *Practical aspects*

The properties of the components have the following practical consequences with regard to currents and voltages.

- The three line currents in a system without earth return or neutral conductor have zero sum. Their transformation into symmetrical components contains positive and negative sequence components but no zero-sequence component.

The currents from a system to a delta-connected winding have this property.

- If there is neutral current to earth or through a neutral conductor (fourth wire), then the system of phase currents may have a zero-sequence component. This is a normal condition in four-wire distribution systems with single-phase loads applied between phase and neutral. High-voltage transmission lines do not normally carry any intentional neutral load current. To the extent that load asymmetry exists, it rather has the character of load between two phases which results in a negative-sequence component, but no zero-sequence component.
- A zero-sequence component is defined as existing in phase, and with the same amplitude, in all three phases. A zero-sequence component of current is, consequently, precisely one-third of the neutral current.
- The set of line-to-line voltages across a delta-connected winding have zero sum, because of the closed connection, and consequently do not contain any zero-sequence voltage component. But inside the delta winding, there may flow zero-sequence current, a short-circuit current circulating around the delta, which is induced from another winding (see 4.5).

4.2 Impedance parameters for symmetrical components

The impedance (or admittance) parameters of different elements of the system may be different for the three components. In practice, components such as transformers and reactors have equal parameters for positive sequence and negative sequence impedance. For a transformer, they are taken as the values measured during the routine tests.

The zero-sequence parameters of a transformer, however, are different. It may be that transformers having equal values of positive-sequence reactance still have unequal zero-sequence characteristics depending on the type of magnetic circuit, the connection and location of the different winding, the way of guiding leakage flux, etc.

In some cases, a zero-sequence impedance will be non-linear. This is described with reference to the physics of the transformer in the following clauses. They also provide some approximate quantitative estimates for general guidance. If more accurate evidence about a specific transformer is wanted, measurements of its zero-sequence characteristics may be carried out as a special test, on request (see 10.7 of IEC 60076-1).

4.3 Single-line equivalent diagram of the transformer for zero-sequence phenomena

The fundamentals of the symmetrical component method have been outlined in 4.1, 4.1.1, 4.1.2 and 4.2. It was stated that the analysis of asymmetrical, linear, sinusoidal phenomena is handled in the form of simultaneous, single-phase equations, one for each component. For positive and negative sequence, the transformer is represented with its normal no-load and short-circuit impedances but, for zero-sequence, the diagram is sometimes different, depending on the design. Quantitative information about the zero-sequence parameters can be found in this subclause.

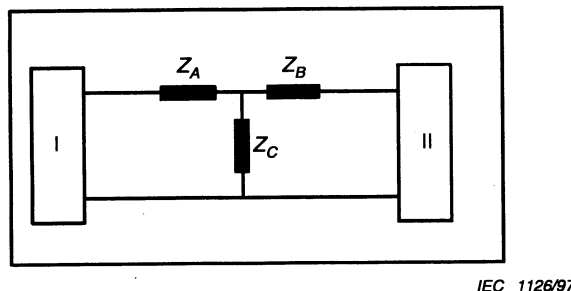


Figure 8 – Zero-sequence diagram for two-winding transformer

The equivalent diagram of a two-winding three-phase transformer for zero-sequence is composed of a series impedance and a shunt branch. In figure 8, the sum of the two series impedance elements Z_A and Z_B is equal to the ordinary short-circuit impedance for positive-sequence current. The subdivision between the two elements is arbitrary, and either can be put equal to zero.

Z_m is a magnetizing impedance, the order of magnitude of which depends on the design of the magnetic circuit. A five-limb core or a shell-form three-phase magnetic circuit presents very high magnetizing impedance for zero-sequence voltage (see 4.4).

