NSCET E-LEARNING PRESENTATION

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EE8002- DESIGN OF ELECTRICAL APPARATUS

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UNIT 02 – Design of Transformers
“Imagination is more important than knowledge.”

—ALBERT EINSTEIN
DESIGN FEATURES

Power transformer
1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise. The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.
Distribution transformer
1. Load on the transformer does not remain constant but varies instant to instant over 24 hours a day.
2. Generally designed for maximum efficiency at about half full load. In order that the all day efficiency is high, iron loss is made less by selecting a lesser value of flux density. In other words distribution transformers are generally designed for a lesser value of flux density. Since the distributed transformers are located in the vicinity of the load, voltage regulation is an important factor.
3. Generally the distribution transformers are not equipped with tap changers to maintain a constant voltage as it increases the cost, maintenance charges etc., Thus the distribution transformers are designed to have a low value of inherent regulation by keeping down the value of leakage reactance.
OUTPUT EQUATIONS

Single phase core type transformer

The induced emf in a transformer, \( E = 4.44 f \phi_m \ T \) Volts

Emf per turn, \( E_t = E / T = 4.4 f \phi_m \) Volts.

The window in single phase transformer contains one primary and one secondary winding. The window space factor \( K_w \) is the ratio of conductor area in window to total area of window.

Window space factor, \( K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w} \)

\[ \therefore \text{Conductor area in window, } A_c = K_w A_w \]
The current density $\delta$ is same in both the windings.

\[ \therefore \text{Current density, } \delta = \frac{I_p}{a_p} = \frac{I_s}{a_s} \]

Area of cross-section of primary conductor, $a_p = \frac{I_p}{\delta}$

Area of cross-section of secondary conductor, $a_s = \frac{I_s}{\delta}$

If we neglect magnetizing mmf then primary ampere turns is equal to secondary ampere turns.

\[ \therefore \text{Ampere turns, } AT = I_p T_p = I_s T_s \]
Total copper area in window \( A_c \) = Copper area of primary winding + Copper area of secondary winding

= Number of primary turns \( T_p \) \times area of cross-section of primary conductor + Number of secondary turns \( T_s \) \times area of cross-section of secondary conductor

\[ \begin{align*}
A_c &= T_p a_p + T_s a_s = T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta} \\
\Rightarrow a_p &= \frac{I_p}{\delta} \quad \text{and} \quad a_s = \frac{I_s}{\delta}
\end{align*} \]

\[ \begin{align*}
\frac{1}{\delta} \left( T_p I_p + T_s I_s \right) &= \frac{1}{\delta} (AT + AT) \\
\Rightarrow AT &= I_p T_p = I_s T_s
\end{align*} \]

\[ \begin{align*}
A_c &= \frac{2AT}{\delta}
\end{align*} \]
Equating equation (2) and (4), we get

\[ K_w A_w = \frac{2 \, AT}{\delta} \]

\[ \therefore \text{Ampere turns, } AT = \frac{1}{2} K_w A_w \delta \]

The kVA rating of single phase transformer is given by,

\[ \text{kVA rating, } Q = V_p I_p \times 10^{-3} = E_p I_p \times 10^{-3} \quad \left( \because E_p \approx V_p \right) \]

\[ = \left( \frac{E_p}{T_p} \right) T_p I_p \times 10^{-3} \quad \left( \because E_t = \frac{E_p}{T_p} \text{ and } AT = T_p I_p \right) \]

\[ = E_t \, AT \times 10^{-3} \]
Substituting equations (1) and (4) in equation (5), we get

\[ Q = 4.44 \ f \phi_m \ \frac{K_w A_w \ \delta}{2} \times 10^{-3} \]

\[ = 2.22 \ f \phi_m \ K_w A_w \ \delta \times 10^{-3} \]

\[ B_m = \frac{\phi_m}{A_i} \]

\[ Q = 2.22 \ f \ B_m \ A_i K_w A_w \ \delta \times 10^{-3} \]

**OUTPUT EQUATION OF THREE PHASE TRANSFORMER**

The induced emf in a transformer, \( E = 4.44 \ f \phi_m \ T \) Volts

Emf per turn, \( E_i = \frac{E}{T} = 4.4 \ f \phi_m \) Volts

In case of three phase transformer, each window has two primary and two secondary windings.
Hence the area of copper is taken twice that of single phase core type transformer.

The window space factor $K_w$ is the ratio of conductor area in window to total area of window,

$$
Window \ space \ factor, \ K_w = \frac{Conductor \ area \ in \ window}{Total \ area \ of \ window} = \frac{A_c}{A_w}
$$

$\therefore$ Conductor area in window, $A_c = K_w A_w$
The current density $\delta$ is same in both the windings.

\[ \therefore \text{Current density, } \delta = \frac{I_p}{a_p} = \frac{I_s}{a_s} \]

Area of cross-section of primary conductor, $a_p = \frac{I_p}{\delta}$

Area of cross-section of secondary conductor, $a_s = \frac{I_s}{\delta}$

If we neglect magnetizing mmf then primary ampere turns is equal to secondary ampere turns.

