### List of Symbols

- **S**: Power rating of transformer in kilovolt-amperes
- **B**: Flux density in Wb/m²
- **w**: Width of Lamination in mm
- **h**: Height of Lamination limb in mm
- **p**: Density of copper in kg/m³
- **t**: Thickness of Lamination in mm
- **J**: Current density in A/mm²
- **V**: Terminal voltage in volts
- **f**: Frequency of operation in Hertz (Hz)
- **A₄**: Cross sectional area of core in m²
- **Vₜ**: Volts per turn
- **A₆**: Gross Cross sectional area of core in m²
- **D**: Diameter of circle enclosing the core in m
- **h**: Height of winding in mm
- **A₅**: Window area in m²
- **N**: Number of turns of primary or secondary windings
- **Nₐ**: Number of Laminations
- **Nₜ₉**: Number of high voltage turns
- **Nₗ₉**: Number of Low voltage turns
- **n**: Turns Ratio of transformer
- **I**: Current specification
- **Iₗ₉**: Current Rating of Low Voltage Side in amperes
- **Iₗ₉**: Current Rating of high voltage side in amperes
- **A₉**: Conductor Cross Sectional area in mm²
- **A₉₉**: Area of low voltage conductor in mm²
- **Aₗ₉**: Area of high voltage conductor in mm²
- **Dₗ₉**: Diameter of high voltage conductor
- **lₐ**: Mean length of one turn
- **lₐ₉**: Mean length of one high voltage turn
- **lₐ₉**: Mean length of one low voltage turn
- **R₉**: Mean Radius of one high voltage turn
- **R₉**: Mean Radius of one low voltage turn
- **R**: Radius of core in m
- **r**: Radius of low voltage coil in mm
- **n**: Number of low or high voltage coil group
- **tₗ**: Thickness of low voltage former and low voltage coil group separator mm.
- **tₙ**: Thickness of the major separator between low and high voltage, coil groups respectively in mm.
- **r**: Radius of high voltage coils
tₗ: Thickness of insulation separating high voltage coils
- **M**: Mass of Copper in kg
- **Xₗ₉**: Number of turns per layer
- **Xₗ₉**: Number of low voltage turns per layer
- **Xₗ₉**: Number of high voltage turns per layer
- **Y**: Number of layers
- **Yₗ₉**: Number of layers of low voltage coil groups.
1.2 Introduction

The work is based on the principle copy creativity using certain standard formulae with slight modifications based on practical experience. The rating of 10KVA was chosen such that small communities might easily afford one. The voltage rating of 11/0.415KV and the frequency rating of 50Hz are with the supply authority specifications. The core-type is based on the rigidity of its build and compactness (1,2). The designed model compromises standard existing ones; theoretical designs, specific practical works on power and distribution transformer transdesigns, refurbishing and repairs. The design specifications are as specified with other details in subsequent sections.

1.3 DESIGN PARAMETERS/SPECIFICATIONS

| KVA Rating | 10KVA |
| Voltage Rating | 11000/415V |
| Operation frequency | 50 Hz |
| Cooling | ONAN |
| Number of phases | 3 |
| Winding connection/type | Dy 11 |

1.4 Other Specifications

- Flux density, \( B = 1.7 \, \text{wb/m}^2 \), (1)
- Laminaion Dimension: width, \( w = 89\, \text{mm} \)
  - Height, \( h = 223\, \text{mm} \)
- Laminaion type: 3-phase
- Density of copper \( Q = 8930\, \text{kg/m}^3 \)
- Thickness of laminaion, \( t = 0.5\, \text{mm} \), (1) - (4)
- Current density, \( J = 3.5\, \text{A/mm}^2 \), (1) - (4)

1.5 BASIC DESIGN EQUATIONS (1) - (4)

- Voltage Equation, \( V = 4.44fBAgN \) ...
- Volts per turn Equation, \( V_t = 4.44f BA_g \) ...
- Cross Core area, \( A_g = \pi D^2/4 \) (for this design) ...
  - \( = 0.5D^2 \) (theoretical) ...
- Winding height, \( H = 0.97h \) ...
- Window area, \( A_w = 0.97hw \) ...

