

DC Machines and Transformers

Chapter 5

Three Phase Transformer

Detailed Notes for Engineering Students

with Diagrams, Tables, 15 MCQs (with Answer Key) and 10 Broad Questions

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Introduction

Electric power is generated, transmitted and distributed almost entirely as **three-phase alternating current**. A three-phase supply needs less conductor material for the same power, gives a constant instantaneous power and permits the use of self-starting induction motors. Voltage levels in such a system must be raised for transmission and lowered again for distribution and utilisation, and this is done by **three-phase transformers**.

A three-phase transformer is a static device that transfers three-phase electrical energy from one voltage level to another at the same frequency by electromagnetic induction. The three primary and three secondary windings may be arranged on three separate single-phase cores or on one common core. Their terminal connection (star, delta or zig-zag) decides the voltage ratio, the phase displacement and the behaviour of the transformer on unbalanced loads and on harmonics.

Basic three-phase relations used throughout the chapter

Connection	Line voltage V_L	Line current I_L	Remarks
Star (Y)	$\sqrt{3} \times V_{ph}$	I_{ph}	Neutral point available; insulation of each winding is for $V_L/\sqrt{3}$
Delta (D)	V_{ph}	$\sqrt{3} \times I_{ph}$	No neutral; circulating path for third harmonic
Zig-zag (Z)	$\sqrt{3} \times V_{ph}$	I_{ph}	Each phase made of two half windings on two limbs

Three-phase power (any connection): $S = \sqrt{3} V_L I_L$ (VA) and $P = \sqrt{3} V_L I_L \cos \phi$ (W).

5.1 Types of Three Phase Transformer

Three-phase transformation can be achieved in two ways: by **connecting three identical single-phase transformers** together (a transformer bank) or by using **one three-phase transformer unit** in which all the windings are placed on a common magnetic core.

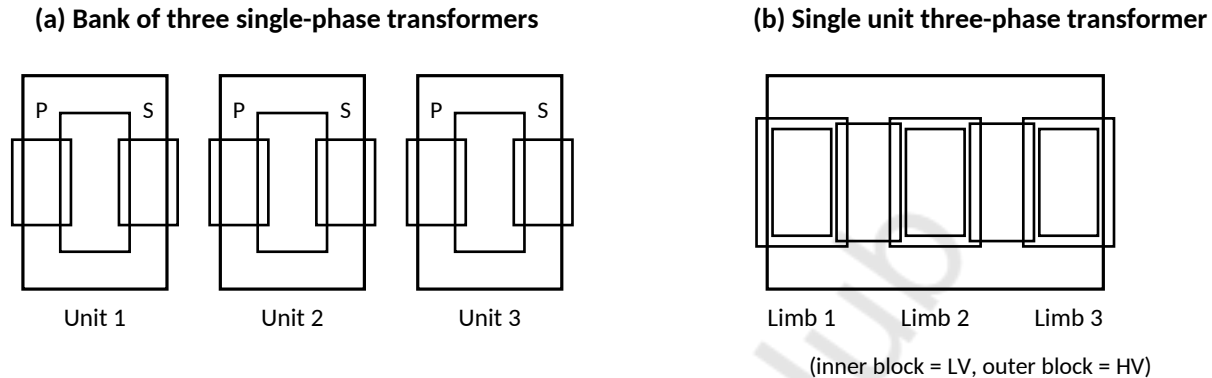


Fig. 5.1 Bank of three single-phase transformers and a single unit three-phase transformer

A. Bank of three single-phase transformers

Three separate single-phase transformers, each having its own core, primary winding and secondary winding, are inter-connected externally in star or delta on both sides to form a three-phase bank. The three units are of identical rating, voltage ratio and impedance. Magnetically the three phases are completely independent of one another.

Advantages

- If one unit fails, the other two can be re-connected in **open delta (V-V)** and supply a reduced load, so supply is not totally lost.
- Only **one spare single-phase unit** is needed as stand-by for the whole bank; this is economical for very large ratings.
- Each unit is lighter and smaller, so transport and installation is easy (very high ratings such as 400 kV, 500 MVA and above).
- Phases are magnetically independent, so there is no problem of unbalanced flux or third harmonic flux in the core.

Disadvantages

- Requires more floor space, more core material, more oil and more connections; **cost is about 15 % higher** than a single three-phase unit.
- Efficiency is slightly lower and no-load loss is higher than the equivalent three-phase unit.
- More bushings, more cabling and a larger switchyard layout are needed.

B. Single unit three-phase transformer

In this type, all the three primary and three secondary windings are wound on a common laminated core that has three limbs (core type) or five limbs/shell form. The whole assembly is placed in one tank. It is the most common type in distribution and in ratings up to a few hundred MVA.

Advantages

- Lower initial cost, less weight, less oil and less floor space for the same kVA.
- Higher efficiency because of lower core loss and better utilisation of core and winding.
- Only one set of bushings, one tank, one tap-changer and one set of fittings; installation and maintenance is simple.

Disadvantages

- A fault in any one phase puts the **entire unit out of service**; a complete spare three-phase unit is costly.
- Heavy and bulky for transport at very high ratings.
- Three-limb core is not suitable for some connections (e.g. Y-Y without delta tertiary) as the zero sequence flux has no return path.

Comparison table

Point	Bank of three single-phase units	Single three-phase unit
Number of cores / tanks	Three / three	One / one
Cost, space and weight	Higher	Lower
Efficiency	Slightly lower	Higher
Spare required	One single-phase unit (about 1/3 of total)	Complete three-phase unit
Effect of one phase fault	Remaining two units can run in V-V (about 58 % of bank rating)	Whole transformer is out of service
Transport	Easy (small units)	Difficult at very high ratings
Typical use	Very large EHV transformers, power stations	Distribution, sub-stations, industry

5.2 Construction of 3-Phase Transformer: Different Types of Winding

The main parts of a three-phase oil-immersed transformer are the **magnetic core**, the **windings**, the **insulation**, the **tank** with oil and the accessories such as bushings, conservator, breather, Buchholz relay, tap changer and radiators.

A. Magnetic core

- The core is built of thin **CRGO (cold rolled grain oriented) silicon steel laminations**, 0.23 to 0.35 mm thick, each coated with a thin insulating varnish. Lamination reduces eddy current loss and grain orientation reduces hysteresis loss.
- **Core type:** the windings surround the limbs of the core. A three-limb core is the usual form; the three fluxes are 120° apart, so their sum is zero at every instant and the centre limb does not need a separate return path. The limbs are joined by upper and lower yokes.
- **Five-limb core:** two extra outer limbs provide a return path for the zero-sequence (third harmonic) flux; used in large EHV units to reduce height.
- **Shell type:** the core surrounds the windings; it has a central limb and outer limbs, giving better short-circuit strength and natural return path for flux.
- Joints between limbs and yokes are **mitred and overlapped (step-lap)** to reduce reluctance. The limb cross-section is made **stepped (cruciform)** to fit the circular coils and utilise space.

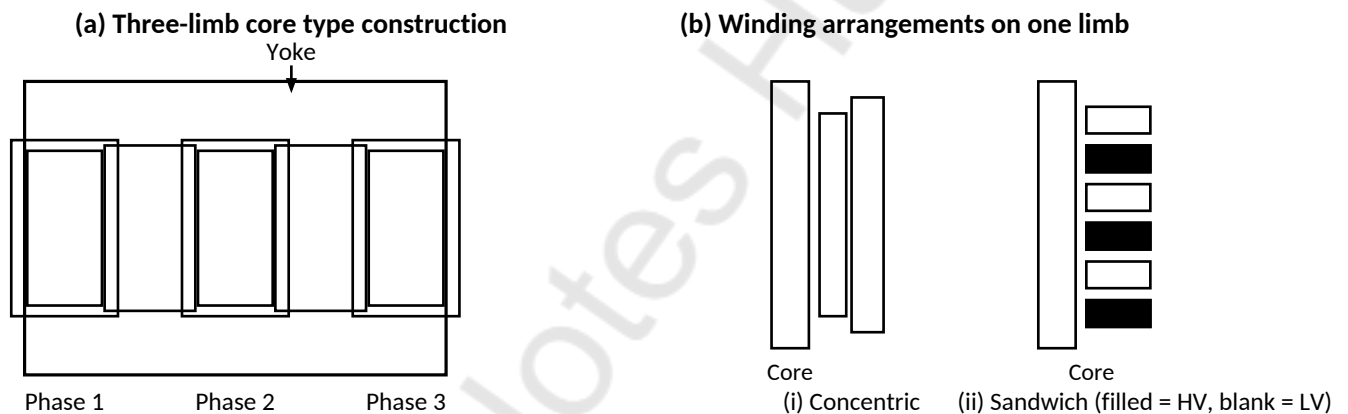


Fig. 5.2 Three-limb core type transformer and types of winding arrangement

B. Windings

Windings are made of **copper or aluminium** conductors insulated with paper (cotton, kraft) or enamel. For a core type transformer the **LV winding is placed nearer the core** (it needs less insulation to the core) and the **HV winding is placed outside it**, with insulating cylinders and oil ducts between them.