\[ \therefore \text{Ampere turns, } AT = I_p T_p = I_s T_s \]
\[
\frac{4AT}{\delta} = \frac{2(T_p p_p + T_s s_s)}{\delta (AT + AT)}
\]

\[
\therefore AT = I_p T_p = I_s T_s
\]

Total copper area in window
\[
A_c = 2 \times \text{Number of primary turns} \times \text{Area of cross-section of primary conductor}
\]

\[
+ 2 \times \text{Number of secondary turns} \times \text{Area of cross-section of secondary conductor}
\]
Equating equation (8) and (9), we get

\[ \frac{4AT}{\delta} = K_w A_w \]

\[ \therefore \text{Ampere-turn, } AT = \frac{K_w A_w \delta}{4} \]

The kVA rating of three phase transformer is given by,

\[ \text{kVA rating, } Q = 3 \times \text{Volt-ampere per phase} \times 10^{-3} = 3V_p I_p \times 10^{-3} \]

\[ = 3E_p I_p \times 10^{-3} \]

\[ (\because E_p \approx V_p) \]

\[ = 3 \times \frac{E_p}{T_p} \times T_p I_p \times 10^{-3} \]

\[ \therefore E_t = \frac{E_p}{T_p} \text{ and } AT = T_p I_p \]

\[ = 3 E_t AT \times 10^{-3} \]
Substituting equations (7) and (10) in equation (11), we get

\[ Q = 3 \times 4.44 f \phi_m \times \frac{K_w A_w \delta}{4} \times 10^{-3} \]

\[ = 3.33 f \phi_m K_w A_w \delta \times 10^{-3} \]

\[ \therefore B_m = \frac{\phi_m}{A_i} \]

**OUTPUT EQUATION – VOLT PER TURN**

Let,

\[ r = \frac{\phi_m}{AT} \]

ratio of specific magnetic and electric loading
The volt-ampere per phase of a transformer is given by the product of voltage and current per phase. Considering the primary voltage and current per phase we can write,

\[ kVA\ per\ phase, \ Q = V_p I_p \times 10^{-3} \]

\[ = 4.44 f \phi_m \frac{T_p I_p}{10^{-3}} \]

\[ = 4.44 f \phi_m AT \times 10^{-3} \quad (\because T_p I_p = AT) \]

\[ = 4.44 f \phi_m \frac{\phi_m}{r} \times 10^{-3} \quad (\because AT = \frac{\phi_m}{r}) \]

\[ \therefore \phi_m^2 = \frac{Q r}{4.44 f \times 10^{-3}} \]

\[ \phi_m = \sqrt{\frac{Q r \times 10^3}{4.44 f}} \]
We know that,

\[ \text{Emf per turn, } E_t = 4.44 f \phi_m \]

\[ E_t = 4.44 f \sqrt{\frac{Q r \times 10^3}{4.44 f}} = \sqrt{4.44 f r \times 10^3} \sqrt{Q} = K \sqrt{Q} \]

\[ E_t = K \sqrt{Q} \]

where, \( K = \sqrt{4.44 f r \times 10^3} = \sqrt{4.44 f \frac{\phi_m}{AT} \times 10^3} \)
RATIO OF IRON LOSS TO COPPER LOSS

Ratio of iron loss to copper loss

\[ \frac{P_i}{P_c} = \frac{p_i G_i}{p_c G_c} \]
DESIGN FOR MINIMUM COST

Let us consider a single phase transformer. In kVA output is:

\[ Q = 2.22 f B_m \delta K_w A_w A_i \times 10^{-3} = 2.22 f B_m \delta A_r A_i \times 10^{-3}. \]

Assuming that the flux and current densities are constant, we see that for a transformer of given rating the product \( A_r A_i \) is constant.

Let this product \( A_r A_i = M^2 \) \( ...(i) \)

The optimum design problem is, therefore, that of determining the minimum value of total cost.

Now, \( r = \Phi_m/AT \) and \( \Phi_m = B_m A_i \) and \( AT = \delta K_w A_w/2 = \delta A_r/2 \)

\[ r = \frac{2B_m A_i}{\delta A_r} \text{ or } \frac{A_i}{A_r} = \frac{\delta}{2B_m} \quad r = \beta \quad ...(ii) \]

where \( \beta \) is a function of \( r \) only as \( B_m \) and \( \delta \) are constant.

Thus from (i) and (ii) we have

\[ A_i = M \sqrt{\beta} \quad \text{and} \quad A_r = M/ \sqrt{\beta} \]

Let \( C_i = \text{total cost of transformer active materials}, \)
\[ C_t = \text{total cost of iron, and } C_c = \text{total cost of conductor} \]
\[ C_t = C_i + C_c = c_i g_i + c_c g_c \]
\[ = c_i g_i l_i A_i + c_c g_c L_{mt} A_c \]

\( c_i \) and \( c_c \) are the specific costs of iron and copper respectively.

