DESIGN OF TRANSFORMER
Classification of transformer

Depending upon the type of construction used:
I. Core type
II. Shell type
Comparison of core type and shell type transformers:

I. Construction:- Core type transformers are much simpler in design and permit easier assembly and insulation of winding.

II. Mechanical forces:- The forces produced between windings is proportional to the product of the currents carried by them. Very large electromagnetic forces are produced when secondary winding is short circuited. Since the windings carry currents in opposite direction, there exists a force of repulsion between them. Hence, the inner winding experiences a compressive force and outer winding experiences a tensile force.
In a shell type transformer, windings have greater capability of withstanding forces produced under short circuit as these windings are surrounded and supported by the core. But in a core type transformer windings have a poorer mechanical strength.
III. Leakage reactance:- In core type transformer large space required between the high and low voltage winding, it is not possible to subdivided the winding, while, in shell type transformer the windings can be easily subdivided by using sandwich coil. So it is possible to reduce the leakage reactance of shell type transformers.

IV. Repairs:- The winding of core type transformer is completely accessible so coils can be easily inspected. And also core type transformer is easy to dismantle for repair. In shell type transformer, the coils are surrounded by core, therefore difficulty in inspection and repair of coils.

V. Cooling:- In core type transformer windings are exposed and therefore the cooling is better in winding than core. In case of shell type transformer core is exposed therefore cooling is better than winding.
Classification on the basis of type of service:
I. Distribution transformer
II. Power transformer

Classification on the basis of power utility:
I. Single phase transformer
II. Three phase transformer
Construction of transformer

I. Transformer core
II. Winding
III. Insulation
IV. Tank
V. Bushings
VI. Conservator and breather
VII. Tapping and tap changing
VIII. Buchholz Relay
IX. Explosion vent
X. Transformer oil
Design detail

Output of transformer: let

\[ \Phi_m = \text{main flux, Wb}; \quad B_m = \text{maximum flux density, Wb/m}^2; \]
\[ \delta = \text{current density A./m}^2; \quad A_{gi} = \text{gross core area, m}^2; \]
\[ A_j = \text{net core area, m}^2 = \text{stacking factor} \times \text{gross core area}; \]
\[ A_c = \text{area of copper in the window, m}^2; \quad A_w = \text{window area, m}^2; \]
\[ D = \text{distance between core centres, m}; \]
\[ d = \text{diameter of circumscribing circle, m}; \]
\[ K_w = \text{window space factor}; \quad f = \text{frequency, Hz}; \quad E_i = \text{emf per turn, V}; \]
\[ T_p, T_s = \text{number of turns in primary and secondary windings respectively}; \]
\[ I_p, I_s = \text{current in primary and secondary windings respectively, A}; \]
\[ V_p, V_s = \text{terminal voltage of primary and secondary windings respectively, V}; \]
\[ a_p, a_s = \text{area of conductors of primary and secondary windings respectively, m}^2 \]
\[ l_i = \text{mean length of flux path in iron, m}; \]
\[ L_{mt} = \text{length of mean turn of transformer windings, m}; \]
\[ G_i = \text{weight of active iron, kg}; \quad G_c = \text{weight of copper, kg}; \]
\[ g_i = \text{weight per m}^3 \text{ of iron, kg}; \quad g_c = \text{weight per m}^3 \text{ of copper, kg}; \]
\[ p_i = \text{loss in iron per kg, W}; \quad p_c = \text{loss in copper per kg, W}. \]
Output equation of transformer

Single phase transformer :-

\[ Q = 2.22 \, f \, B_m \, \delta \, K_w \, A_w A_i \cdot 10^{-3} \, \text{kVA} \]

Three Phase Transformer :-

\[ Q = 3.33 \, f \, B_m \, \delta \, K_w \, A_w A_i \cdot 10^{-3} \, \text{kVA} \]
Optimum design

Transformer may be designed to make one of the following quantity as minimum

i. Total volume
ii. Total weight
iii. Total cost
iv. Total loss

All these quantities vary with ratio \( r = \phi_m / AT \). If we choose high value of ‘r’ then flux will be high, so large cross section is required which will increase volume, weight and cost of iron and also give higher iron loss. Also due to decrease in value of ‘AT’ the volume, weight and cost of copper decreased and also decrease in copper losses. Thus ‘r’ is a controlling factor for above mention quantities.
Design of core

**Rectangular core:** It is used for core type distribution transformer and small power transformer for moderate and low voltages and shell type transformers.

In core type transformer the ratio of depth to width of core varies between 1.4 to 2.

In shell type transformer width of central limb is 2 to 3 times the depth of core.

**Square and stepped cores:** For high voltage transformers, where circular coils are required, square and stepped cores are used.
Square and stepped core

Square core

Stepped Core
Cross-section and dimensions of Stepped cores

![Diagram showing cross-sections of stepped cores](image)

<table>
<thead>
<tr>
<th>Area percentage of circumscribing circle</th>
<th>Square</th>
<th>Cruciform</th>
<th>Three stepped</th>
<th>Four stepped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross core area $A_{gi}$</td>
<td>64</td>
<td>79</td>
<td>84</td>
<td>87</td>
</tr>
<tr>
<td>Net core area $A_i$</td>
<td>58</td>
<td>71</td>
<td>75</td>
<td>78</td>
</tr>
<tr>
<td>Net core area $A_i = k_a d^2$, $k_c$</td>
<td>0.45</td>
<td>0.56</td>
<td>0.6</td>
<td>0.62</td>
</tr>
</tbody>
</table>
Choice of flux density

The value of flux density in the core determines the core area.