Types of winding used in 3-phase transformers

Type of winding	Description	Used for
Concentric (cylindrical) winding	HV and LV coils are cylindrical and concentric on a limb. Includes helical, spiral and layer forms: turns wound in layers or helix with ducts for oil.	Core type transformers; low current windings (LV side of distribution transformers)
Cross-over winding	Several layers of wire wound in coil form, each coil having many turns; the end of each coil is taken to the start of the next (cross-over).	HV windings of small rating (up to about 20 kVA, 6 kV)
Helical winding	Several parallel strips wound as a helix along the limb; turns are placed side by side with spacers.	High current LV windings (up to a few hundred amps)
Disc and continuous disc winding	Flat discs of turns stacked axially with radial oil ducts; continuous disc is a single winding wound without joints between discs.	HV windings of medium and large power transformers (above 33 kV)
Sandwich (interleaved) winding	HV and LV coils are flat discs placed alternately along the limb with LV discs at both ends; reduces leakage reactance.	Shell type transformers
Foil winding	Thin sheet (foil) of copper/aluminium wound with insulating sheet between turns.	LV windings of dry type and distribution transformers; good short-circuit strength

C. Insulation and cooling ducts

- Insulation between turns and layers is of **paper and pressboard**; between windings and to earth it is of pressboard barriers and oil gaps.
- Transformer oil** (mineral oil) serves a double purpose: it is a good insulator (dielectric strength of 30 kV or more for 2.5 mm gap) and carries heat from the core and windings to the tank and radiators.

D. Main parts and accessories

Part	Function
Tank	Steel container with the core, windings and oil; provided with cooling tubes or radiators
Conservator	Auxiliary tank above the main tank which allows oil to expand and contract with temperature
Breather (silica gel)	Dries the air that enters the conservator, removing moisture and keeping oil healthy
Buchholz relay	Gas-operated relay between tank and conservator; gives alarm for slow faults and trips for serious faults (above about 500 kVA)
Bushings	Porcelain insulators that bring HV and LV terminals out of the tank
Tap changer	Changes the number of turns to adjust output voltage (off-circuit or on-load)
Explosion vent / pressure relief device	Releases excess internal pressure in case of a severe fault
Oil and winding temperature indicators	Show the top-oil and winding temperature; give alarm and trip signals

5.3 Connections of 3-Phase Transformer as per IS:2026 (Part-IV)-1977

The three primary and three secondary windings of a three-phase transformer can be connected in **star**, **delta** or **zig-zag**. IS:2026 (Part-IV)-1977 deals with the **terminal marking**, **tappings and connections** of power transformers. It classifies the connections into groups according to the **phase displacement between the HV and LV line voltages** and gives a symbol (vector group) for each connection.

Symbols used in the vector group notation

Symbol	Meaning
Capital letters Y, D, Z	Connection of the HV winding: Y = star, D = delta, Z = interconnected star (zig-zag)
Small letters y, d, z	Connection of the LV winding
N or n	Neutral point of the HV (N) or LV (n) winding is brought out
Number 0, 1, 6, 11	Clock-hour figure: the angular displacement of the LV line voltage with respect to the HV line voltage, one hour = 30°. HV phasor is kept at 12 o'clock.

Classification into groups

According to the standard, the connections are placed in four groups. The numbers show how far the LV voltage phasor is shifted in clock position:

Group	Phase displacement	Clock position	Connections
Group I	0°	0	Yy0, Dd0, Dz0
Group II	180°	6	Yy6, Dd6, Dz6
Group III	-30° (LV lags HV by 30°)	1	Dy1, Yd1, Yz1
Group IV	$+30^\circ$ (LV leads HV by 30°)	11	Dy11, Yd11, Yz11

Long hand = HV phasor (fixed at 12); thick short hand = LV phasor (hour position)

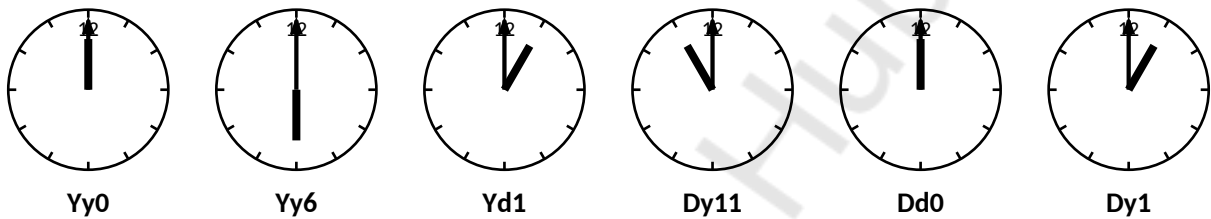


Fig. 5.3 Clock diagrams of some vector groups

Common connections and their features

Connection	Voltage ratio (line)	Advantages	Disadvantages / limitations
Star-Star (Y-y)	(N_1/N_2)	Economical for small high voltage units (less turns, insulation for $V/\sqrt{3}$); neutral for earthing and 4-wire supply; no phase shift	Unbalanced load disturbs neutral; third harmonic voltages appear unless neutral earthed or tertiary delta is used
Delta-Delta (D-d)	(N_1/N_2)	No phase shift; third harmonic currents circulate inside delta; can run in open delta if one unit fails; suitable for large low voltage heavy currents	No neutral; more insulation; difficult to earth; no 4-wire supply
Star-Delta (Y-d)	$\sqrt{3} (N_1/N_2)$	Used for step-down at the receiving end; HV neutral can be earthed; no third harmonic trouble; stable under unbalanced load	30° phase shift; LV has no neutral; secondary insulation costly
Delta-Star (D-y)	$(1/\sqrt{3})(N_1/N_2)$	Step-up at generating stations; most common distribution connection (Dyn11) giving 3-phase 4-wire LV supply with neutral and good balance	30° phase shift; earth fault on LV not reflected as earth fault on HV
Star-Zig-zag (Y-z)	$(2/\sqrt{3})(N_1/N_2)$	Good for unbalanced loads; no third harmonic; low zero-sequence impedance	More copper (about 15 % extra on secondary); costlier

Star-delta and delta-star in detail

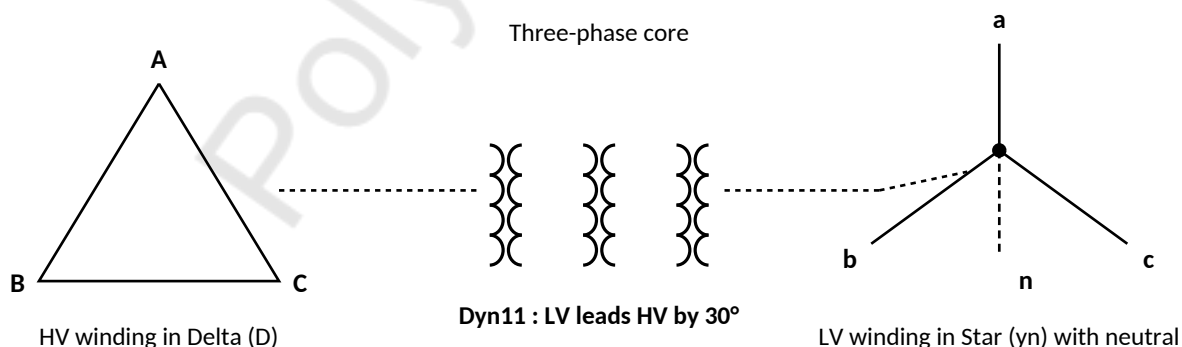


Fig. 5.4 Delta-star (Dyn) connection of a three-phase transformer

- **Delta primary, star secondary (Dyn11):** line voltage ratio $V_{L2}/V_{L1} = \sqrt{3} N_2/N_1$. The primary line current is $\sqrt{3}$ times the winding current. The secondary line voltage leads the primary line voltage by 30°.
- **Star primary, delta secondary (Yd1):** $V_{L2}/V_{L1} = N_2/(\sqrt{3} N_1)$. The secondary line voltage lags the primary by 30°.