1.6 DESIGN CONSIDERATION/ANALYSIS

Consider the laminaion shown in Fig. 1
For a circle, \( A_g = \pi w^2/4 \)

\[
= \pi w^2/4 = 3.142 \times 89^2 \times 0.25 = 6222\, \text{mm}^2 (62.22 \times 10^{-6} \text{m}^2)
\]

This is approximately the useful core area, \( A_i \)
Therefore \( A_i = 62.22 \times 10^{-6} \text{m}^2 \).

1.7 Number of Laminaion, \( N_L \)

The number of laminaion put together to give a thickness of \( 89\, \text{mm} \) in approximately the required total number of laminaions.

\[
t_{N_L} = w = D.
\]

\[
N_L = w \text{ or } D/t = 89/0.5 = 178 \text{ laminaions.}
\]
1.8 Volts per turn, \( V_t \); (1) - (4)
\[
V_t = 4.44 fBA = 4.44 \times 50 \times 1.7 \times 62.22 \times 10^{-6} = 2.35 \text{ volts per turn.}
\]

1.9 Number of turns per phase, \( N/\text{ph} \); (1) - (4)
For the high voltage coil (delta connected), each phase must withstand the 11KV impressed on it.
\[
N_{HV}/\text{ph} = \frac{V_{HV}}{V_t} = \frac{11000}{2.35} = 4685 \text{ Turns}
\]
For the low voltage coil, the turns per phase is given as
\[
N_{LV}/\text{ph} = \frac{V_{LV}}{V_t} = \frac{415}{2.35} = 102 \text{ Turns}
\]

1.10 Turns Ratio, \( n \); (1) - (4)
\[
n = \frac{N_{HV}}{N_{LV}} = \frac{V_{HV}}{V_{LV}} = \frac{I_{LV}}{I_{HV}} = \frac{11000}{415} = 3/415 = 4685/102 = 45.9 = 46
\]

1.11 Current Specification, \( I \); (1) - (4)
For the low voltage, \( I_{LV} = \frac{KVA}{3V_{LV}} = \frac{10 \times 1000}{1.732 \times 415} = 13.9 \text{A}
\]
For the high voltage, \( I_{HV} = \frac{KVA}{3V_{HV}} \) per phase
\[
I_{HV} = \frac{0.30}{3} = 0.30 \text{A}
\]

1.12 Conductor Area, \( A_c \); Wire gauge, conductor diameter, \( D_c \); (1)-(4)
\[
A_c = \text{current}/\text{Current density} = I/J.
\]
For the L.V.
\[
A_{cLV} = \frac{13.91}{3.5} = 3.974 \text{ mm}^2
\]
\[
A_c = \frac{\pi D_c^2}{4} = \frac{\pi}{4} \frac{3.974}{3.142} = 2.25 \text{ mm}
\]
\[
D_{cLV} = 2.25 \text{ mm (2.3 mm used)}
\]
For the H.V.
\[
A_{cHV} = \frac{0.303}{3.5} = 0.0867 \text{ mm}
\]
\[
D_{cHV} = \frac{0.0867}{3.142} = 0.0532 \text{ mm}
\]
\[
(0.45 \text{ mm used})
\]

The wire gauges are respectively 13 and 26 for the low and high voltage sides, due to the diameter specification as computed and dictated by the nearest possible wire sizes (in mm) available, this being a function of the current rating.

1.15 Mean Length of turn
The idea of how long averagely each turn per coil will be, leads us to the 'idea of the mean length of turn.' There are fifteen to sixteen coil groups with insulators of various thickness interposed.