Now,
\[ C_t = c_i g_i l_i M \sqrt{\beta} + c_c g_c L_{mt} M / \sqrt{\beta} \]

where \( g_i \) = weight per m\(^3\) of iron, kg ; \( g_c \) = weight per m\(^3\) of copper, kg ;

Differentiating \( C_t \) with respect to \( \beta \),
\[ \frac{dC_t}{d\beta} = \frac{1}{2} c_i g_i l_i M (\beta)^{-1/2} - \frac{1}{2} c_c g_c L_{mt} M \beta^{-3/2} \]

For minimum cost \( \frac{dC_t}{d\beta} = 0 \)

\[ \therefore c_i g_i l_i = c_c g_c L_{mt} \beta^{-1} \quad \text{or} \quad c_i g_i l_i = c_c g_c L_{mt} \frac{A_c}{A_i} \]

or \[ c_i g_i l_i A_i = c_c g_c L_{mt} A_c \quad \text{or} \quad c_i G_i = c_c G_c \]

or \[ C_t = C_c \]

\textit{Hence, for minimum total cost, the cost of iron must equal the cost of conductor.}

Now \[ G_i / G_c = c_c / c_i \] for minimum cost.

Knowing the value of specific costs of iron and conductor the ratio of weight of iron to conductor can be determined.
Similar conditions apply to other quantities e.g.,

*For minimum volume of transformer, Volume of iron = volume of conductor*

\[ G_i/g_i = G_c/g_c \quad \text{i.e.,} \quad G_i/G_c = g_i/g_c \]

*For minimum weight of transformer*

weight of iron = weight of conductor \quad \text{i.e.,} \quad G_i = G_c.

*For minimum losses in transformer i.e., for maximum efficiency,*

iron loss = \( I^2R \) loss in conductor \quad \text{or} \quad P_i = x^2P_c
DESIGN FOR MINIMUM LOSS OR MAXIMUM EFFICIENCY

Total losses at full load = $P_i + P_e$

At any fraction $x$ of full load, the total losses are $P_i + x^2 P_e$

If $Q$ is the output at full load, the output at fraction $x$ of full load is $xQ$.

∴ Efficiency at output $xQ$, $\eta_x = \frac{xQ}{xQ + P_i + x^2 P_e}$

This efficiency is maximum when $\frac{d\eta_x}{dx} = 0$

Differentiating $\eta_x$ we have $\frac{d\eta_x}{dx} = \frac{(xQ + P_i + x^2 P_e) Q - xQ(Q + 2xP_e)}{(xQ + P_i + x^2 P_e)^2}$

For maximum efficiency, $(xQ + P_i + x^2 P_e) Q - xQ(Q + 2xP_e) = 0$

we have:

$$\frac{P_i}{P_e} = \frac{P_i}{P_e} \frac{G_i}{G_e}$$

∴

$$x^2 = \frac{P_i}{P_e} \frac{G_i}{G_e} \quad \text{or} \quad \frac{G_i}{G_e} = x^2 \frac{P_e}{P_i} \quad \text{for maximum efficiency.}$$

Now knowing the values of densities in iron and copper the specific losses $p_i$ and $p_e$ can be determined and the value of $x$, i.e., the fraction of full load where the maximum efficiency occurs depends upon the service conditions of the transformer and is, therefore, known.
WINDOW SPACE FACTOR

Window space factor is defined as the ratio of copper area in the window to the area of the window.

\[ K_w = \frac{\text{Conductor area in window}}{\text{total area of window}} \]

=Ac/Aw

DESIGN OF CORE

- The core section of core type of transformers may be rectangular, square or stepped.
- Shell type transformers use cores with rectangular cross section.
- With small size transformers, rectangular core can be used with either circular or rectangular coils.
- With medium size transformers, square core can be used.
- With large transformers, cruciform (stepped) cores, which utilize the space better are used.
- The circle represents the inner surface of the tubular form carrying the windings. This circle is known as the circumscribing circle.
- Circular coils are preferred over rectangular coils because of their superior mechanical characteristics. On circular coils the forces are radial and there is no tendency for the coil to change its shape. On rectangular coils the forces are perpendicular to the conductors and tend to give the coil a circular form, thus deforming it. Hence circular coils are employed in high voltage and high capacity transformers.
Note:

\[ S_f = k_i = \text{Stacking factor} \]

Stacking factor, \( S_f = \frac{\text{Area of cross-section of iron in the core}}{\text{Area of cross-section of the core including the insulation area}} \)

The usual value of stacking factor is 0.9.

By increasing the number of steps, the area of circumscribing circle is more effectively utilized. The most economical dimensions of various steps for a multi-stepped core can be calculated. The results are tabulated in table.
CALCULATION OF CORE AREA

The voltage per turn is calculated from Eqn.

\[ E_t = K \sqrt{Q} \]

where, \[ K = \sqrt{\frac{4.44 f \times \Phi_m}{AT \times 10^3}} \]

Now, flux

\[ \Phi_m = \frac{E_t}{4.44 f} \]

Therefore, the value of flux in the core can be calculated. The area of the core is found out by assuming a suitable value of maximum flux density \( B_m \).