Necessity of different connections

- To obtain different **voltage ratios** at the same turns ratio (a star-delta transformer steps down by an additional factor of $\sqrt{3}$).
- To provide a **neutral** for earthing or for a 4-wire LV supply (star secondary with neutral, Dyn).
- To **suppress third harmonic** voltages and currents by circulating them in a delta winding.
- To obtain the required **phase displacement** so that the transformer can be paralleled with others or connected with another system (e.g. 30° shift between two grids).
- To maintain **balance on unbalanced loads** (delta or zig-zag windings carry the unbalance without shifting the neutral).
- To limit **earth fault current** and to provide a path for zero-sequence currents according to the protection scheme.

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5.4 Practical Application of Zig-zag Connection in Earthing Transformer

Zig-zag (interconnected star) connection

In a zig-zag connection each phase winding is split into **two equal halves placed on two different limbs** of the core. The half-winding of one limb is connected in **series opposition** with a half-winding of the next limb, and the three phase groups are joined to a common neutral point. The resultant phase voltage is the **phasor difference** of the induced voltages of two limbs, which are 60° apart, therefore:

Resultant phase voltage = $2 E \cos 30^\circ = \sqrt{3} E$ (E = voltage of one half winding)

The phase voltage is only $\sqrt{3}/2 = 0.866$ of the arithmetic sum of the two halves, so about 15 % more copper is needed than for an ordinary star.

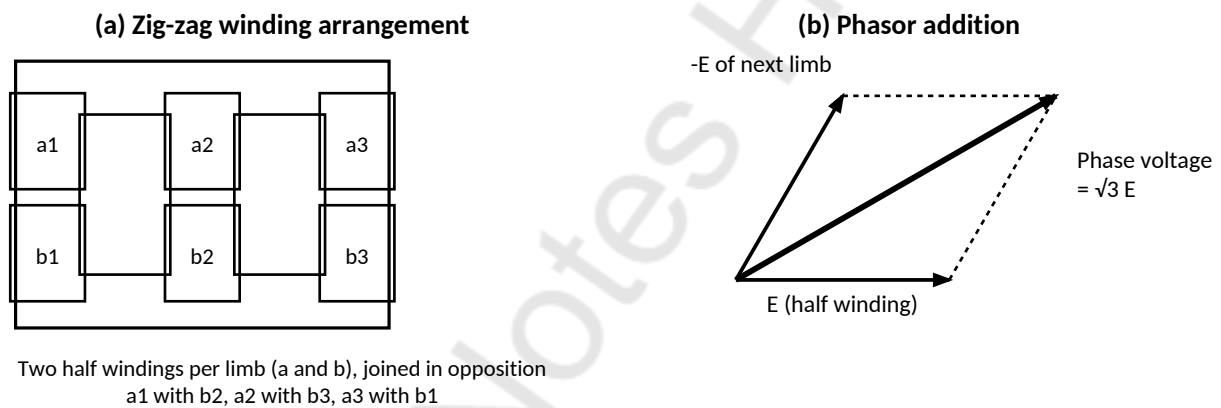


Fig. 5.5 Zig-zag winding and phasor addition of half-winding voltages

Behaviour of the zig-zag winding to sequence currents

- **Positive and negative sequence currents:** the two half-windings on a limb carry currents that are 120° apart, ampere-turns balance poorly with the other winding, so the winding offers **high impedance** (magnetising impedance) to these currents.
- **Zero sequence currents:** the currents in all three phases are in phase. The two half-windings on each limb carry equal currents in opposite directions, so the mmf and the zero-sequence flux in the core cancel out. The winding therefore offers only **leakage impedance, which is very low**, to zero sequence current.

Earthing transformer (neutral coupler)

A system with an ungrounded delta or ungrounded star has no neutral point for earthing. An **earthing transformer** is a three-phase zig-zag (or star-delta with open delta) transformer connected to the bus bars and used **only to create an artificial neutral** that can be connected to earth, directly or through a resistor or reactor. It has no secondary load (or only a small auxiliary winding).

Working

- Under normal balanced conditions the earthing transformer draws only a **small magnetising current**; it behaves as a high-impedance device and carries practically no load.
- When a **single line to earth fault** occurs, the zero-sequence fault current flows through the earthed neutral and divides equally into the three phases. As the winding presents a low zero sequence impedance, the fault current is carried by the earthing transformer and flows back to the fault, so the fault current is high enough for the relay to operate.
- A **neutral earthing resistor** is added to limit the fault current to a safe value (typically 100 A to 1000 A).

Practical applications

Application	Purpose
Creating a neutral on 11 kV / 33 kV delta-connected system	Provides a neutral point for earthing so that earth faults can be detected by protection
Neutral earthing of the delta side of a power transformer	Gives path for zero-sequence current to operate earth fault relays
Limiting earth fault current	Combined with a neutral resistor/reactor to keep fault current within safe limits and avoid damage to equipment
Suppressing arcing grounds and over-voltages	Solid or resistance earthing prevents severe transient over-voltage on healthy phases
Zig-zag secondary in Dz / Yz distribution transformers	Gives good performance with unbalanced and rectifier loads; no DC magnetisation problem
Providing auxiliary supply	A secondary winding on the earthing transformer can supply station auxiliaries (e.g. 415 V)

Rating note: an earthing transformer carries fault current for a short time only (typically 10 seconds), so it is rated for short-time duty and is much smaller than a normal transformer of the same continuous kVA.

5.5 Concept of Tertiary Winding and Its Utility

A **tertiary winding** is a **third winding** provided in addition to the primary and secondary windings of a transformer. It is usually connected in **delta** and is of lower voltage and smaller rating than the main windings. It may be brought out to terminals or kept closed inside the tank (a *stabilising winding*).