A three-limb core, on the other hand, has a moderate magnetizing impedance for zero-sequence voltage. This impedance is non-linear with the current or voltage magnitude and varies from design to design. The yoke leakage flux (see 4.4) induces flow of eddy currents around the whole tank. There is, therefore, a difference between transformers having corrugated tanks of thin steel sheet and those having tanks of flat boilerplate. For boilerplate tank transformers, the per unit zero-sequence impedance is, in general, of the order of 0,25 to 1,0 when the neutral current $3 \times I_0$ is equal to the rated current of the winding. The general variation of impedance with current is shown in figure 9.

For a new transformer, the manufacturer will perform a measurement of the zero-sequence impedance on request (see 10.1.3 and 10.7 of IEC 60076-1).

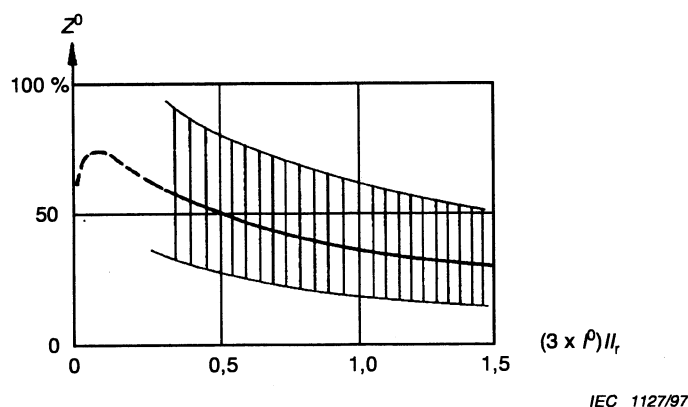


Figure 9 – Variation with current of zero-sequence magnetizing impedance of three-limb transformer without a delta winding

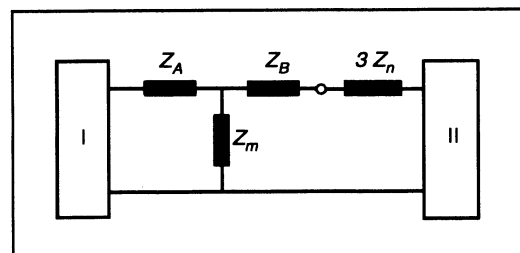
The consequences for particular cases of transformer connections are described in 4.3.1 and 4.3.2.

4.3.1 YNyn transformer without additional delta winding

When both winding neutrals are connected to effectively earthed systems, zero-sequence current may be transferred between the systems, meeting low impedance in the transformer. The system impedances are not, in this case, larger than the transformer series impedance. With a three-limb core, the moderate magnetizing impedance is not negligible. It lowers the effective through impedance of the transformer to approximately 90 % to 95 % of the positive-sequence short-circuit impedance. With a five-limb core or a shell-form transformer, there is no such reduction.

If the opposing winding system does not accept zero-sequence current, the input impedance of either winding is the magnetizing impedance, which is dependent on the magnetic circuit design as outlined above.

If the opposing winding system has its neutral earthed through an impedance element Z_n , this is represented in the zero-sequence diagram by an additional series impedance equal to $3Z_n$ (see figure 10).



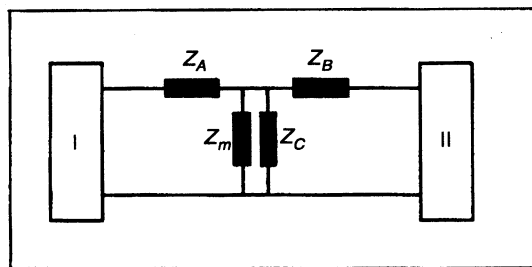
IEC 1128/97

Figure 10 – YNyn transformer with neutral earthing impedance – zero-sequence representation

4.3.2 YNynd, or YNyn + d transformer

This is a three-winding combination. There is a star configuration of series impedance elements, in combination with the magnetizing impedance for zero-sequence. In figure 11, $Z_A + Z_C$ is the short-circuit impedance between winding A and the delta-connected third winding C, within which a zero-sequence current may circulate (see 4.5). This impedance is the input impedance for zero-sequence current from system I into winding A.

Similarly, the impedance for zero-sequence current from system II into winding B is $Z_B + Z_C$.