Net core area required

\[ A_i = \frac{\Phi_m}{B_m} \]

and gross core area

\[ A_{gi} = \frac{A_i}{k_i} \]
DESIGN OF WINDINGS

Number of turns in primary winding \( T_p = \frac{V_p}{E_t} \)

Number of turns in secondary winding \( T_s = \frac{V_s}{E_t} \)

Current in primary winding \( I_p = \frac{KVA \times 10^3}{V_p} \)

Area of each primary winding \( a_p = \frac{I_p}{\delta_p} \)

Area of each secondary winding \( a_s = \frac{I_s}{\delta_s} \)

- The current densities in the two windings should be taken equal in order to have minimum copper losses. i.e. \( \delta_p = \delta_s \)

- In practice, however, the current density in the relatively better cooled outer winding is made 5 percent greater than the inner winding.
Overall dimensions

The main dimensions of the transformer are
(i) Height of window ($H_w$)
(ii) Width of the window ($W_w$)

The other important dimensions of the transformer are
(i) width of largest stamping (a)
(ii) diameter of circumscribing circle

As the iron area of the leg $A_i$ and the window area $A_w = (\text{height of the window } H_w \times \text{width of the window } W_w)$ increases, the size of the transformer also increases. The size of the transformer increases as the output of the transformer increases.
1. Output-kVA
2. Voltage-V1/V2 with or without tap changers and tapings
3. Frequency-f Hz
4. Number of phases – One or three
5. Rating – Continuous or short time
6. Cooling – Natural or forced
7. Type – Core or shell, power or distribution
8. Type of winding connection in case of 3 phase transformers – star-star, star-delta, delta-delta, delta-star with or without grounded neutral
9. Efficiency, per unit impedance, location (i.e., indoor, pole or platform mounting etc.), temperature rise etc.,
REGULATION

\[
\text{Percentage regulation} = \frac{I_l R_2 \cos \phi + I_l X_2 \sin \phi}{V_1} \times 100
\]

NO LOAD CURRENT

The phasor sum of the magnetizing current (Im) and the loss component of current (Il); Im is calculated using the MMF/m required for the core and yoke and their respective length of flux path. Il is determined using the iron loss curve of the material used for the core and yoke and the flux density employed and their weight. The no-load current I0 is the vectorial sum of the magnetizing current Im and core loss or working component current Ic. [Function of Im is to produce flux \( \varphi_m \) in the magnetic circuit and the function of Ic is to satisfy the no load losses of the transformer]. Thus,
Transformer under no-load condition

No load input to the transformer = $V_1I_0\cos\phi_0 = V_1I_c$ = No load losses as the output is zero and input = output + losses.
TEMPERATURE RISE IN TRANSFORMERS

Losses dissipated in transformers in the core and windings get converted into thermal energy and cause heating of the corresponding transformer parts. The heat dissipation occurs as follows: i) from the internal heated parts to the outer surface in contact with oil by conduction ii) from oil to the tank walls by convection and iii) from the walls of the tank to the atmosphere by radiation and convection.

\[ Q = \text{Power loss (heat produced)}, \ J/s \text{ or } W \]
\[ G = \text{weight of the active material of the Machine}, \ \text{kg} \]
\[ h = \text{specific heat}, \ J/kg-\circ C \]
\[ S = \text{cooling surface area}, \ m^2 \]
\[ \lambda = \text{specific heat dissipation}, \ W/m^2 -\circ C \]
\[ c = 1/\lambda = \text{cooling coefficient}, \ m^2 -\circ C/W \]
\[ \theta_m = \text{final steady temperature rise}, \circ C \]

The temperature of the machine rises when it is supplying load. As the temperature rises, the heat is dissipated partly by conduction, partly by radiation and in most cases largely by air cooling. The temperature rise curve is exponential in nature. Assuming the theory of heating of homogeneous bodies,

\[ \text{Heat developed} = \text{heat stored} + \text{heat dissipated} \]
Design of Tank
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 be in a position to cool the transformer effectively and keeps the temperature rise well with in the permissible limits. As the capacity of the transformer increases, the losses and the temperature rise increases. In order to keep the temperature rise with in 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 surrounding atmosphere due to radiation and convection. Further as the capacity of the transformer increases, the increased loss demands a higher dissipating area of the tank or a bigger sized tank. These 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 and
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 tanks with tubes are much used in practice. Tubes in more number of rows are to be avoided as the screening of the tank and tube surfaces decreases the dissipation. Hence, when more number of tubes are to be provided, a radiator attached with the tank is considered. For much larger sizes forced cooling is adopted.
DIMENSIONS OF THE TANK

The dimensions of tank depends on the type and capacity of transformer, voltage rating and electrical clearance to be provided between the transformer and tank, clearance to accommodate the connections and taps, clearance for base and oil above the transformer etc,. These clearances can assumed to be between
(30 and 60) cm in respect of tank height
(10 and 20) cm in respect of tank length and
(10 and 20) cm in respect of tank width or breadth.
Tank height \( H_t = [ H_w + 2H_y \text{ or } 2a + \text{clearance (30 to 60) cm}] \text{ for single and three phase core, and single phase shell type transformers.} \)

\[ = [3(H_w + 2H_y \text{ or } 2a) + \text{clearance (30 to 60) cm}] \text{ for a three phase shell type transformer.} \]