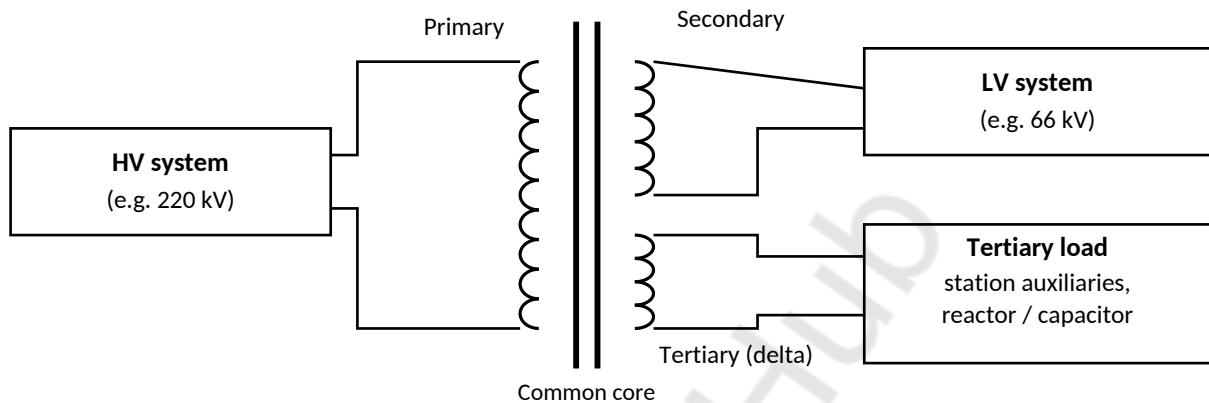


Fig. 5.6 Transformer with primary, secondary and tertiary windings

Utility (uses) of tertiary winding

- 1 **Providing a path for third harmonic currents:** in a star-star transformer the third harmonic magnetising current cannot flow, giving distorted voltage. A delta tertiary allows these triple-frequency currents to circulate and so removes them.
- 2 **Stabilising the neutral:** in a Y-Y transformer with isolated neutral, load unbalance shifts the neutral point. A delta tertiary reduces the zero-sequence impedance and keeps phase voltages balanced.
- 3 **Supplying auxiliary loads:** a separate lower voltage (e.g. 11 kV or 415 V) from the tertiary can supply station auxiliaries, lighting or local consumers without an extra transformer.
- 4 **Reactive power compensation:** shunt reactors, capacitors or synchronous condensers are connected to the tertiary to control voltage and power factor of the system.
- 5 **Interconnection of three systems:** a three-winding transformer ties together three networks of different voltages (e.g. 220 kV, 132 kV and 33 kV) with a single unit.
- 6 **Reducing zero-sequence impedance** and allowing sufficient earth fault current for protection (when the main windings are star with earthed neutral).
- 7 **Supplying a measuring and protective load**, such as the voltage source for relays, in some EHV transformers.

Points to remember

- The tertiary winding must withstand the same through fault currents as the main windings; the short circuit stress on a closed-delta stabilising winding is severe.
- The impedance of tertiary winding is chosen so that fault current is limited, and it is usually rated for about one-third of the main kVA when it is only a stabilising winding.

- Common vector groups with tertiary: **YNyn0d11** (HV star earthed, LV star, tertiary delta) used in 400/220 kV and 220/132 kV auto transformers and power transformers.
- The tertiary adds cost and complexity; it is used only where the above benefits are required.

Connection summary

Winding	Usual connection	Typical role
Primary	Star (earthed neutral)	Connected to higher voltage system
Secondary	Star (earthed neutral)	Connected to lower voltage system
Tertiary	Delta (closed or brought out)	Harmonic path, auxiliary supply, reactive compensation

5.6 Different Cooling Methods of Transformer

The core loss and copper loss appear as heat. If this heat is not removed the temperature of the insulation rises and the life of the transformer reduces (a rise of about 6–8 °C above the limit halves the insulation life). The **cooling method** is chosen according to size, rating and location. Cooling is designated by a four-letter code as per **IS:2026 (Part II)**.

Coding of cooling methods

Letter position	Meaning	Letters used
First	Internal cooling medium in contact with windings	O = mineral oil, A = air, G = gas, L = non-flammable synthetic liquid
Second	Circulation mechanism for internal medium	N = natural, F = forced (non-directed), D = forced and directed through windings
Third	External cooling medium	A = air, W = water
Fourth	Circulation mechanism for external medium	N = natural, F = forced (fans or pumps)

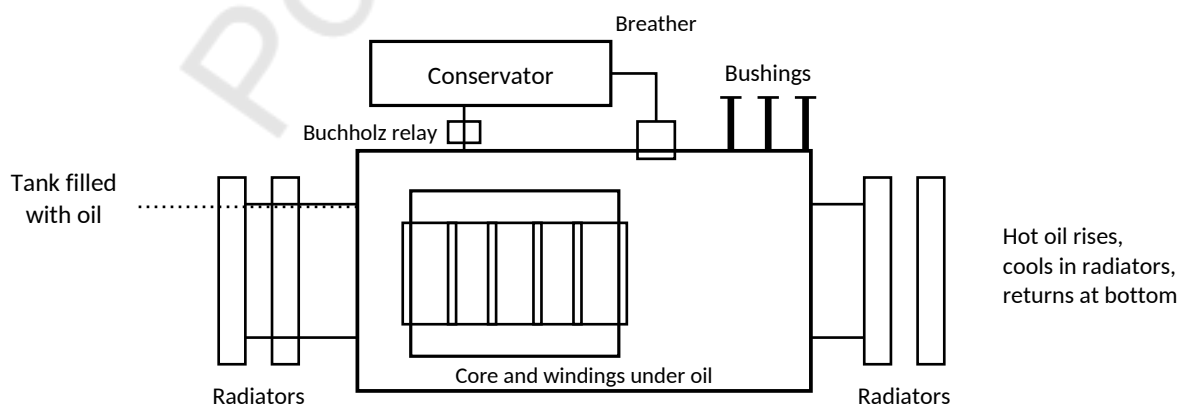


Fig. 5.7 Oil immersed transformer with conservator, breather and radiators (ONAN)

Types of cooling

Designation	Name	Method of cooling	Typical use
AN	Air Natural (dry type)	Heat dissipated by natural air convection from core and winding surfaces; no oil	Small dry type transformers up to about 1.5 MVA, indoor
AF / AB	Air Forced / Air Blast	Fans blow air over the core and windings	Dry type transformers of higher ratings; furnaces, mines
ONAN	Oil Natural Air Natural	Oil circulates by natural convection to tank walls and radiators; air cools tank by natural convection	Most distribution and small power transformers (up to about 30 MVA)
ONAF	Oil Natural Air Forced	Natural oil circulation; fans on radiators increase heat removal	Medium power transformers; fans switched on at higher load; increases rating by about 25–60 %
OFAF	Oil Forced Air Forced	Pumps circulate oil through external air-cooled radiators/coolers with fans	Large power transformers
OFWF	Oil Forced Water Forced	Pumps circulate oil through oil-to-water heat exchangers; water is also forced	Large transformers in power stations where water is available
ODAF / ODWF	Oil Directed Air/Water Forced	Oil is forced and directed through the winding ducts by pumps, then cooled by air or water	Very large EHV transformers; very high loading density

Other points

- **Self-cooled sealed type** (hermetically sealed) transformers have no conservator; the tank corrugations give the cooling surface. Used up to about 1–2 MVA.
- **Radiator and corrugated tank** increase the cooling surface; corrugations are common in distribution transformers.
- **Transformer oil** must be tested regularly for dielectric strength, moisture and dissolved gases.
- Where more than one cooling stage is provided, the nameplate shows ratings like **ONAN/ONAF** (e.g. 20/25 MVA).

5.7 Three-phase Auto Transformer

Construction

An autotransformer has **only one winding per phase**, part of which is common to the primary and the secondary. The three-phase autotransformer has three such windings on a three-limb core, usually connected in **star** with the common neutral point **solidly earthed**. The full winding of each phase is connected to the HV terminal (A, B, C), and a tapping at an intermediate point is connected to the LV terminal (a, b, c).

- The winding between the tapping and the HV terminal is called the **series winding**; the winding between the tapping and neutral is the **common winding**.
- Core, oil, tank and cooling are the same as in a two-winding transformer; HV terminal bushing is at line to earth insulation level, LV bushing at its own level.
- A delta connected **tertiary winding** is generally added in large autotransformers to suppress third harmonics and for stabilisation (YNa0d11).