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Figure 11 – YNynd transformer – zero-sequence representation

The magnetizing impedance Z_m which is also indicated in figure 11, is usually neglected in calculations for this winding combination. It is accepted that the zero-sequence impedances of the diagram differ somewhat from values measured with positive sequence current. The difference depends on the arrangement of the windings with respect to each other and usually stays within 10 % to 15 %.

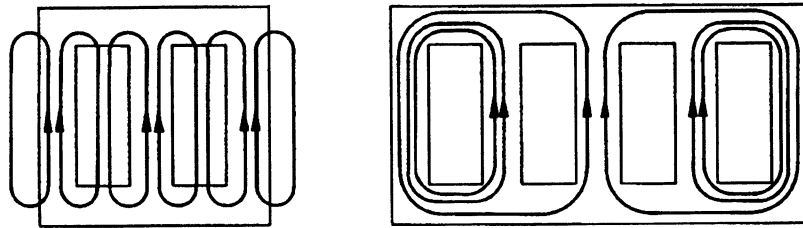
4.4 Magnetizing impedance under asymmetrical conditions – zero-sequence voltage and magnetic circuit geometry

For several reasons, the symmetry of three-phase voltages in transmission systems under normal service conditions is maintained quite well and does not in general cause any concern for the operation of the transformer.

During asymmetrical earth faults in the network, the system of phase-to-earth voltages contains a zero-sequence component. The degree of asymmetry depends on the method of system earthing. The system is characterized by an earth fault factor which is, briefly, the ratio between phase-to-earth a.c. voltage on an unfaulted phase during the fault and the symmetrical phase-to-earth voltage prior to the fault. This is of importance with regard to insulation coordination.

If the three-phase limbs of a transformer are subjected to a system of induced voltages which contains a zero-sequence component (i.e. has a non-zero sum), then the reaction depends on the magnetic circuit geometry and the connection of the windings.

In a three-limb core type transformer (see figure 12), the unequal flux contributions from the three limbs do not cancel in the yokes. The residual, zero-sequence flux instead completes its path outside the iron core. This represents high reluctance and a low magnetizing impedance for zero-sequence voltage. Quantitative information is given in 4.3. The phenomenon of considerable flux leaving the magnetic circuit and closing outside may also occur during switching transient conditions.



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Figure 12 – Zero-sequence magnetization of three-limb and five-limb cores

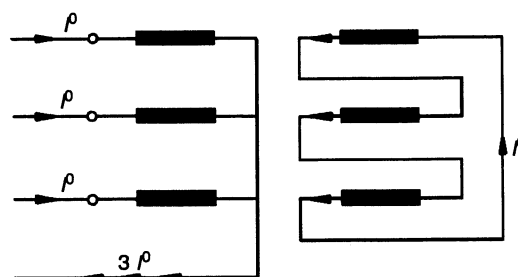
In a five-limb core type transformer (see figure 12), the unwound outer limbs present a low-reluctance return path, where zero-sequence flux may pass. The corresponding magnetizing impedance is high, as for normal positive-sequence flux. The same applies for shell-form three-phase transformers, and, of course, for a bank of three separate single-phase units.

However, applied zero-sequence voltage and current is also influenced by the winding three-phase connection; see the following clauses.

4.5 Zero-sequence and delta windings

The phase-to-phase voltages across a delta-connected winding automatically sum up to zero because of the closed triangle connection. Alternatively, a delta winding can be looked on as a short circuit with regard to zero-sequence voltages.

Zero-sequence current cannot be exchanged between the three terminals of the delta winding and an external system. But a circulating short-circuit current may be induced from another (YN-connected) winding (see figure 13). The zero-sequence impedance of the transformer, seen from the other winding, has the character of a short-circuit impedance between the other winding and the delta winding. For quantitative information, see 4.3.



