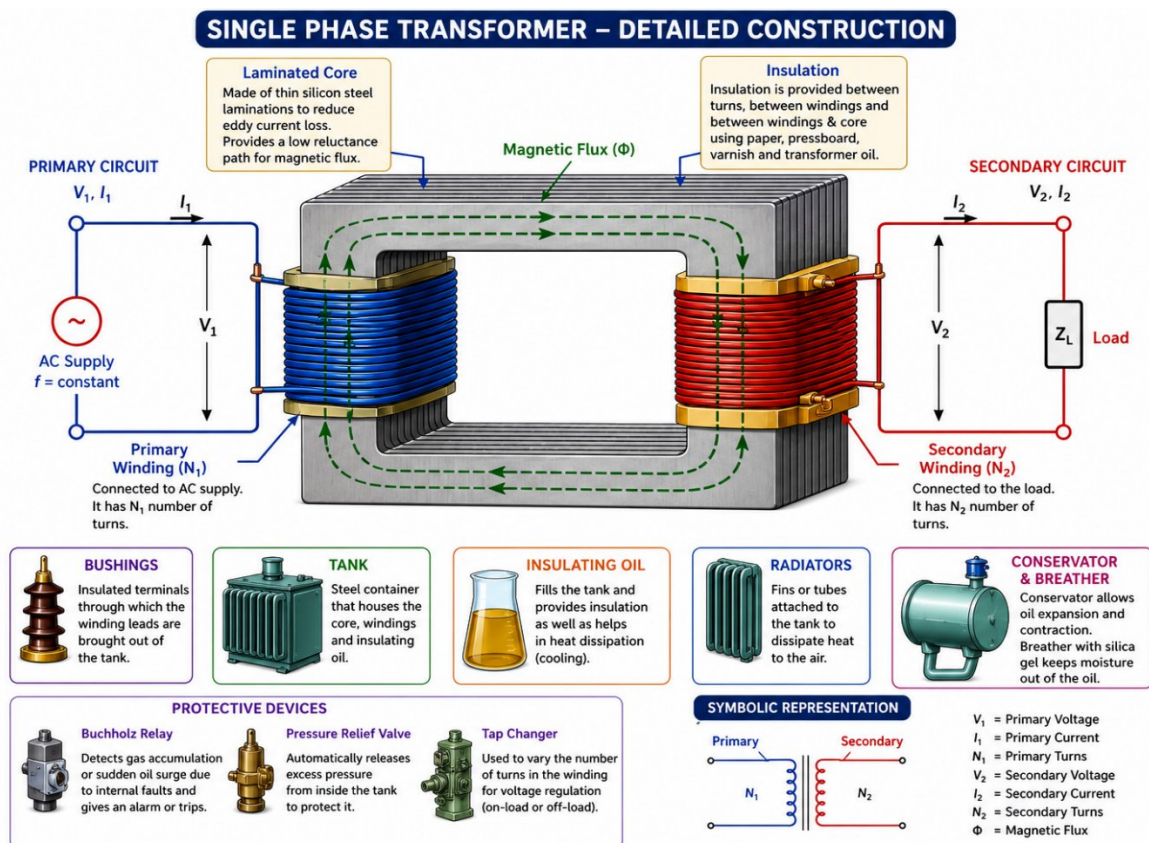


# TRANSFORMERS AND SPECIAL MACHINES

## Single Phase Transformer

A transformer is a static electro-magnetic device that transfers electrical energy from one circuit to another through mutual induction, at the same frequency, usually changing the voltage/current level. It has no rotating parts and is one of the most efficient electrical machines (efficiency 95–99%).

### Construction



A transformer essentially has two parts – the magnetic circuit (core) and electric circuit (windings):

- **Core:** Built of high-silicon steel laminations (0.35–0.5 mm thick), insulated from each other to reduce eddy current loss; provides a low-reluctance path for flux. Consists of limbs (carry windings) and yokes (connect limbs).
- **Windings:** Primary (connected to supply,  $N_1$  turns) and Secondary (connected to load,  $N_2$  turns), made of insulated copper/aluminium conductor.
- **Insulation:** Between turns, between windings, and between windings & core (paper, press-board, varnish, transformer oil).
- **Tank, conservator & breather:** House the oil-immersed core-coil assembly; accommodate oil expansion; keep moisture out using silica gel.
- **Bushings:** Insulated terminals bringing winding leads out through the tank.
- **Cooling:** ONAN, ONAF, OFAF, OFWF methods depending on rating.

- **Protective devices:** Buchholz relay (detects internal faults), tap changer (voltage regulation), pressure relief valve.