The low voltage coil has two layer each of fifty-one turns with three insulators of identical thickness while the high voltage coils (14 coil groups in number) sandwich thirteen insulator layers of identical thickness. For this design a mean radius \( R_n \), was computed for, given by the formulae. These formulae are derived based on experience and knowledge obtained from mathematics.
\[
R_n = (R + r) + 2(n' - 1)r + (2t_1 + t_2) + 15r' + 7t_3 \quad \ldots (1)
\]
\[
R_n = (R + r) + 2(n' - 1)r + (t_1 + t_2) \quad \ldots (2)
\]
After substituting the values as specified for the various parameters, \( R_N = 6.2 \times 10^{-2} \text{m} \)
\( R_{n1} = 49.6 \times 10^{-3} \text{m} \)
\( R_{n2} = 53.45 \times 10^{-3} \text{m} \)

In general the mean length of turns of radii \( R_N, R_{n1}, R_{n2} \) is given as
\[ l_m = 2 \pi R \] (3)
where \( R \) is either \( R_N, R_{n1}, R_{n2} \).

By substituting values of \( R_N, R_{n1}, R_{n2} \) into equation 3,
\[ l_{m_{RV1}} = 0.312 \text{m} \] for the two coil groups of the low voltage coil side respectively.
\[ l_{m_{LV2}} = 0.336 \text{m} \]

1.14 Mass of Copper, \( M \) (in kg) (1) - (4)
\[ M = \text{number of turns per phase} \times \text{conductor Area} \times \text{conductor mean length} \times \text{specific gravity of copper} \]
\[ = N_{AC} l_m \]
where, for copper, specific gravity = 8930 kg/m\(^3\),
\( l_m, N \) are as given in design analysis.
The computed mass of copper is 4 kg per phase with high voltage coil. The practical weight of coils plus insulation was 6 kg meaning the insulation weight is 2 kg.

1.15 Winding height, \( H \)
The total available window height is 223 mm. To avoid short circuits between the end conductors per layer of the various coils and between conductor per layer a slight excess overhang is allowed above and below the wound coil. This results in a reduction in the height of the lamination by about 3.5%. The winding height is therefore given as
\[ H = 0.965h \]
\[ = 0.965 \times 223 \]
\[ = 215 \text{mm (0.215m)} \]
This is shown in figure 2. The assumption made is based on experience.

1.16 Number of turns per layer (TPL), \( X \)
The ratio of the total available winding height to the conductor diameter, gives a figure for the total number of turns of conductor that can be accommodated in any particular layer. If the given symbol are considered
\[ X_{DC} = H \]
\[ X = H/D_c \]
For the low voltage side
\[ X_{LV} = H/D_{CLV} = 215/2.3 = 95 \text{Turns/layer} \]
If a single layer of 102 turns was to be accommodated then
\[ H = 2.3 \times 102 = 235 \text{mm} \]
But two layers each of fifty-one turns was considered i.e. \( H = 2 \times 51 = 102 \text{mm} \)
\[ X_{HR} = 117/0.332 = 352 \text{Turns/layer} \]

1.17 Number of Layers, \( Y \)
\[ Y = \text{Number of turns/turns per layer} \]
\[ Y_{LV} = 102/51 = 2 \text{ layers} \]
\[ Y_{HV} = 4685/352 = 13.3 \text{ layers (14 layers)} \]
1.18 Coil Thickness (or Coil Width)

This is required in order to ensure that the available window space can accommodate the three coils of the various phases. Consider the spatial outlay of fig. 3.

- The core thickness = 89mm
- Thickness of low voltage former = 2x4mm = 8mm
- Thickness of low voltage conduction = 4x2.3mm = 9.2mm
- Low voltage coils separator = 2x2mm = 4mm
- Major separator = 2x4mm = 8mm
- High voltage coil thickness = 2x14x0.45 = 12.6mm
- High voltage internal insulation = 2x13x0.1 = 2.6mm

Coil thickness with core inclusive = 134mm

and without the core it is two halves each of 22.5mm thick on either side of the core. Thus the central limb provides two halves of 22.5mm thick coils and the outer limbs provide 22.5mm respectively. Each window is occupied by two layers of 22.5mm thick coils and thus the window width of 89mm can adequately occupy 45mm thick coils.