Tank length \( L_t = [ D + D_{ext} + \text{clearance (10 to 20) cm}] \text{ for single phase core type transformer} = [2D + D_{ext} + \text{clearance (10 to 20) cm}] \text{ for three phase core type transformer} = [4a + 2W_w + \text{clearance (10 to 20) cm}] \text{ for single and three phase shell type transformer.} \)

Width or breadth of tank \( W_t = [D_{ext} + \text{clearance (10 to 20) cm}] \text{ for all types of transformers with a circular coil.} \)

\[ = [b + W_w + \text{clearance (10 to 20) cm}] \text{ for single and three phase core type transformers having rectangular coils.} \]

\[ = [b + 2W_w + \text{clearance (10 to 20) cm}] \text{ for single and three phase shell type transformers.} \]
When the tank is placed on the ground, there will not be any heat dissipation from the bottom surface of the tank. Since the oil is not filled up to the brim of the tank, heat transfer from the oil to the top of the tank is less and heat dissipation from the top surface of the tank is almost negligible. Hence the effective surface area of the tank $St$ from which heat is getting dissipated can assumed to be $2H_t (L_t + W_t)$ m$^2$.

Heat goes dissipated to the atmosphere from tank by radiation and convection. It has been found by experiment that $6.0$ W goes radiated per m$^2$ of plain surface per degree centigrade difference between tank and ambient air temperature and $6.5$ W goes dissipated by convection / m$^2$ of plain surface / degree centigrade difference in temperature between tank wall and ambient air. Thus a total of $12.5$ W/m$^2$/0°C goes dissipated to the surrounding. If $\Delta T$ is the temperature rise, then at final steady temperature condition, losses responsible for temperature rise is losses dissipated or transformer losses $= 12.5$ $St$. 
Number and dimensions of tubes

If the temperature rise of the tank wall is beyond a permissible value of about 500°C, then cooling tubes are to be added to reduce the temperature rise. Tubes can be arranged on all the sides in one or more number of rows. As number of rows increases, the dissipation will not proportionally increase. Hence the number of rows of tubes are to be limited. Generally the number of rows in practice will be less than four.

With the tubes connected to the tank, dissipation due to radiation from a part of the tank surface screened by the tubes is zero. However if the radiating surface of the tube, dissipating the heat is assumed to be equal to the screened surface of the tank, then tubes can assumed to be radiating no heat. Thus the full tank surface can assumed to be dissipating the heat due to both radiation and convection & can be taken as 12.5 St watts.

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. Because of this siphoning action, it has been found that the convection from the tubes increase by about 35 to 40%.
Thus if the improvement is by 35%, then the dissipation in watts from all the tubes of area $At = 1.35 \times 6.5At = 8.78\ At$.

Thus in case of a tank with tubes, at final steady temperature rise condition, $\text{Losses} = 12.5\ St + 8.78\ At$

Round, rectangular or elliptical shaped tubes can be used. The mean length or height of the tubes is generally taken as about 90% of tank height.

In case of round tubes, 5 cm diameter tubes spaced at about 7.5cm (from centre to centre) are used. If $dt$ is the diameter of the tube, then dissipating area of each tube at $= \pi dt \times 0.9Ht$. if $nt$ is the number of tubes, then $At = atnt$.

Now a days rectangular tubes of different size spaced at convenient distances are being much used, as it provides a greater cooling surface for a smaller volume of oil. This is true in case of elliptical tubes also. The tubes can be arranged in any convenient way ensuring mechanical strength and aesthetic view.
OVERALL DIMENSIONS

When dealing with overall dimensions in transformer problems, refer to the following details and diagrams:

- \( a \) = width of largest stamping,
- \( d \) = diameter of circumscribing circle,
- \( D \) = distance between centres of adjacent limbs,
- \( W_w \) = width of window,
- \( H_w \) = Height of window,
  \( = \) length of limb,
- \( H_y \) = height of yoke,
- \( H \) = Overall height of transformer over yokes or overall height of frame,
- \( W \) = length of yoke = overall length of frame.
We have the following relations for single phase core type transformers

\[ D = d + W_w, \quad D_Y = a, \]
\[ H = H_w + 2H_Y, \quad W = D + a, \]

Width over one limb = outer diameter of h.v. winding.

Width over two limbs = \( D + \) outer diameter of h.v. winding
Fig. Three phase core type transformer.

Fig. Single phase shell type transformer.
We have, for a 3 phase core type transformers

\[ D = d + W_w; \quad D_Y = a; \quad H = H_w + 2H_Y; \quad W = 2D + a, \]

Width over one limb = outer diameter of h.v. winding
Width over 3 limbs = \(2D + \) outer diameter of h.v. winding.

For single phase shell type referring to Fig.

\[ D_Y = b, \quad H_Y = a, \quad W = 2W_w + 4a, \quad H = H_w + 2a. \]
Show that the output of a 3 phase core type transformer is:

\[ Q = 5.23 \times 10^{-2} f B_m H d^2 H_w \times 10^{-2} \text{kVA} \]

where \( f \) = frequency, Hz; \( B_m \) = maximum flux density, Wb/m\(^2\); \( d \) = effective diameter of core, m; \( H \) = magnetic potential gradient in limb, A/m; \( H_w \) = height of limb (window), m.