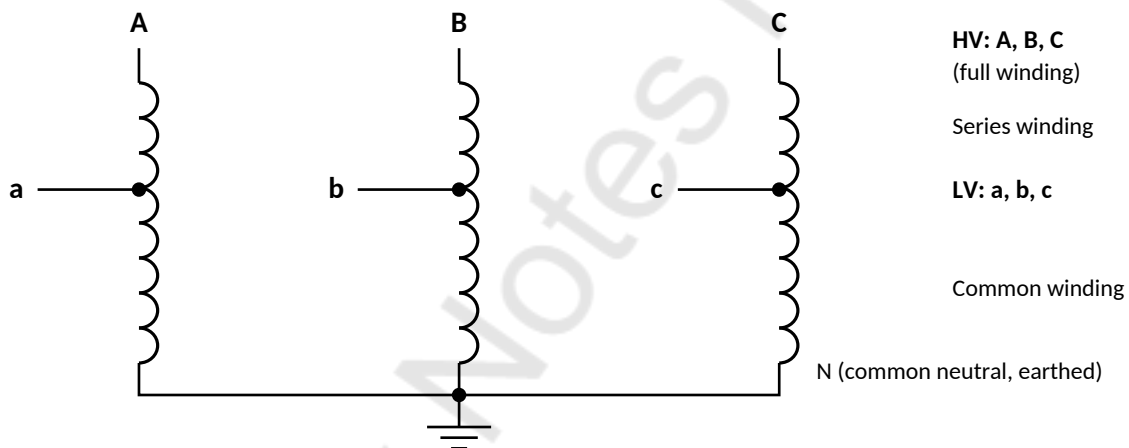


Fig. 5.8 Three-phase star-connected autotransformer (step-down)

Working principle

When the HV winding is energised, an alternating flux in the core induces an e.m.f. in every turn. Voltage per turn is the same everywhere, so the voltage between tapping and neutral is proportional to the number of turns in the common winding. Load current of the LV side is partly supplied directly from the source through the series winding (**conduction**) and partly by **transformer action** (induction).

Let $K = V_2 / V_1 = N_2 / N_1$ ($K < 1$ for step-down). Input apparent power $S = V_1 I_1$.

Power transferred by transformer action = $(1 - K) S$; power transferred directly by conduction = $K S$.

Current in common winding = $I_2 - I_1 = I_1 (1/K - 1)$; copper required = $(1 - K) \times$ that of a two-winding transformer.

Saving in copper = $K \times$ (weight of copper of an equivalent two-winding transformer).

Advantages and disadvantages

Advantages	Disadvantages
Smaller size, lower weight and lower cost, especially when K is near 1	No electrical isolation between HV and LV sides
Less copper and iron, so lower losses and higher efficiency	Higher short-circuit current because impedance is lower
Better voltage regulation (lower leakage reactance)	A fault on HV side can transfer high voltage to LV side; LV equipment must have HV-level insulation
Greater kVA rating for the same size	Neutral must be solidly earthed; unsuitable when ratio is high (K much less than 0.5)

Applications

- Interconnecting EHV transmission systems of nearby voltage levels, e.g. **400/220 kV**, **220/132 kV**, **132/66 kV** grid auto transformers.
- **Starting of induction and synchronous motors** (auto-transformer starter with 50 %, 65 %, 80 % taps) to reduce starting current.
- Boosting or reducing supply voltage in **rural distribution lines** (voltage booster).
- Variable output voltage supply (**variac** / dimmerstat) in laboratories and testing.
- Voltage regulation and as 'tap' for traction and railway supply.

5.8 Scott-connected Transformer

The **Scott connection** (Scott-T connection) uses **two single-phase transformers** to convert a **three-phase supply into two-phase supply** (two equal voltages displaced by 90°), or vice versa. It was devised by C. F. Scott.

Connection

- Two single-phase transformers of identical secondary ratings are used: the **main transformer (M)** and the **teaser transformer (T)**.
- The primary of the main transformer has a **centre tap (D)** and is connected across two lines (B and C) of the three-phase supply, with N_1 turns.
- One end of the teaser primary is connected to the **third line (A)** and the other end to the centre tap D of the main primary.
- The teaser primary has **86.6 % ($\sqrt{3}/2$) of the main primary turns**, i.e. $0.866 N_1$.
- Both secondaries have the **same number of turns N_2** and give two equal voltages with a 90° phase difference (two-phase 2-wire or 3-wire output).

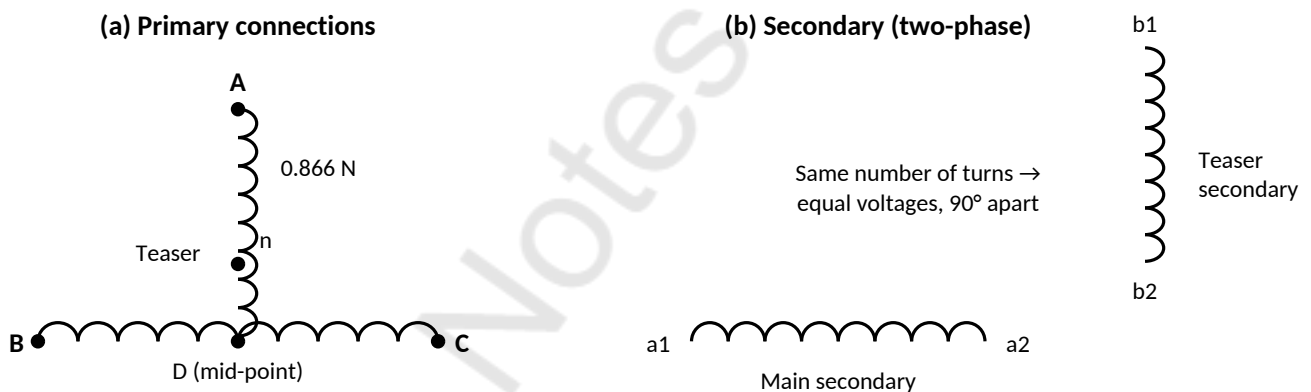


Fig. 5.9 Scott connection: three-phase primary and two-phase secondary

Working principle

The voltage across the main primary is the line voltage $V_{BC} = V_L$. The point D is at the middle of BC, so the voltage V_{DA} is the perpendicular median of the equilateral triangle formed by line voltages and has magnitude $(\sqrt{3}/2) V_L = 0.866 V_L$, and it is **at 90° to V_{BC}** . To produce the same voltage per turn in both cores, the teaser primary is given $0.866 N_1$ turns. Equal turns on both secondaries then produce equal voltages, 90° apart.

$$V_{\text{main}} = V_L (N_2/N_1) \text{ at } 0^\circ$$

$$V_{\text{teaser}} = 0.866 V_L \times N_2/(0.866 N_1) = V_L (N_2/N_1) \text{ at } 90^\circ$$

Neutral point n on the teaser primary is at **$1/3$ of the teaser turns from D** ($2/3$ from A), so a 3-phase 4-wire supply is also possible.

Important points

- Under a balanced two-phase load the three-phase primary currents are also balanced and equal in magnitude; thus a Scott-T presents a balanced load to the three-phase supply.
- Main transformer carries current in phase with line B-C, teaser carries current in quadrature; the rating of the transformers is not fully utilised (utilisation factor about 0.866 of the rated sum for the teaser).
- The connection is **reversible**: a two-phase supply can be converted into three-phase supply.

Practical applications

Application	Explanation
Electric traction (railways)	Two single-phase traction feeders (90° apart) are supplied from a three-phase grid, giving balanced loading of the three-phase system
Two-phase supply for old two-phase motors and servo systems	Conversion from the three-phase mains to a two-phase supply (e.g. for servo motors and control equipment)
Electric arc furnaces and welding	Two large single-phase loads are balanced across the three-phase supply
Three-phase to two-phase conversion in testing and laboratories	Generation of two-phase quadrature voltage for instruments
Interconnecting 2-phase and 3-phase systems	Both directions of conversion are possible

5.9 Open Delta Connection (V-V Connection)

If one transformer of a delta-delta bank of three single-phase transformers is removed (because of a fault or for maintenance), the other two units can still supply a three-phase load. This is called the **open delta** or **V-V connection**. The three line voltages remain balanced and equal (the third voltage is the phasor sum of the other two), although the capacity of the bank is reduced.