1.19 Window Space Factor, \(W_{wp}\) (1) - (4)

This is the ratio of the window area available to accommodate the winding \(A_w\) to the total available window area, \(A_w\).

\[
W_{wp} = \frac{A'_w}{A_w} \times 100
\]

- \(A_w = 223 \times 89 = 19847\)mm
- \(A'_w = 117 \times 45 = 5268\)mm

Hence \(W_{wp} = \frac{5268}{19847} \times 100 = 27\%\).

1.20 Tank Design

1.21 Tank Length (L): This should be such that the end limb coils are adequately isolated from the tank side walls. An addition is made to the total core-coil length to achieve this goal.

- But core length of \(L = 445\)mm \((0.45\)m)
- Overhang end coils = 43mm \((0.045)\)

If a third of this is allowed as guard, then the tank length will be \(1.33L = 1.33 \times 445 = 595.17\)mm \((0.59517\)m).

Thus a clearance of 80mm is made on both sides of the side walls.

1.22 Tank Width (Wt): By a similar analysis the tank width, \(W_t\) can be computed.

\[
W_t = 2 \times 80 + 89 + 2 \times 22.5
\]

- \(W_t = 168 + 89 + 45 = 294\)mm \((0.29\)m)

1.24 Tank Height, \(H_t\): The core is isolated from the tank, some overhang is allowed for end connections.

\[
H_t = 401 + 2 \times 80
\]

- \(H_t = 401 + 160 = 561\)mm \((0.561\)m)
1.24 Quantity of oil (by volume) (1)-(4)

\[
\text{Volume of oil} = \text{Volume of tank} = LW_x H_y = 0.490 \times 0.294 \times 0.050 = 0.0808 \text{m}^3 (81 \text{ litres})
\]

1.25 Design Table: 1.1 Transformer Design Specification

<table>
<thead>
<tr>
<th>S/N</th>
<th>Parameters per phase</th>
<th>High Voltage Winding</th>
<th>Low Voltage Winding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Number of turns</td>
<td>4685</td>
<td>102</td>
</tr>
<tr>
<td>2.</td>
<td>Wire gauge</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>3.</td>
<td>Current Rating</td>
<td>0.820A</td>
<td>12.87A</td>
</tr>
<tr>
<td>4.</td>
<td>Volts per turn</td>
<td>2.35</td>
<td>2.35</td>
</tr>
<tr>
<td>5.</td>
<td>Number of lamination</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Mass of copper</td>
<td>2.5-3kg</td>
<td>1.2-1.4kg</td>
</tr>
<tr>
<td>7.</td>
<td>Number of layers</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>8.</td>
<td>Window space factor</td>
<td>&lt;---- 27% -------------&gt;</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Conductor diameter</td>
<td>0.45mm</td>
<td>2.3mm</td>
</tr>
<tr>
<td>10.</td>
<td>Winding height</td>
<td>&lt;---- 117mm ----------&gt;</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Direction of winding</td>
<td>&lt;---- Counter clockwise ---&gt;</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Tank Dimension</td>
<td>544x288x537mm</td>
<td></td>
</tr>
</tbody>
</table>

1.26 Winding Outlay/Connection: The high voltage windings are connected in star and the low voltage windings are connected in delta. This is as shown in Figure 4.

1.27 Design of the low voltage former/wooden block

The former thickness is specified by the voltage stress between the low voltage coils and the tank. The physical dimensions are specified by the core stack thickness (89mm x 89mm), and lamination dimensions. The size of the wooden block should be such that the lamination stack can conveniently be accommodated after the coil is wound. Thus the actual former dimension is slightly bigger than the dimension of the lamination. The diagrams are shown in Figure 5.