Solution

kVA output of a three phase transformer \( Q = 3EI \times 10^{-3} \)

In a three phase core type transformer each limb has one primary and one secondary winding wound on it and therefore total mmf over one limb = \( 2TI \).

\[ : \text{Magnetic potential gradient } H = \frac{\text{mmf}}{\text{height of limb}} \]

\[ = \frac{2TI}{H_w} \quad \text{or } TI = \frac{HH_w}{2} \quad \text{Also } A_i = \frac{\pi}{4}d^2 \]

Substituting the value of \( A_i \) and \( TI \) in the expression for \( Q \), we have

\[ Q = 3 \times 4.44 f B_m \times \frac{\pi}{4} d^2 \times H \frac{H_w}{2} \times 10^{-3} \]

\[ Q = 5.23 f B_m H d^2 H_w \times 10^{-3} \text{kVA}. \]
Calculate the kVA output of a single phase transformer from the following data:

- core height / distance between core centres = 2.8
- diameter of circumscribing circle / distance between core centres = 0.56
- net iron area / area of circumscribing circle = 0.7
- current density = 2.3 A/mm²
- frequency = 50 Hz
- distance between core centres = 0.4 m
- window space factor = 0.27
- flux density of core = 1.2 Wb/m²

Given Data:
Hw/D=2.8
d/D=0.56
Ai/Acc=0.7
δ=2.3 A/mm²
Kw=0.27
f=50 Hz  Bm=1.2 wb/m²  D=0.4 m
Distance between core centres \( D = 0.4 \) m.

\[ \therefore \text{Core height (window height)} \ H_w = 2.8 \times 0.4 = 1.12 \text{ m.} \]

Diameter of circumscribing circle \( d = 0.56 \times 0.4 = 0.224 \text{ m.} \)

Width of window \( W_w = D - d = 0.4 - 0.224 = 0.176 \text{ m} \)

\[ \therefore \text{Area of window} \ A_w = H_w \times W_w = 1.12 \times 0.176 = 0.197 \text{ m}^2 \]

Area of circumscribing circle \( = (\pi/4) d^2 = 0.0394 \text{ m}^2 \)

\[ \therefore \text{Net iron area} \ A_i = 0.7 \times 0.0394 = 0.0276 \text{ m}^2 \]

for a single phase transformer

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

\[ = 2.22 \times 50 \times 1.2 \times 0.27 \times 2.3 \times 10^6 \times 0.197 \times 0.0276 \times 10^{-3} = 450 \text{ kVA.} \]

\[ Q = 450 \text{ kVA.} \]
Determine the dimensions of core and yoke for a 200 kVA, 50 Hz single phase core type transformer. A cruciform core is used with distance between adjacent limbs equal to 1.6 times the width of core laminations. Assume voltage per turn 14 V, maximum flux density 1.1 Wb/m², window space factor 0.32, current density 3 A/mm², and stacking factor 0.9. The net iron area is 0.56 d² in a cruciform core where d is the diameter of circumscribing circle. Also the width of largest stamping is 0.85 d.

Given Data:

\[
\begin{align*}
Q &= 200 \text{ KVA} \\
f &= 50 \text{ Hz} \\
D &= 1.6 \text{ a} \\
E_t &= 14 \text{ V} \\
B_m &= 1.1 \text{ wb/m}^2 \\
K_w &= 0.32 \\
\delta &= 3 \text{ A/mm}^2 \\
k_i &= 0.9 \\
A_i &= 0.56 \text{ d}^2 \\
a &= 0.85 \text{ d}
\end{align*}
\]

Solution

\[
\begin{align*}
\text{Voltage per turn } E_t &= 4.44 f \Phi_m = 4.44 f B_m A_i \\
\therefore \text{Net iron area } A_i &= \frac{14}{4.44 \times 50 \times 1.1} = 0.0573 \text{ m}^2 \\
\therefore \text{Diameter of circumscribing circle } d &= \sqrt{A_i / 0.56} = \sqrt{0.0573 / 0.56} = 0.32 \text{ m.}
\end{align*}
\]

Width of largest stamping \( a = 0.85 \times d = 0.85 \times 0.32 = 0.272 \text{ m.}\)

Distance between core centres \( D = 1.6 \text{ a (given)} = 1.6 \times 0.272 = 0.435 \text{ m.}\)

Width of window \( W_w = D - d = 0.435 - 0.32 = 0.115 \text{ m.}\)
for a single phase transformer,

\[ Q = 2.22 f B_m K_w \delta A_w A_i \times 10^{-3} \]

\[ 200 = 2.22 \times 50 \times 1.1 \times 0.32 \times 3 \times 10^6 \times A_w \times 0.0573 \times 10^{-3} \]

\[ \therefore \text{Window area } A_w = 0.0298 \text{ m}^2 \]

\[ \therefore \text{Height of window } H_w = 0.0298/0.115 = 0.26 \text{ m.} \]

Using the same stepped section for the yoke as for core
Depth of yoke \( D_y = a = 0.272 \text{ m} \) and height of yoke \( H_y = 0.272 \text{ m} \).