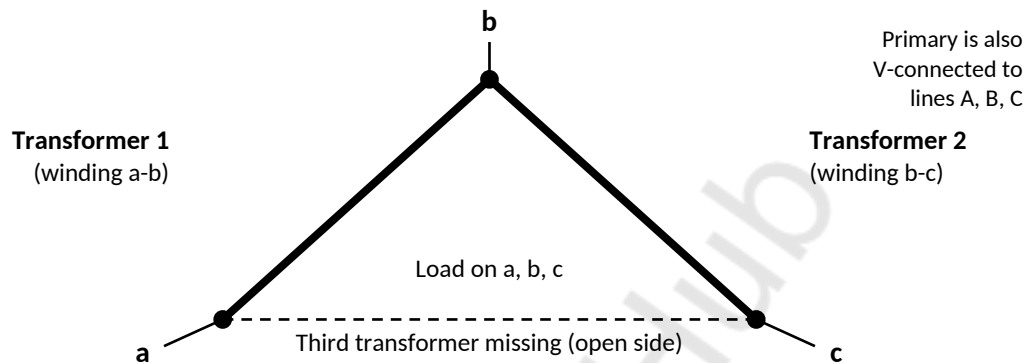


Fig. 5.10 Open delta (V-V) connection of two single-phase transformers

Working principle

- Let the rating of each single-phase transformer be $S_t = V I$ (V = rated winding voltage, I = rated winding current).
- In the V-V connection the line current equals the winding current ($I_L = I$), and the line voltage equals the winding voltage ($V_L = V$).
- The total three-phase output is therefore $S_{V-V} = \sqrt{3} V_L I_L = \sqrt{3} V I = \sqrt{3} S_t$.

Closed delta (three units) rating = $3 S_t$; Open delta rating = $\sqrt{3} S_t = 1.732 S_t$

Ratio of open delta to closed delta output = $\sqrt{3} S_t / 3 S_t = 1/\sqrt{3} = \mathbf{0.577 (57.7 \%)}$

Utilisation factor = $\sqrt{3} S_t / 2 S_t = \sqrt{3}/2 = \mathbf{0.866 (86.6 \%)}$

Power factor of the two transformers: $\cos(30^\circ - \phi)$ and $\cos(30^\circ + \phi)$ for load p.f. = $\cos \phi$ (they are unequal; at unity p.f. each works at 0.866).

Merits and demerits

Merits	Demerits
Supply of three-phase power continues if one transformer fails or is taken out for maintenance	Output is only 57.7 % of closed delta (not 66.7 %), so the two units are utilised to just 86.6 %
Cheaper installation; two transformers instead of three; useful when the load is small and likely to grow later (a third unit can be added)	Secondary voltages become slightly unbalanced because of unequal impedance drops
Lighter, needs less space; easy for rural and temporary supply	Cannot supply a neutral (no 4-wire supply) and not good for heavily unbalanced loads
No phase shift between primary and secondary line voltages	Windings are loaded unequally (different p.f.), so heating is unequal and regulation is poor

Practical applications

- Emergency operation of a delta-delta bank when one unit of the bank is damaged.
- Supplying a **small three-phase load in rural and remote areas** where the load will be increased later, so a third transformer can be added to make closed delta.
- Temporary supply at construction sites, small industrial loads and agricultural pump sets.
- As a **V-V (open delta) potential transformer** arrangement for measurement in sub-stations (two PTs measure three line voltages).

5.10 Selection of Power and Distribution Transformer; Amorphous Core; IS:1180 (Part I)-1989

Power transformer and distribution transformer

Power transformers are used in generating stations and transmission sub-stations to step voltage up or down at high ratings. **Distribution transformers** are used at the last step to reduce the voltage (such as 11 kV or 33 kV) to the utilisation voltage (415 V / 240 V). The difference between the two decides how they are selected.

Point	Power transformer	Distribution transformer
Location	Power stations, EHV/HV sub-stations	Pole-mounted or plinth-mounted near the consumers
Rating and voltage	Above 500 kVA to several hundred MVA; voltage 33 kV and above (66, 132, 220, 400 kV)	Up to about 2500 kVA; 11 kV, 22 kV or 33 kV to 415 V
Loading	Operates near full load (high load factor) most of the time	Load varies widely during the day; often lightly loaded
Design for efficiency	Maximum efficiency at or near full load (copper loss = iron loss at full load)	Low iron loss ; maximum efficiency at about 50–60 % load; evaluated by all-day efficiency
Flux density and size	Core designed with higher flux density, large size	Lower flux density, compact
Voltage control	On-load tap changer (OLTC)	Off-circuit tap changer (typically $\pm 5\%$ in 2.5 % steps)
Protection and fittings	Buchholz relay, OTI/WTI, differential and REF relays, PRD, forced cooling	Simple fuses/HG fuse, breather; conservator on larger units; usually ONAN
Vector group	As per system need: YNyn0d11, YNd1, YNa0d11 etc.	Dyn11 for 3-phase 4-wire LV
Cost and maintenance	Costly; scheduled maintenance and monitoring	Cheap, low maintenance

Criteria for selection of a transformer

- 1 **kVA/MVA rating** to suit the maximum demand with provision for future growth (typically 20–25 %) and overload capacity.
- 2 **Voltage ratio and tapping range** to match the system voltages and the variations at the sub-station.
- 3 **Frequency, number of phases and vector group** required by the system and the parallel operation needs.

- 4 **Percentage impedance:** it governs voltage regulation, short circuit level and parallel operation; a low impedance gives good regulation but high fault current.
- 5 **Losses:** no-load loss and load loss, and the capitalised cost of losses; the lowest **total owning cost** (purchase price + cost of losses) is the best choice, not the lowest price.
- 6 **Type of cooling,** ambient temperature, altitude and the site (indoor/outdoor, dust, pollution, humidity).
- 7 **Insulation level** (impulse level) and clearances, as per system voltage.
- 8 **Type of loading:** continuous, cyclic or with harmonics (rectifier load requires K-rated or derated transformers).
- 9 **Noise level,** size and weight (limits at site and during transport), fire safety (oil vs dry type, especially in buildings).
- 10 **Conformity with standards** (IS:2026, IS:1180, IS:10028) and availability of spares and service.

Amorphous core distribution transformer

An **amorphous core transformer** uses a core made of **amorphous metal** (metallic glass), an alloy of iron, boron and silicon, instead of conventional CRGO steel. The alloy is produced by **rapid solidification** (cooling at about one million °C per second) of molten metal into very thin ribbons about 0.025 mm thick. The atoms have a random, non-crystalline structure, so there are no grain boundaries to resist magnetisation.

Property	Amorphous core	CRGO silicon steel
Thickness of lamination	About 0.025 mm	0.23–0.35 mm
No-load (core) loss	About 60–70 % lower	Higher (base)
Saturation flux density	About 1.5 T (lower)	About 1.9–2.0 T (higher)
Stacking factor	Lower (about 0.85–0.9)	Higher (about 0.95–0.97)
Mechanical nature	Very brittle and hard; special cutting and handling; annealing required	Easy to cut and handle
Cost	Higher initial cost; saving in energy repays it	Lower initial cost
Size and weight	Core is bigger and heavier for the same rating	Compact

- **Benefit:** since a distribution transformer is energised for 24 hours a day, even at light load, the **drastic reduction in no-load loss** saves a large amount of energy in the year and reduces CO₂ emission.
- Suitable for rural and city distribution networks where average loading is low (20–50 %). Standard ratings used are 25 kVA to 2000 kVA.

- Disadvantages: brittle ribbon, difficulty in manufacturing, higher short circuit forces consideration, slightly higher noise, higher initial cost.

Specification of three-phase distribution transformer as per IS:1180 (Part I)-1989

IS:1180 (Part I)-1989 covers **outdoor type, oil immersed three-phase distribution transformers up to and including 2500 kVA, with highest system voltage up to 33 kV**. The main specifications are given below (indicative values; check the latest edition, since IS:1180 has been revised and has introduced energy-efficiency loss levels in later editions).