1.28 Making the Low and High Voltage Coils, (1), (3), (4):

The low voltage former was tightly fitted unto the wooden block by means of a masking tape and securely clamped onto the winding machine. Another layer of insulation paper (about 0.1mm thick) introduced to level off the surface. The wire bobbin (2.3mm) fitted into the bobbin carrier such that smooth, parallel runs could be made. Insulating sleeve was introduced at the start of the coil which is rigidly marked and hinged in the proper direction to commence the winding. The machine rail is adjusted to move front and within 117mm. With the left leg on the trottle pedal, the right leg as support with the hands as wire guide and tensioner, the winding is commenced. The turns counter records the number of turns. At the end of the first layer another thick insulation introduced to act as base for the next layer. The procedure was repeated until 102 turns was recorded. The end was secured by means of masking tape and sleeved to mark the end of the low voltage winding. A thick insulation was introduced securely in place to serve as base for the high voltage coil. The exercise was repeated on its merit until 4685 turns were wound. Three identical coils were made in each case.
1.29 Core-Coil Assembly; (1), (3), (4)

The core was arranged per layer (E's and corresponding I's). The coils were put horizontally on a smooth insulated surface. The E's were introduced with the corresponding I's alternately such that a smooth interleaving was made. When all the laminations were fitted, the core-coil assembly was faked and kept in a vertical position. In this position the core was compacted by smooth steady taps, this together with the interleaving, reduces possible air spaces, thereby reducing the reluctance of the magnetic circuit. The core was then clamped with the aid of treated wooden blocks with bolts and nuts.

2. Tests

2.1 D.C. Resistance Test

This was carried out using an ammeter (analogue) and digital meter for both the high voltage and low voltage coil. The results are shown in table 1.

Table 1.2: D.C. Resistance Test Results

<table>
<thead>
<tr>
<th>Coil Number</th>
<th>High Voltage Winding (Ohms)</th>
<th>Low Voltage Winding (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>275</td>
<td>0.3</td>
</tr>
<tr>
<td>II</td>
<td>275</td>
<td>0.3</td>
</tr>
<tr>
<td>III</td>
<td>275</td>
<td>0.3</td>
</tr>
</tbody>
</table>

2.2 Megger Test

The insulation resistance between coils and between coils and earth were taken. The result was as shown in table 2.

Table 1.3: Results of Insulation Resistance Test

<table>
<thead>
<tr>
<th>Coil Number</th>
<th>L.V. to earth (M)</th>
<th>High Voltage to earth (M)</th>
<th>High Voltage to low voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1000</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>II</td>
<td>1000</td>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>III</td>
<td>1000</td>
<td>0</td>
<td>00</td>
</tr>
</tbody>
</table>

2.3 No Load Test (Voltage Ratio)

This was carried out and the results are shown on table 3.

Table 3: No Load Test Results (per phase)

<table>
<thead>
<tr>
<th>Input Voltage (V)</th>
<th>Coil I Voltage (V)</th>
<th>Coil II Voltage (V)</th>
<th>Coil III Voltage (V)</th>
<th>Turn Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>30.</td>
</tr>
<tr>
<td>20</td>
<td>650</td>
<td>650</td>
<td>650</td>
<td>32.5</td>
</tr>
<tr>
<td>30</td>
<td>988</td>
<td>988</td>
<td>988</td>
<td>32.9</td>
</tr>
<tr>
<td>40</td>
<td>1325</td>
<td>1325</td>
<td>1325</td>
<td>33.1</td>
</tr>
<tr>
<td>50</td>
<td>1675</td>
<td>1675</td>
<td>1675</td>
<td>33.5</td>
</tr>
<tr>
<td>60</td>
<td>2050</td>
<td>2050</td>
<td>2050</td>
<td>34.2</td>
</tr>
<tr>
<td>70</td>
<td>2413</td>
<td>2413</td>
<td>2413</td>
<td>34.5</td>
</tr>
</tbody>
</table>
3.1 CONCLUSIONS

The results in Tables 1, 2, and 3 fall within acceptable limits. A three phase, power/distribution, 10KVA, ONAN, 11/0.415KV transformer prototype without tappings has been designed, constructed and partially commissioned. More work is still being done on the prototype. From the design table any searching mind and skillful rewinder can imitate the prototype design by meticulously putting in place the specified items. At full commissioning it might be reasonably ascertained that this local prototype will perform to fair efficiency of above eighty percent like an imported model of same capacity.