## Core Type vs Shell Type

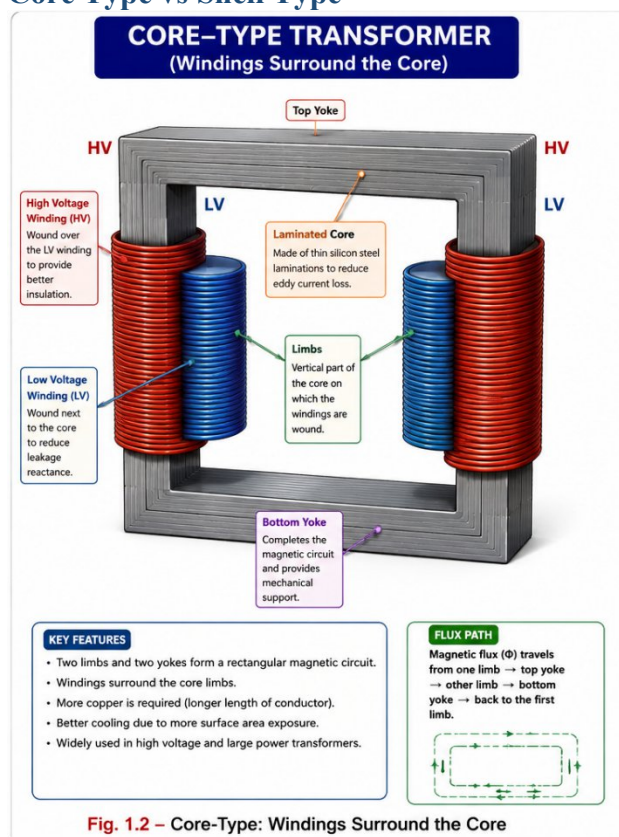


Fig. 1.2 – Core-Type: Windings Surround the Core

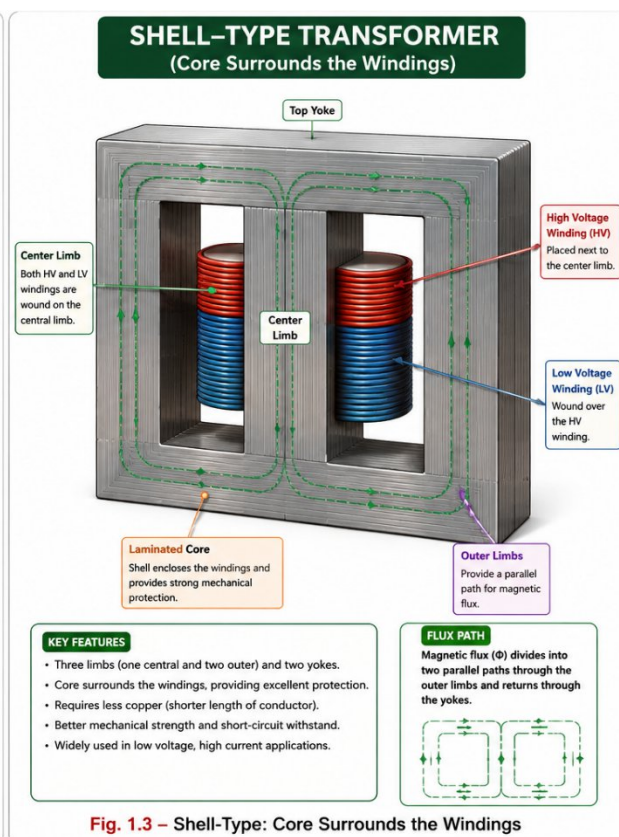


Fig. 1.3 – Shell-Type: Core Surrounds the Windings

| Feature           | Core Type                  | Shell Type                      |
|-------------------|----------------------------|---------------------------------|
| Arrangement       | Windings surround the core | Core surrounds the windings     |
| Magnetic circuit  | Single path                | Double/parallel path            |
| Limbs             | Two                        | Three (winding on central limb) |
| Winding type      | Cylindrical (concentric)   | Sandwich (disc)                 |
| Leakage reactance | Higher                     | Lower                           |
| Preferred use     | High voltage, low current  | Low voltage, high current       |

## Principle of Operation

A transformer works on the principle of Mutual Electromagnetic Induction. An alternating voltage applied to the primary sets up an alternating current, which produces an alternating flux in the core. This flux links both windings and induces an EMF in each — a self-induced EMF ( $E_1$ ) in the primary opposing the applied voltage, and a mutually-induced EMF ( $E_2$ ) in the secondary, at the same frequency as the supply. When the secondary circuit is closed through a load,  $E_2$  drives a current through the load, transferring power without any direct electrical connection between the two circuits.

## EMF Equation

Let flux vary sinusoidally:  $\Phi = \Phi_m \sin \omega t$ . Induced EMF per turn =  $-d\Phi/dt$ .

$$E_1 = 4.44 f N_1 \Phi_m = 4.44 f N_1 B_m A$$

$$E_2 = 4.44 f N_2 \Phi_m = 4.44 f N_2 B_m A$$

where  $f$  = supply frequency (Hz),  $N_1, N_2$  = number of primary/secondary turns,  $\Phi_m$  = maximum flux (Wb),  $B_m$  = maximum flux density (T),  $A$  = net core cross-sectional area ( $m^2$ ).