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Figure 13 – Zero-sequence short-circuit current induced in a delta winding

4.6 Zero-sequence and zigzag windings

In a zigzag connected winding (see figure 14), each limb of the transformer carries part windings from two phases which have opposite winding directions. The number of ampere-turns of a zero-sequence current component cancel out on each limb, with no resulting magnetization. The current meets only a low short-circuit impedance associated with the leakage flux between the part windings on the limb (see also 4.7.3).

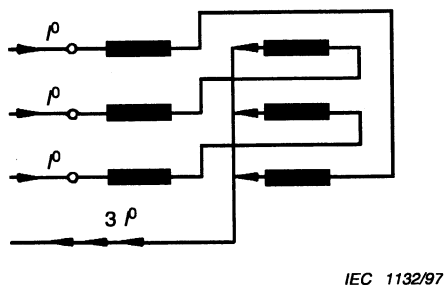


Figure 14 – A zigzag connected winding inherently balanced for zero-sequence current

4.7 Zero-sequence impedance properties of different transformer connections

Previous subclauses have described zero-sequence characteristics of specific magnetic circuits and of specific individual windings in transformers. This subclause summarizes the zero-sequence characteristics of whole transformers having usual winding combinations.

Table 1 indicates approximate zero-sequence impedance values for two and three-winding combinations when either of the windings is excited from a system. This table as it stands is valid for designs with concentric windings, here numbered (1) – (2) – (3) with (1) as the outermost winding. The winding symbols in the first column are written in the same order. It is unimportant which one is the high-voltage winding.

The following subclauses provide further descriptive text.

In table 1, the symbol YN indicates that the winding neutral is earthed directly or via a low impedance. Symbol Y indicates that the neutral is not connected to earth.

Percentage figures, when given, are in relation to the usual reference impedance U^2/S .

Some connections are marked with an asterisk (*). In these cases, the zero-sequence current in the excited winding is not balanced by current in any other winding. The zero-sequence impedance is then a magnetizing impedance of relatively high or very high value, depending on the magnetic circuit.

In all other cases, there is current balance between the windings, and the zero-sequence impedance is equal to, or at least close to, the ordinary short-circuit impedance between the windings involved.

The table only indicates the contribution of the transformer itself. Impedances of associated systems are regarded as negligible.

This means that, in the zero-sequence diagram representation, a YN output winding is regarded as having all three phases short-circuited to earth.

Table 1 – Zero-sequence impedances, typical values

Winding symbol			Impedance %						Subclauses
			Excited winding, 3-limb core			Excited winding, 5-limb core (or shell)			
(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	
YN	Y	*	≈ 50	—		≈ 10 ⁴	—		4.3, 4.4
Y	YN	*	—	≈ 60		—	≈ 10 ⁴		4.3, 4.4
YN	YN		a ₁ z ₁₂	a ₂ z ₁₂		z ₁₂	z ₁₂		4.7.1
YN	D		a ₁ z ₁₂	—		z ₁₂	—		4.7.2
D	YN		—	a ₂ z ₁₂		—			4.7.2
YN	Y	Y*	≈ 50	—	—	≈ 10 ⁴	—	—	4.3, 4.4
Y	YN	Y*	—	≈ 60	—	—	≈ 10 ⁴	—	4.3, 4.4
Y	Y	YN*	—	—	≈ 70	—	—	≈ 10 ⁴	4.3, 4.4
YN	YN	Y	a ₁ z ₁₂	a ₂ z ₁₂	—	z ₁₂	z ₁₂	—	4.7.1
YN	Y	YN		—	a ₃ z ₁₃	z ₁₃	—	z ₁₃	4.7.1
Y	YN	YN	—		a ₃ z ₂₃	—	z ₂₃	z ₂₃	4.7.1
YN	YN	D	a ₁ (z ₁ +z ₂ z ₃)	a ₂ (z ₂ +z ₁ z ₃)	—	z ₁ +z ₂ z ₃	z ₂ +z ₁ z ₃	—	4.7.2
YN	D	D	a ₁ (z ₁ +z ₂ z ₃)	—	—	z ₁ +z ₂ z ₃	—	—	4.7.2
YN	Y	D		—	—	z ₁₃	—	—	4.7.2
D	YN	YN	—	a ₂ (z ₂ +z ₁ z ₃)	a ₃ (z ₃ +z ₁ z ₂)	—	z ₂ +z ₁ z ₃	z ₃ +z ₁ z ₂	4.7.2
D	YN	Y	—	a ₂ z ₁₂	—	—	z ₁₂	—	4.7.2
D	Y	YN	—	—	a ₃ z ₁₃	—	—	z ₁₃	4.7.2
D	YN	D	—	a ₂ (z ₂ +z ₁ z ₃)	—	—	z ₂ +z ₁ z ₃	—	4.7.2