REFERENCES

2.4 Cost Estimate (As at December 1993)

<table>
<thead>
<tr>
<th>S/N</th>
<th>Item</th>
<th>Quantity</th>
<th>Unit Price N</th>
<th>Total Cost N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Insulation Tape</td>
<td>1 roll</td>
<td>350</td>
<td>350.00</td>
</tr>
<tr>
<td>2.</td>
<td>Insulation Sleeve</td>
<td>3 m</td>
<td>150</td>
<td>450.00</td>
</tr>
<tr>
<td>3.</td>
<td>Binding cloth</td>
<td>1 roll</td>
<td>375</td>
<td>375.00</td>
</tr>
<tr>
<td>4.</td>
<td>Copper Wire</td>
<td>36kg</td>
<td>300</td>
<td>10,800.00</td>
</tr>
<tr>
<td>5.</td>
<td>Flex Wire (4.5mm)</td>
<td>3m</td>
<td>10</td>
<td>30.00</td>
</tr>
<tr>
<td>6.</td>
<td>Laminations</td>
<td>356</td>
<td>15</td>
<td>5340.00</td>
</tr>
<tr>
<td>7.</td>
<td>Sheet steel (Gauge 18)</td>
<td>2 sheets</td>
<td>960</td>
<td>1800.00</td>
</tr>
<tr>
<td>8.</td>
<td>Low Voltage bushings (Porcelain) complete</td>
<td>8 Nos.</td>
<td>550</td>
<td>4400.00</td>
</tr>
<tr>
<td>9.</td>
<td>High voltage bushings (Porcelain) complete</td>
<td>6 Nos.</td>
<td>850</td>
<td>5100.00</td>
</tr>
<tr>
<td>10.</td>
<td>Connecting (od) (Earth Rods)</td>
<td>2 Nos.</td>
<td>100</td>
<td>200.00</td>
</tr>
<tr>
<td>11.</td>
<td>Bolts/Nuts</td>
<td>-</td>
<td>-</td>
<td>250.00</td>
</tr>
<tr>
<td>12.</td>
<td>Washers</td>
<td>-</td>
<td>-</td>
<td>100.00</td>
</tr>
<tr>
<td>13.</td>
<td>Transformer oil</td>
<td>1 drum</td>
<td>20,000</td>
<td>20,000.00</td>
</tr>
<tr>
<td></td>
<td>(Elf tranfo 50)</td>
<td>(2051)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Tank Construction and Spraying</td>
<td>2 tanks</td>
<td>-</td>
<td>3500.00</td>
</tr>
<tr>
<td>15.</td>
<td>Insulation Paper (Normex)</td>
<td>20m</td>
<td>250</td>
<td>5000.00</td>
</tr>
<tr>
<td>16.</td>
<td>Miscellaneous</td>
<td>-</td>
<td>-</td>
<td>6000.00</td>
</tr>
<tr>
<td>17.</td>
<td>Labour</td>
<td>(20% of total cost)</td>
<td>-</td>
<td>12,739.06</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td>76,434.00</td>
</tr>
</tbody>
</table>

The approximate cost per unit will be N38,217.00
Fig. 1: E/I-Shape Core Type Lamination Blade

Fig. 2: Winding Height Implications

Fig. 3: Spatial Cutout of Windings/Insulations
Fig. 1: Winding Connection

Fig. (a) L.V. Former

Fig. (b) Wooden Block