## Transformation Ratio

$$K = E_2/E_1 = N_2/N_1 = V_2/V_1 \text{ (ideal)} \quad \text{and} \quad I_1/I_2 = N_2/N_1 = K$$

- Step-up transformer:  $N_2 > N_1 \rightarrow K > 1 \rightarrow V_2 > V_1$
- Step-down transformer:  $N_2 < N_1 \rightarrow K < 1 \rightarrow V_2 < V_1$

## Losses in a Transformer

Since a transformer has no moving parts, it has no mechanical (friction/windage) losses. Its losses are entirely electrical, and are of two types:

### (a) Core / Iron Losses ( $P_i$ )

Occur in the core due to the alternating flux, and are practically constant at all loads (since flux is nearly constant from no-load to full-load, being set by the constant supply voltage).

- **Hysteresis Loss ( $W_h$ ):** Due to reversal of magnetization of the core,  $W_h = K_h B_m^{1.6} f V$  watts ( $K_h$  = Steinmetz hysteresis constant,  $V$  = volume of core). Reduced by using core material with low hysteresis coefficient (silicon steel).
- **Eddy Current Loss ( $W_e$ ):** Due to circulating currents induced in the core body itself,  $W_e = K_e B_m^2 f^2 t^2 V$  watts ( $t$  = lamination thickness). Reduced by laminating the core.

$$\text{Core loss, } P_i = W_h + W_e \text{ (found from Open Circuit Test)}$$

### (b) Copper Losses ( $P_{cu}$ )

Occur in the primary and secondary winding resistances due to load current, and vary as the square of the load current (i.e., vary with the square of the load).

$$P_{cu} = I_1^2 R_1 + I_2^2 R_2 = I_2^2 R_{o2} \text{ (found from Short Circuit Test)}$$

where  $R_{o2}$  is the total resistance referred to the secondary side.

## Efficiency of a Transformer

Efficiency is the ratio of output power to input power:

$$\eta = \text{Output Power} / \text{Input Power} = \text{Output} / (\text{Output} + \text{Losses}) = (V_2 I_2 \cos \Phi) / (V_2 I_2 \cos \Phi + P_i + P_{cu})$$

For a fraction  $x$  of full load ( $x = I_2/I_{2,\text{full-load}}$ ), copper loss becomes  $x^2 P_{cu}(\text{FL})$ , so:

$$\eta = (x \cdot S \cdot \cos \Phi) / (x \cdot S \cdot \cos \Phi + P_i + x^2 P_{cu}(\text{FL}))$$

where  $S$  = rated (full-load) VA of the transformer.

## Condition for Maximum Efficiency

Differentiating  $\eta$  with respect to  $x$  and equating  $d\eta/dx = 0$  gives the condition:

$$P_i = x^2 P_{cu}(FL) \quad \text{i.e.} \quad \text{Iron Loss} = \text{Copper Loss (at that load)}$$

The load at which this occurs:

$$x = \sqrt{(P_i / P_{cu}(FL))}$$
$$\eta_{max} = (x S \cos\Phi) / (x S \cos\Phi + 2 P_i)$$

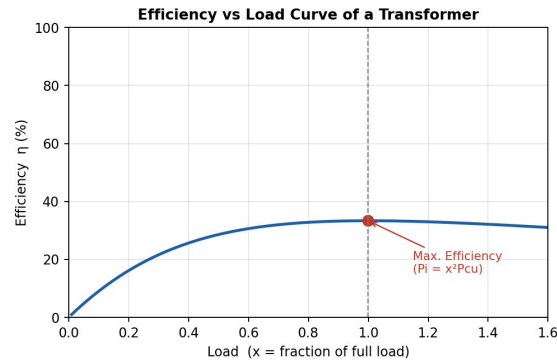


Fig. 1.4 – Efficiency vs Load curve; maximum efficiency occurs where iron loss = copper loss

**Note:** All-day efficiency (energy efficiency) is defined as the ratio of total energy output to total energy input over a 24-hour period, and is more meaningful than commercial efficiency for distribution transformers that carry varying load throughout the day.

## Voltage Regulation

Voltage regulation is the change in secondary terminal voltage from no-load to full-load (at a given power factor), expressed as a percentage of the no-load (or rated) secondary voltage, when the primary voltage is held constant.

$$\% \text{ Regulation} = [(E_2 - V_2) / V_2] \times 100$$

In terms of equivalent circuit parameters referred to secondary ( $R_{02}$  = equivalent resistance,  $X_{02}$  = equivalent reactance), for a load current  $I_2$  at power factor  $\cos\Phi$ :

$$\% \text{ Regulation} \approx [I_2 (R_{02} \cos\Phi \pm X_{02} \sin\Phi)] / V_2 \times 100$$

Use '+' sign for lagging power factor loads and '-' sign for leading power factor loads. Voltage regulation indicates how much the output voltage 'sags' (or rises) as load is applied — a smaller regulation value indicates better voltage-holding capability.

## Applications of Single Phase Transformer

- **Power distribution:** Step-down transformers supplying 230 V AC to homes.
- **Instrument transformers:** CT and PT for metering and protection.
- **Isolation transformers:** Electrical isolation in medical/lab equipment.
- **Control transformers:** Low-voltage supply for relay/PLC control panels.
- **Welding & furnace transformers:** Low-voltage, high-current supply.
- **Audio/impedance matching and rectifier transformers:** Used in electronics and power supplies.