NOTES

1 z_{12} , z_{13} and z_{23} are short-circuit positive-sequence impedances.

2 $z_1 = \frac{z_{12} + z_{13} - z_{23}}{2}$, similarly z_2 and z_3

3 $z_1 \parallel z_2 = \frac{z_1 z_2}{z_1 + z_2}$ similarly $z_1 \parallel z_3$ and $z_2 \parallel z_3$

4 a_1 , a_2 and a_3 are multiplying factors generally in the range $0,8 < a_1 < a_2 < a_3 < 1$

5 Particular aspects of zero-sequence impedance properties are given in 4.7.1, 4.7.2 and 4.7.3.

6 Connections marked with an asterisk (*) indicate cases where the zero-sequence impedance is a magnetizing impedance of relatively high or very high value, depending on the nature of the magnetic circuit.

4.7.1 *YNyn or YNauto without delta winding*

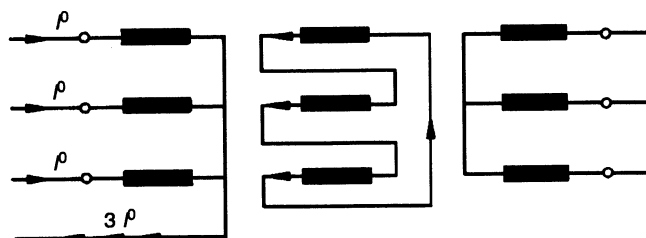
The transformer receives and transfers zero-sequence current between the two systems, provided that the neutrals are earthed. It then presents normal short-circuit impedance for the current.

If the neutral of an auto-connected transformer is not earthed, transfer of zero-sequence current is still possible but it meets a different impedance.

If no transfer of incoming zero-sequence current from a system to the opposing system is possible, then the transformer presents magnetizing impedance to the current. This magnetizing impedance is very high in five-limb core-form transformers, in shell-form transformers, and also in a bank of three single-phase transformers.

4.7.2 *YNd or Dyn or YNynd or YNyn + d (equalizer winding)*

The transformer presents low impedance (of short-circuit impedance character) to zero-sequence current from an effectively earthed system into a yn-connected winding. A circulating current around the delta winding provides compensating ampere-turns (see figure 15).



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Figure 15 – The function of an equalizer winding

This is why an additional delta-connected equalizer winding in a Yy transformer (or bank of three single-phase transformers) serves to reduce the zero-sequence impedance of the connected system and thereby its earth fault factor (see 4.4). A consequence is that the prospective earth fault current increases.

It is important to ensure that the short-circuit withstand strength of a tertiary delta winding or an equalizer winding is sufficient for the maximum induced zero-sequence current during an earth fault in either of the connected systems. Alternatively, built-in current-limiting reactors may be connected inside the delta in order to bring down the induced fault current to a tolerable value.

4.7.3 *Yzn or ZNy*

The transformer presents low impedance (of short-circuit impedance character) to zero-sequence current from the Z side system. There is inherent ampere-turn balance for the zero-sequence current within the Z-winding itself.

This is why a transformer with a ZN-connected winding is used to provide a neutral point for connection of a neutral earthing impedance to a system when the winding of the main transformer is a delta winding. The Z-connected transformer is referred to as an earthing transformer or neutral coupler; see section 6 of IEC 60289. The same function can be achieved with a winding combination YNd on the earthing transformer.