Overall height of frame \( H = H_w + 2H_y = 26 + 2 \times 0.272 = 0.804 \text{ m}. \)
Overall length of frame \( W = D + a = 43.5 + 0.272 = 0.737 \text{ m} \)
Calculate approximate overall dimensions for a 200 kVA, 6600/440 V, 50 Hz, 3 phase core type transformer. The following data may be assumed: emf per turn = 10 V; maximum flux density = 1.3 Wb/m²; current density = 2.5 A/mm²; window space factor = 0.3 overall height = overall width; stacking factor = 0.9. Use a 3 stepped core.

For a three stepped core:

Width of largest stamping = 0.9 d, and

Net iron area = 0.6 d² where d is the diameter of circumscribing circle.

Given Data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Q</td>
<td>200 KVA</td>
</tr>
<tr>
<td>V_p</td>
<td>6600 V</td>
</tr>
<tr>
<td>V_s</td>
<td>440 V</td>
</tr>
<tr>
<td>f</td>
<td>50 Hz</td>
</tr>
<tr>
<td>E_t</td>
<td>10 V</td>
</tr>
<tr>
<td>B_m</td>
<td>1.3 Wb/m²</td>
</tr>
<tr>
<td>δ</td>
<td>2.5 A/mm²</td>
</tr>
<tr>
<td>K_w</td>
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</tr>
<tr>
<td>H</td>
<td>W</td>
</tr>
<tr>
<td>k_r</td>
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</tr>
<tr>
<td>a</td>
<td>0.9 d</td>
</tr>
<tr>
<td>A_i</td>
<td>0.6 d²</td>
</tr>
</tbody>
</table>

Solution

Net iron area \( A_i = \frac{E_t}{4.44 \times B_m} = \frac{10}{4.44 \times 50 \times 1.3} = 0.0347 \text{ m}^2 \).

Diameter of circumscribing circle \( d = \sqrt{\frac{0.0347}{0.5}} = 0.24 \text{ m}, \)
and width of largest stamping \( a = 0.9 \times 0.24 = 0.216 \text{ m}, \)
Using a 3 stepped section for the yoke
Height of yoke \( H_y = a = 0.216 \text{ m}, \)
Depth of yoke \( D_y = a = 0.216 \text{ m}, \)
for a 3 phase transformer,

\[ Q = 3.33 \times f \times B_m \times K_w \times \delta \times A_w \times A_i \times 10^{-3} \]

or

\[ 200 = 3.33 \times 50 \times 1.3 \times 0.3 \times 2.5 \times 10^6 \times A_w \times 0.0347 \times 10^{-8} \]
\[ \therefore \text{Window area } A_w = 0.0355 \text{ m}^2 \quad \text{or} \quad H_w \times W_w = 0.0355 \text{ m}^2 \]

The given condition is, overall height = overall width \quad \text{or} \quad H = W

\[ H = H_w + 2H_y = H_w + 2 \times 0.216 = H_w + 0.432 \]
\[ W = 2D + \alpha = 2(W_w + d) + \alpha = 2W_w + 0.48 + 0.216 = 2W_w + 0.696 \]

As \[ H = W, \text{ we have } : H_w + 0.432 = 2W_w + 0.696 \]
or \[ H_w = 2W_w + 0.264 \]
\[ (2W_w + 0.264) W_w = 0.0355 \quad \text{or} \quad 2W_w^2 + 0.264 W_w - 0.0355 = 0 \]

or \quad width of window \( W_w = 0.083 \text{ m} \) \quad \text{and height of window} \( H_w = \frac{0.0355}{0.083} = 0.428 \text{ m} \).

Thus the dimensions of core are:

Distance between adjacent core centres \( D = W_w + d = 0.323 \text{ m} \).

Overall height \( H = H_w + 2H_y = 0.86 \text{ m} \).

Overall width \( W = 2D + \alpha = 0.862 \text{ m} \).
A 6600 V, 60 Hz single phase transformer has a core of sheet steel. The net iron cross-sectional area is $22.6 \times 10^{-3} \, m^2$, the mean length is 2.23 m, and there are four lap joints. Each lap joint takes $1/4$ times as much reactive mmf as is required per metre of core. If $B_m = 1.1 \, Wb/m^2$, determine (a) the number of turns on the 6600 V winding and (b) the no load current. Assume an amplitude factor of 1.52 and that for given flux density, mmf per metre = 232 A/m; specific loss = 1.76 W/kg. Specific gravity of plates = 7.5.