Item	Specification
Type	Outdoor, three-phase, oil-immersed, double-wound, naturally cooled (ONAN)
Frequency	50 Hz
Rating (kVA)	Preferred ratings between 16 / 25 kVA and 2500 kVA, e.g. 25, 63, 100, 160, 200, 315, 400, 500, 630, 1000, 1250, 1600, 2000, 2500
Rated primary voltage (HV)	11 kV, 22 kV and 33 kV (6.6 kV also in some editions)
Rated secondary voltage (LV)	415 V / 433 V line, 240 V / 250 V phase (4-wire with neutral)
Connection / vector group	Dyn11 (HV delta, LV star with neutral brought out, LV leads HV by 30°)
Tappings	Off-circuit tap changer on HV winding (typically +5 % to -10 % in 2.5 % steps)
Percentage impedance	About 4.5 % for small ratings; 5–6.25 % for higher ratings (as per the standard's table)
Core	CRGO silicon steel laminations (or amorphous alloy in energy-efficient versions)
Cooling and oil	ONAN; mineral oil to IS:335 with conservator for larger ratings
Fittings	Rating and terminal marking plate, oil level gauge, breather, drain valve, earthing terminals, lifting lugs, HV and LV bushings, thermometer pocket, Buchholz relay for larger ratings
Tests	Routine, type and special tests: ratio, polarity/vector group, winding resistance, no-load loss, load loss, impedance voltage, insulation resistance, induced over-voltage, separate-source voltage, impulse, temperature rise

5.11 Need of Parallel Operation of Three-phase Transformer, Conditions for Parallel Operation

Two or more transformers are said to be in **parallel operation** when their primaries are connected to the same supply bus and their secondaries to the same load bus.

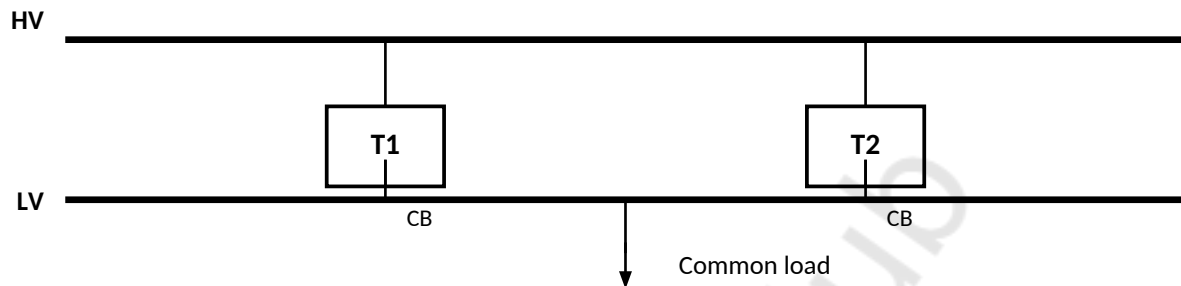


Fig. 5.11 Two transformers in parallel feeding a common load

Need of parallel operation

- **To meet increased load demand:** if the load exceeds the capacity of the existing transformer, another is added in parallel rather than replacing the existing transformer.
- **Continuity of supply:** if one transformer is out of order or under maintenance, the other keeps the supply (reliability, partial supply).
- **Higher efficiency at light loads:** at light load one transformer can be switched off so that the other works near its best efficiency.
- **Standardisation and economy:** instead of one very large unit, several smaller standard units are easier to transport, install and keep as spares.
- **Future expansion:** capacity can be raised in stages as the load grows.

Conditions for parallel operation

Condition	Importance	If not satisfied
Same polarity (terminals of same polarity joined)	Essential	Dead short circuit across the secondaries
Same phase sequence	Essential	Phase voltages of different phases get connected; large circulating currents, short circuit
Same phase displacement (same vector group / clock position)	Essential	Voltage difference between secondaries; heavy circulating current
Same voltage ratio (primary and secondary rated voltages)	Essential	Circulating current even at no load, $I = (E_A - E_B)/(Z_A + Z_B)$, causing loss and heating
Same frequency	Essential	Unequal reactance and unstable sharing
Same percentage impedance (referred to own rating)	Desirable	Load is not shared in proportion to ratings; the unit with lower impedance gets overloaded
Same X/R ratio	Desirable	Currents of the two units are not in phase; total capacity is not fully utilised
Rated kVA ratio not more than 2:1 (or 3:1)	Desirable	Larger unit's impedance is much different; difficult to share load correctly

Load sharing

If the transformers have the same voltage ratio, the load is shared in the **inverse proportion to their impedances**. For two transformers A and B with rated kVA S_A, S_B and per-unit impedances z_A, z_B supplying a total load S :

$S_A = S \times (S_B / z_A) / (S_A / z_A + S_B / z_B)$ and $S_B = S - S_A$
 If $z_A = z_B$, the load is shared in proportion to kVA ratings. The transformer with **lower per-unit impedance takes more load relative to its rating**.

Parallel operation of different vector groups

- Transformers of the **same group** can be paralleled directly: Yy0 with Dd0 or Dz0; Dy1 with Yd1 or Yz1; Dy11 with Yd11 or Yz11.
- Group I and II** cannot be paralleled with each other (180° shift) and **Group III with Group IV** only by interchanging two phase connections on one transformer (e.g. Yd1 with Dy11).
- Always confirm by a **phasing out test** before closing the breaker.

5.12 Phasing Out Test on Three-phase Transformer

The **phasing out test** is performed to identify the **corresponding phases** of the secondary terminals of two three-phase transformers (or of a transformer and a live system), and to confirm that the **phase sequence and phase displacement** are correct before the units are put in parallel. It is also used to check the vector group of a single transformer and the correct marking of its terminals.

Purpose

- To check whether secondary terminals of the same phase are to be connected together when paralleling.
- To check the **phase sequence** (RYB or RBY) of the two sides.
- To verify the vector group and the terminal markings after manufacture, repair or re-connection.

Circuit and procedure

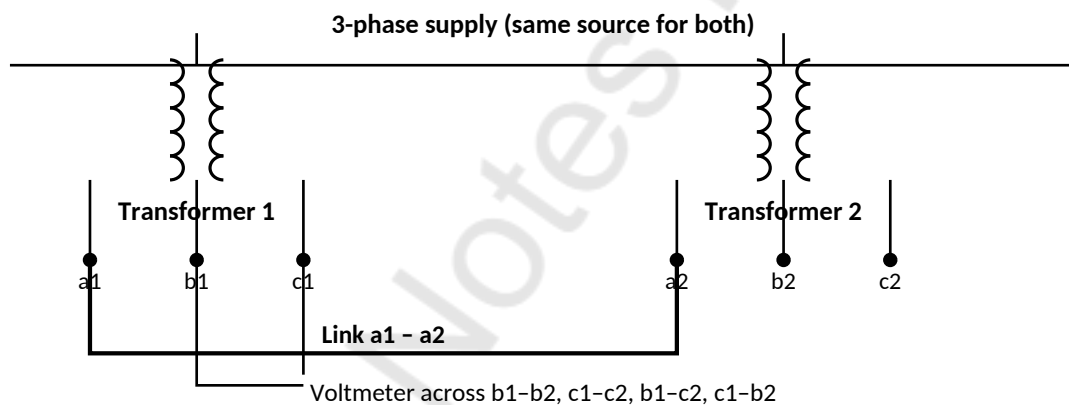


Fig. 5.12 Phasing out test on two three-phase transformers

- 1 Energise both transformers from the **same three-phase supply** on the primary side, keeping the secondary circuit breaker open.
- 2 Tentatively mark the secondary terminals a1, b1, c1 of transformer 1 and a2, b2, c2 of transformer 2.
- 3 **Link terminal a1 to a2** with a connecting lead.
- 4 Using a voltmeter (or phasing lamps), measure the voltage between the other terminals: b1-b2, c1-c2, b1-c2 and c1-b2.
- 5 Interpret the readings as shown in the table below; interchange the leads of one transformer if necessary and repeat the test until the readings show correct phasing.
- 6 When the readings are satisfactory, remove the link and close the parallel connection.

Voltmeter reading	Observation	Conclusion
b1-b2 = 0 and c1-c2 = 0; b1-c2 and c1-b2 = line voltage	Corresponding phases are the same	Correct phasing. Join a1-a2, b1-b2, c1-c2 and parallel the transformers.

Voltmeter reading	Observation	Conclusion
$b_1 - c_2 = 0$ and $c_1 - b_2 = 0$; $b_1 - b_2, c_1 - c_2 = \text{line voltage}$	Phase sequence of the two units is opposite	Interchange two secondary leads (b_2 and c_2) of one transformer and repeat the test.
No reading is zero (all readings about 0.5 or 1.0 times line voltage)	Phase displacement (vector group) is different	The transformers are not of the same group; they must not be paralleled (or change connection).