If the Y side has its neutral connected to earth (YNzn), the transformer presents magnetizing impedance to zero-sequence from that side, about the same as YNyn above. The Z-winding, which is inherently balanced for zero-sequence, cannot provide compensating ampere-turns for zero-sequence current in the opposing Y-winding.

4.8 Continuous zero-sequence loading (neutral point current)

A single-phase load on a three-phase transformer may be placed either between phases or between phase and neutral.

In the first case, the system of currents on the primary and secondary sides contain positive and negative sequence components, but not zero-sequence. The distribution of phase currents on the primary side of the transformer depends on the three-phase connection. It is not possible to convert a single-phase load to a symmetrical three-phase load on the primary side by a particular transformer connection. The allowable loading is referred to rated current of the respective windings.

If the load is drawn between phase and neutral of the transformer, there may be other restrictions than those given by the rated current of the winding. Subclause 8.1 of IEC 60076-1 requires that the neutral terminal shall always be dimensioned for the recognised earth fault current and for continuous load current through the neutral when specified (this is a normal condition for distribution transformers). It is required in annex A of IEC 60076-1 that an enquiry shall contain information on:

- the intended method of operation of the system to which the transformer windings will be connected, particularly when an equalizer winding is specified;
- any anticipated unbalanced loading.

In line with what has been described in the previous subclauses, a secondary winding neutral may in general be continuously loaded as follows, depending on winding connections, magnetic circuit design, and system earthing:

- a Dyn transformer neutral may be loaded with rated current of the winding;
- a YNyn transformer with both neutrals earthed may be loaded with rated current through its neutrals, provided that the system earthing permits this (with regard to voltage asymmetry);
- a Z-connected winding neutral may be loaded with rated current;
- a Yyn + d transformer (a transformer provided with an equalizer winding) may have its secondary neutral terminal loaded with current up to the rated current, provided that the delta-connected winding has a power rating equal to at least one-third of the power rating of the secondary winding. (The circulating current per phase of the tertiary winding balances the zero-sequence current in the secondary winding, which is, by definition, one-third of the current in the neutral);

- in a Yynd transformer which has a loadable tertiary, this tertiary will function in the same way as an equalizer winding (see previous indent). Any circulating current in the delta winding will combine with the external load current of that winding. (The total current may be measured if there are current transformers inside the delta connection in the transformer);
- a Yyn transformer without any additional delta-connected winding does not provide well-defined symmetry of the phase voltages. (This case presupposes that the primary neutral is not earthed.)
- a three-limb, core-form distribution transformer having a Yyn connection is not in general suitable for loading between phase and neutral. The voltage asymmetry will be objectionable if the neutral carries more than about 10 % of the rated current of the winding. Therefore, mixed connections, Dyn or Yzn, are preferred for distribution transformers feeding four-wire distribution systems;
- a medium-size, medium voltage transformer with this connection may carry about 25 % of the rated current for a duration of 2 h to an arc-suppression coil, in addition to full symmetrical load, without thermal risk. Such requirements should, however be specifically confirmed.

4.9 *Magnetic circuit reluctance and magnetizing impedance, steady-state saturation under abnormally high power frequency voltage*

An equivalent single-line diagram of the power transformer contains a shunt element, representing the excitation current of the magnetic circuit. In normal service, this current is very small and negligible, e.g. in conjunction with voltage drop calculations, which justifies the pattern of the equivalent circuit (see clause 7). In other words, the magnetizing inductance is very high. In terms of magnetization characteristics, the reluctance which the magnetic flux encounters is very low, i.e. the path of the main flux is easily magnetized.

If a power frequency voltage applied across the windings of any limb of the transformer is abnormally high, the core material gets saturated during part of each half-cycle. During the saturated condition, the magnetic reluctance increases considerably. A peaked, drastically increased magnetizing current is drawn from the power source.

During phenomena with saturation of the core, there is also a considerable flux outside the core-steel, between the core and the winding. This may induce high eddy currents in metallic parts outside the windings, resulting in local heating and discharges across unintentional contacts.