Given Data:

- $E_p = 6600 \, V$
- $f = 60 \, Hz$
- $A_i = 22.6 \times 10^{-3} \, m^2$
- lap joint = 4
- Specific gravity = $7.5 \times 10^{-3} \, Kg/m^3$
- $l = 2.23 \, m$
- mmf for joint = $1/4 \times$ mmf/m of core
- mmf/m of core = 232
- specific loss = 1.76 W/kg

**Solution.**

(a) Number of turns 

$$T = \frac{E}{4.44 \times f \times B_m \times A_i} = \frac{6600}{4.44 \times 60 \times 11 \times 22.6 \times 10^{-3}} = 1100.$$

(b) Mmf required for iron parts 

$$= 232 \times 2.23 = 517 \, A.$$

Mmf required for joints 

$$= 4 \times \frac{1}{4} \times 232 = 232 \, A.$$

Total magnetizing mmf 

$$A_T = 517 + 232 = 749 \, A.$$

Magnetizing current 

$$I_m = \frac{A_T}{K_{ph} T_p} = \frac{749}{1.52 \times \sqrt{2} \times 1100} = 0.318 \, A.$$
(as peak factor $K_{pk} =$ amplitude factor $\times \sqrt{2}$).

Weight of core $= 2.23 \times 22.6 \times 10^{-3} \times 7.5 \times 10^3 = 378$ kg.

Total iron loss $P_t = 1.76 \times 378 = 665$ W. Loss component $I_t = \frac{665}{6600} = 0.1$ A.

No load current $I_0 = \sqrt{(0.318)^2 + (0.1)^2} = 0.333$ A.
The tank of 1250 kVA, natural oil cooled transformer has the dimensions length, width and height as $0.65 \times 1.55 \times 1.85$ m respectively. The full load loss $= 13.1$ kW, loss dissipation due to radiations $= 6$ W/m²-°C, loss dissipation due to convection $= 6.5$ W/m²-°C, improvement in convection due to provision of tubes $= 40\%$, temperature rise $= 40$ °C, length of each tube $= 1$ m, diameter of tube $= 50$ mm. Find the number of tubes for this transformer. Neglect the top and bottom surface of the tank as regards the cooling.

**Given Data**

<table>
<thead>
<tr>
<th>kVA</th>
<th>1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_t$</td>
<td>1 m</td>
</tr>
<tr>
<td>$d_t$</td>
<td>50 mm</td>
</tr>
</tbody>
</table>
**Given Data**

- kVA = 1250
- $l_t = 1$ m
- $d_t = 50$ mm
- $\theta = 40^\circ$C

- Tank dimension = $0.65 \times 1.55 \times 1.85$ m
- $\lambda_{\text{conv}} = 6.5$ W/m$^2$ - $^\circ$C
- $\lambda_{\text{rad}} = 6$ W/m$^2$ - $^\circ$C
- Improvement in cooling = 40%
- Full load loss = 13.1 kW.

**Solution**

- $L_T = \text{Length} = 0.65$ m
- $W_T = \text{Width} = 1.55$ m
- $H_T = \text{Height} = 1.85$ m

Heat dissipating surface of tank

\[ S_t = \text{Total Area of vertical sides} = 2(L_T H_T + W_T H_T) = 2H_T(L_T + W_T) = 2 \times 1.85 \times (0.65 + 1.55) = 8.14 \text{ m}^2 \]

Loss dissipated by tank walls by radiation and convection

\[ = (6 + 6.5)S_t = 12.5S_t \]
Let, heat dissipating area of tubes

\[ X S_t \]

Loss, dissipated by cooling tubes due to convection

\[ = 6.5 \times \frac{140}{100} \times X S_t = 9.1 X S_t \]

Total loss dissipated by tank and tubes

\[ = 12.5 S_t + 9.1 X S_t \]

\[ = S_t (12.5 + 9.1 X) \]

Temperature rise in transformer with cooling tubes

\[ \theta = \frac{\text{Total loss}}{\text{Total loss dissipated}} \]

Given that total loss, \( P_{\text{loss}} = 13.1 \text{ kW} = 13.1 \times 10^3 \text{ W} \)
Hence, $\theta = \frac{13.1 \times 10^3}{S_t (12.5 + 9.1X)}$

$12.5 + 9.1X = \frac{13.1 \times 10^3}{\theta S_t}$

$X = \frac{1}{9.1} \left( \frac{13.1 \times 10^3}{\theta S_t} - 12.5 \right) = \frac{1}{9.1} \left( \frac{13.1 \times 10^3}{40 \times 8.14} - 12.5 \right) = 3.0476$

Total area of tubes = $X S_t = 3.0476 \times 8.14 = 24.8075 \text{ m}^2$

Total number of cooling tubes = $\frac{\text{Total Area of tubes}}{\text{Area each tube}}$

Area of each tube = $\pi d_t l_t = \pi \times 50 \times 10^{-3} \times 1 = 0.157 \text{ m}^2$

Total number of cooling tubes = $\frac{24.8075}{0.157} = 158$ tubes

The diameter of the tube is 50 mm and the standard distance between the tubes is half of the diameter and so, let distance between tubes = 25 mm.
The width of the tank is 1550 mm. If we leave an edge spacing of 62.5 mm on either sides then we can arrange 20 tubes widthwise with a spacing of 75 mm between centres of tubes. On lengthwise we can arrange 8 tubes with same spacing as that of widthwise tubes. But one row is not sufficient to accommodate the required 158 cooling tubes. Hence three rows of cooling tubes are provided on both lengthwise and widthwise. The plan of the cooling tubes is shown in fig 4.7.1.