High value of flux density give smaller core area, so saving in iron cost. Also small core area provides reduced mean turn of winding which gives reduction in copper cost. But higher flux density increase iron losses resulting high temperature rise.

The value of flux density also depends upon service conditions of transformer. A distribution transformer design with low value of flux density to keep down the iron losses and increase in all day efficiency.
The values of maximum flux density for transformers

i. For hot rolled silicon steel

Distribution Transformer 1.1 to 1.35 $Wb/m^2$

Power transformer 1.25 to 1.45 $Wb/m^2$

ii. For CRGO core

Upto 132 kV 1.55 $Wb/m^2$

For 275 kV 1.6 $Wb/m^2$

For 400kV & Gen. Transf. 1.7 to 1.75 $Wb/m^2$
Design of insulation

Electrical considerations
  • Eddy current losses
  • Leakage reactance

Mechanical considerations

Thermal consideration

Window Space Factor: It is the ratio of copper area in the window to the total window area.

\[ K_w = \frac{10}{30+kV} \] for transformer rating 50 to 200kVA

\[ K_w = \frac{12}{30+kV} \] for rating about 1000 kVA

\[ K_w = \frac{8}{30+kV} \] for rating about 20 kVA
Window dimensions:
The area of window depend upon total conductor area and window space factor.

Area of window $A_w = \frac{\text{total conductor area}}{\text{window space factor}}$

- $= 2.a_p \frac{T_p}{K_w}$ for 1-ph transformer
- $= 4.a_p \frac{T_p}{K_w}$ for 3-ph transformer

$A_w = \text{height of window} \times \text{width of window} = H_w \times W_w$

The ratio of height to width of window, $H_w / W_w$ is b/w 2 to 4.
**Design of Yoke:** The section of yoke can either be taken as rectangular or it may be stepped.

In rectangular section yokes,

- depth of the yoke = depth of core
- area of yoke $A_y = D_y \times H_y$

$D_y = \text{depth of yoke} = \text{width of largest core stamping}$

- $A_y = 1.15$ to $1.25$ of $A_{gi}$ for hot rolled steel
- $= A_{gi}$ for CRGO
Overall dimensions

Single Phase Transformer

d = diameter of circumscribing circle
D = distance b/w centers of adjacent limbs
H = overall height
W = length of yoke

\[
D = d + Ww, \quad Dy = a
\]
\[
H = Hw + 2Hy
\]
\[
W = D + a
\]

Width over two limbs = \( D + \) outer diameter of hv winding

Width over one limb = outer diameter of hv winding
Three Phase Transformer

\[ D = d + W_w, \quad Dy = a \]

\[ H = H_w + 2Hy \]

\[ W = 2D + a \]

Width over two limbs = \( D + \) outer diameter of hv winding

Width over one limb = outer diameter of hv winding
No-load current of transformer

The no-load current $I_0$ is the vectorial sum of the magnetizing current $I_m$ and core loss or working component current $I_c$. [Function of $I_m$ is to produce flux $\phi_m$ in the magnetic circuit and the function of $I_c$ is to satisfy the no load losses of the transformer].

$$\sqrt{I_c^2 + I_m^2}$$

Transformer under no-load condition

Vector diagram of Transformer under no-load condition
No load input to the transformer $= V_1 I_0 \cos \phi_0 = V_1 I_c = \text{No load losses as the output is zero and input} = \text{output} + \text{losses}$.

Since the copper loss under no load condition is almost negligible, the no load losses can entirely be taken as due to core loss only. Thus the core loss component of the no load current $I_c = \frac{\text{core loss}}{V_1}$ for single phase transformers.

RMS value of magnetizing current $I_m = \frac{\text{Magnetizing ampere turns (Max value)}}{\sqrt{2} T_1}$

The magnetic circuit of a transformer consists of both iron and air path. The iron path is due to legs and yokes and air path is due to the unavoidable joints created by the core composed of different shaped stampings. If all the joints are assumed to be equivalent to an air gap of $l_g$, then the total ampere turns for the transformer magnetic circuit is equal to $AT_{\text{for iron}} + 800,000l_g B_m$. 


1. In case of a transformer of normal design, the no load current will generally be less than about 2% of the full load current.

2. No load power factor \( \cos \phi_0 = \frac{I_c}{I_0} \) and will be around 0.2.

3. Transformer copper losses:
   a) The primary copper loss at no load is negligible as \( I_0 \) is very less.
   b) The secondary copper loss is zero at no load, as no current flows in the secondary winding at no load.

4. Core or iron loss:

Total core loss = core loss in legs + core loss in yokes.