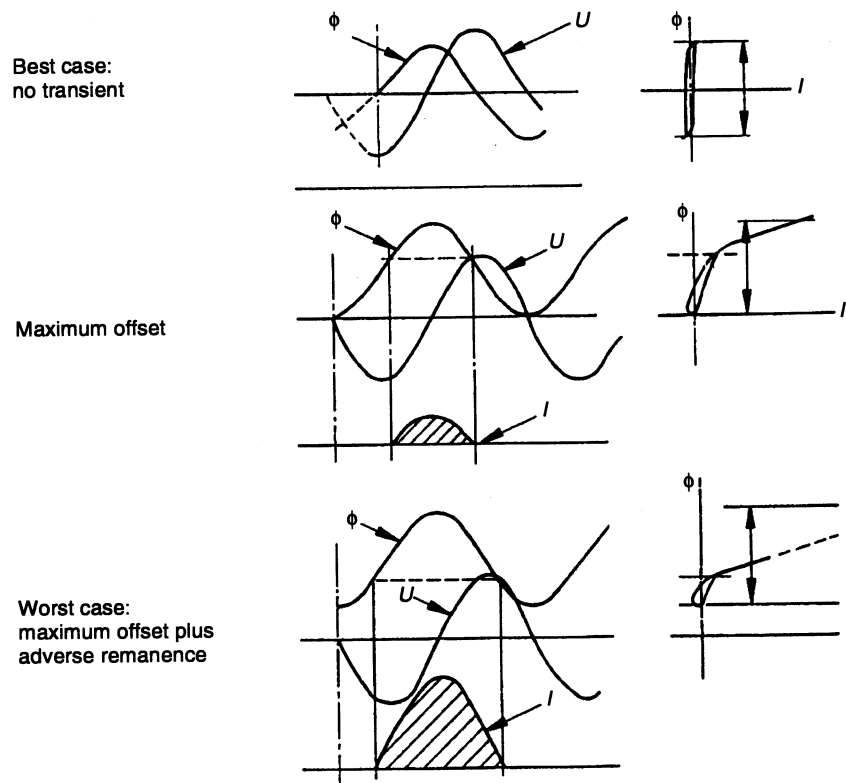
A phenomenon which may give rise to local saturation in a transformer is the excessive magnetic leakage flux occurring during the flow of heavy overload current. The leakage flux passes between the windings and part of it has a return path through the magnetic circuit. In addition, it is likely that, under these conditions, the service voltage is also abnormal. The combined result may be unforeseen saturation conditions in certain parts of the core.

4.10 *Transient saturation, inrush current*

When a transformer is suddenly energized with full system voltage, a random saturation phenomenon may occur, which is usually referred to as an inrush current (see figure 16).

In steady state, the volt-time integral of a full half-cycle of unidirectional voltage between two zero passages, applied across a phase of the winding, corresponds to the flux swing from full density in one direction to full density in the other direction.

Immediately upon energization, however, a disturbed transient condition occurs. Depending on the direction of the existing remanence in the magnetic circuit and the point-of-wave at which the voltage is applied, the transient flux density may reach the saturation limit of the core-steel and have to rise above that value, before the applied voltage changes sign. The transient magnetizing current amplitude may reach any peak value up to a maximum which may be higher than the rated current and approach the through-fault short-circuit current of the transformer.



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Figure 16 – Inrush transients

From the description of the phenomenon, it is evident that it is a random occurrence which develops in full only now and then in several energizations. The inrush current from the system appears with different magnitude in different phases. When a delta-connected winding or a star-connected winding with effectively earthed neutral is energized, the phenomenon is linked to the individual limb, while in a star winding without neutral current connection, a combination of two-limb windings in series is initially involved.

When high inrush current occurs, it is always offset and appears with high amplitudes of one polarity only. The inrush current therefore contains a d.c. component which decays in less than 1 s. The decay time is longer for transformers having low-loss core material and it tends to be longer for large transformers. This d.c. component and the high harmonic content of the current