Precautions

- Use a **voltmeter with range above line voltage** (or lamps with the correct rating) and treat all terminals as live.
- Keep the secondary circuit breaker open until the test is completed and the readings are satisfactory.
- Perform the test with the transformers on the **same tap position** and the same supply, and observe the safety rules for HV work.

Phasing out of a single transformer (identification of terminals)

A single three-phase transformer is checked by applying a **reduced three-phase voltage** to the HV terminals, joining one HV terminal with one LV terminal (A with a) and measuring the voltages between the remaining terminals. The pattern of the readings identifies the vector group and verifies the marking (for example, in a Dyn11 transformer the voltage b-B is smaller than that of b-C, and the voltage pattern differs from that of Yd1).

Quick Revision Formulae and Facts

Topic	Formula / fact
Star connection	$V_L = \sqrt{3} V_{ph}, I_L = I_{ph}$
Delta connection	$V_L = V_{ph}, I_L = \sqrt{3} I_{ph}$
Three-phase power	$S = \sqrt{3} V_L I_L; P = \sqrt{3} V_L I_L \cos \phi$
Y-d line ratio	$V_{L2}/V_{L1} = N_2/(\sqrt{3} N_1)$
D-y line ratio	$V_{L2}/V_{L1} = \sqrt{3} N_2/N_1$
Zig-zag	Phase voltage = $\sqrt{3} E$ (E = half-winding voltage); low zero sequence impedance
Autotransformer	Conduction power = K S; induction power = (1 - K) S; copper saving = K × copper of two-winding
Scott connection	Teaser turns = 0.866 × main turns; neutral at 1/3 of teaser from D
Open delta	Output = $\sqrt{3} S_t = 57.7\%$ of closed delta; utilisation = 86.6 %
Dyn11	HV delta, LV star with neutral, LV leads HV by 30°
Parallel operation	Same polarity, voltage ratio, phase sequence, vector group; impedances equal; kVA ratio within 3:1
Cooling codes	O-oil, A-air, N-natural, F-forced, D-directed, W-water: ONAN, ONAF, OFAF, OFWF, ODAF

Multiple Choice Questions (15)

Choose the correct alternative.

1. If one transformer of a bank of three single-phase transformers connected in delta-delta fails, the remaining two units can be operated in _____.
(A) star-star with earthed neutral (B) open delta (V-V) connection (C) zig-zag connection (D) star-delta with tertiary
2. Which of the following core constructions provides a return path for zero-sequence flux?
(A) Three-limb core type (B) Single limb core (C) Core without yoke (D) Five-limb core
3. The symbol Dyn11 as per IS:2026 (Part IV) means:
(A) HV delta, LV star with neutral, LV leads HV by 30° (B) HV star, LV delta, LV lags HV by 30° (C) HV delta, LV zig-zag, no phase shift (D) HV star, LV star, LV leads HV by 330°
4. A zig-zag earthing transformer offers _____ impedance to zero-sequence currents.
(A) very high (B) infinite (C) very low (D) equal to magnetising
5. The main purpose of a delta-connected tertiary winding in a star-star transformer is to:
(A) increase the voltage ratio (B) reduce the copper loss (C) provide a path for third harmonic currents and stabilise the neutral (D) provide complete isolation of core
6. The cooling designation ONAN stands for:
(A) Oil Natural Air Natural (B) Oil Normal Air Natural (C) Oil Natural Air Normal (D) Oil Not Air Natural
7. In a three-phase step-down autotransformer with $K = 0.8$, the percentage of input power transferred by direct conduction is:
(A) 20 % (B) 64 % (C) 100 % (D) 80 %
8. In a Scott-connected transformer, the number of turns of the teaser primary is _____ of the main primary turns.
(A) 50 % (B) 86.6 % (C) 57.7 % (D) 100 %
9. The output of an open delta bank compared to a closed delta bank of identical transformers is:
(A) 57.7 % (B) 66.7 % (C) 86.6 % (D) 100 %
10. The utilisation factor of the V-V (open delta) connection is:
(A) 0.577 (B) 0.667 (C) 0.5 (D) 0.866

11. The main advantage of an amorphous core distribution transformer is:

- | | | | |
|------------------------|----------------------------------|---------------------------------|-------------------------|
| (A) lower initial cost | (B) very low no-load (core) loss | (C) smaller size than CRGO type | (D) higher flux density |
|------------------------|----------------------------------|---------------------------------|-------------------------|

12. Which of the following is NOT an essential condition for parallel operation of transformers?

- | | | | |
|-------------------|------------------------|-----------------------|-----------------------------|
| (A) Same polarity | (B) Same voltage ratio | (C) Equal kVA ratings | (D) Same phase displacement |
|-------------------|------------------------|-----------------------|-----------------------------|

13. Two transformers are operating in parallel. The transformer with lower per-unit impedance will:

- | | | | |
|---------------------|-------------------|--|---|
| (A) carry less load | (B) carry no load | (C) always carry exactly half the load | (D) carry a larger share of load relative to its rating |
|---------------------|-------------------|--|---|

14. The phasing out test is done to:

- | | | | |
|---|--------------------------|-------------------------|---------------------------------------|
| (A) identify corresponding phases and phase sequence before paralleling | (B) measure no-load loss | (C) find the efficiency | (D) measure the insulation resistance |
|---|--------------------------|-------------------------|---------------------------------------|

15. IS:1180 (Part I)-1989 is the specification for:

- | | | | |
|--|---|---------------------------|-----------------------------|
| (A) EHV power transformers above 100 MVA | (B) outdoor three-phase distribution transformers up to 2500 kVA, 33 kV | (C) dry type transformers | (D) instrument transformers |
|--|---|---------------------------|-----------------------------|

Answer Key – MCQs

Q.	Ans.	Q.	Ans.	Q.	Ans.
1	(B)	6	(A)	11	(B)
2	(D)	7	(D)	12	(C)
3	(A)	8	(B)	13	(D)
4	(C)	9	(A)	14	(A)
5	(C)	10	(D)	15	(B)

Explanation of selected answers:

- **Q7:** Power by conduction = $K \times S = 0.8 \times S = 80\%$ of the input.
- **Q8:** Teaser turns = $(\sqrt{3}/2) \times \text{main turns} = 0.866 N_1$.
- **Q9:** $\sqrt{3} S_t / 3 S_t = 0.577$.
- **Q10:** $\sqrt{3} S_t / 2 S_t = 0.866$.
- **Q12:** Equal kVA ratings are desirable but not essential; polarity, voltage ratio, phase sequence and vector group are essential.

Broad Questions (10)

1. Explain the types of three-phase transformer (bank of three single-phase units and single three-phase unit). Compare them with advantages and disadvantages.
2. Describe the construction of a three-phase core type transformer with a neat diagram. Explain the different types of winding used with their applications.
3. Explain the connections of three-phase transformers as per IS:2026 (Part IV)-1977. What is the meaning of vector group? Explain Dyn11 and Yd1 with clock diagrams and state the necessity of different connections.
4. What is a zig-zag connection? Explain its principle with the help of a phasor diagram and describe its practical application in an earthing transformer.
5. What is a tertiary winding? Explain its utility with a neat sketch. Why is a delta tertiary used in star-star transformers?
6. List and explain the different cooling methods of transformers. Explain the cooling designation (ONAN, ONAF, OFAF, OFWF, ODAF) with their applications.
7. Explain the construction, working principle and applications of a three-phase auto transformer. Show that the saving in copper is K times the copper of a two-winding transformer. State its merits and demerits.
8. Explain the Scott connection with a diagram. Show that the teaser primary requires 0.866 times the main primary turns and state its practical applications.
9. Explain the open delta (V-V) connection with a diagram. Show that its output is 57.7 % of the closed delta and its utilisation factor is 86.6 %. State its applications.
10. (a) State the need and the conditions for parallel operation of three-phase transformers. (b) Explain the phasing out test with a circuit diagram and the interpretation of results. (c) Differentiate between power transformer and distribution transformer and write the specification of a three-phase distribution transformer as per IS:1180 (Part I)-1989.

— End of Chapter 5 —