Core loss in leg = loss/kg in leg \* weight of leg in kg

   = loss / kg in leg \* volume of the leg \( (A_i \* H_w) \) \* density of steel or iron used

Core loss in yoke = loss/kg in Yoke \* volume of yoke \( (A_y \* \text{mean length of the yoke}) \) \* density of iron used
DESIGN OF TANK WITH TUBES

Because of the losses in the transformer core and coil, the temperature of the core and coil increases. In small capacity transformers the surrounding air will cool the transformer effectively and keeps the temperature rise well within the permissible limits. As the capacity of the transformer increases, the losses and the temperature rise increases. In order to keep the temperature rise within limits, air may have to be blown over the transformer. This is not advisable as the atmospheric air containing moisture, oil particles etc., may affect the insulation. To overcome the problem of atmospheric hazards, the transformer is placed in a steel tank filled with oil. The oil conducts the heat from core and coil to the tank walls. From the tank walls the heat goes dissipated to the surrounding atmosphere due to radiation and convection.
Further as the capacity of the transformer increases, the increased losses demands a higher dissipating area of the tank or a bigger sized tank. This calls for more space, more volume of oil and increases the cost and transportation problems. To overcome these difficulties, the dissipating area is to be increased by artificial means without increasing the size of the tank. The dissipating area can be increased by

1. fitting fins to the tank walls  
2. fitting tubes to the tank  
3. using corrugated tank  
4. using auxiliary radiator tanks

Since the fins are not effective in dissipating heat and corrugated tank involves constructional difficulties, they are not much used now a days. The tank with tubes are much used in practice.
Heat goes dissipated to the atmosphere from tank by radiation and convection. It has been found by experiment that 6.0W goes radiated per m. sq. of plain surface per degree centigrade and 6.5W goes dissipated by convection / meter sq. of plain surface / degree centigrade. Thus a total of 12.5W/ meter sq. / degree centigrade goes dissipated to the surrounding. If θ is the temperature rise, then at final steady temperature condition, losses responsible for temperature rise is losses dissipated or transformer losses = 12.5 St θ.

Temp rise θ = \[
\frac{\text{total loss}}{\text{specific heat dissipation* surface}} = \frac{P_i + P_c}{12.5 S_t}
\]

St = Heat dissipating surface of tank
Number & dimensions of TUBES

If the temperature rise of the tank wall is beyond a permissible value of about 50 degree centigrade, then cooling tubes are to be added to reduce the temperature rise. With the tubes connected to the tank, dissipation due to radiation from a part of the tank surface screened by the tubes is zero. So there is no change in surface as far as dissipation of heat due to radiation is concerned. Because the oil when get heated up moves up and cold oil down, circulation of oil in the tubes will be more. Obviously, this circulation of oil increases the heat dissipation and convection from the tubes increase by about 35%.
Let dissipating surface of the tank = $S_t$

It will dissipate $12.5 S_t \ W/^\circ C$

Let the area of tubes = $xS_t$

Loss dissipated by tubes by convection = $1.35 \times 6.5 \times xS_t = 8.8 \times xS_t \ W/^\circ C$

Total loss dissipated by tank & tubes = $12.5 S_t + 8.8 xS_t = S_t(12.5 + 8.8 \times x) \ W/^\circ C$

Total area of tank walls and tubes = $S_t + xS_t = S_t \ (1 + x)$

Loss dissipated = \[
\frac{(12.5 + 8.8x)}{x + 1} \ W/\text{m}^2 - ^\circ C
\]

Temperature Rise with tubes $\theta = \frac{P_i + P_c}{S_t(12.5 + 8.8x)}$

$x = \frac{1}{8.8} \left( \frac{P_i + P_c}{S_t \theta} - 12.5 \right)$
Total area of tubes = \( \frac{1}{8.8} \left( \frac{P_i + P_c}{\theta} - 12.5 \cdot S_t \right) \)

Let \( l_t \) and \( d_t \) be the length and diameter of each tube

Area of each tube = \( \pi d_t l_t \)

Number of tubes \( n_t = \frac{1}{8.8\pi d_t l_t} \left( \frac{P_i + P_c}{\theta} - 12.5 \cdot S_t \right) \)

The diameter of tubes, normally used, is 50 mm and they are spaced at 75 mm
Cooling of transformer

The coolant used in transformers are air and oil. Transformers using air as coolant are called Dry type transformers while transformers which use oil as coolant are called Oil immersed transformers.

Methods of Cooling of Transformers: the choice of cooling method depends upon the size, type of application and the type of conditions of installation sites.

The symbols designated these methods depend upon medium of cooling used and type of circulation employed.

Medium:- Air-A, Gas-G, Oil-O, Water-W, Solid insulation-S
Circulation:- Natural-N, Forced-F
Cooling of Dry-type transformer
Air Natural (AN), Air Blast (AB)

Cooling of oil immersed transformer
Oil Natural (ON)
Oil Natural Air Forced (ONAF)
Oil Natural Water Forced (ONWF)
Forced Circulation of Oil (OF)
  i. Oil Forced Air Natural (OFAN)
  ii. Oil Forced Air Forced (OFAF)
  iii. Oil Forced Water Forced (OFWF)