2 Conventional Transformer Design

Abstract This chapter deals with conventional design of wound core type transformers. It formulates the transformer design optimization (TDO) problem and solves it using a multiple design method that is commonly referred to as the conventional TDO method. A design example of an actual commercial transformer is worked out throughout this chapter showing all the calculations that are needed to design a transformer. The example-driven presentation of the conventional TDO method makes this chapter unique in transformer design texts.

2.1 Nomenclature

A	No-load loss cost rate throughout the transformer lifetime ($/W)
$area_{HV}$	Cross-section area of high voltage (HV) conductor (mm^2). See Fig. 2.6
$area_{LV}$	Cross-section area of low voltage (LV) conductor (mm^2). See Fig. 2.6
B	Load loss cost rate throughout the transformer lifetime ($/W)
BIL_{HV}	Basic insulation level of HV winding (kV)
BIL_{LV}	Basic insulation level of LV winding (kV)
BLD_{HV}	Thickness of HV winding (mm). See Fig. 2.6
BLD_{LV}	Thickness of LV winding (mm). See Fig. 2.6
BP	Transformer bid price ($)
$CCEE$	Core to coil each end (mm). See Fig. 2.6
C_{Lab}	Labor cost to manufacture the transformer ($)
CM	Cost of transformer materials ($)
CMM	Cost of transformer main materials ($)
CPA	Area of corrugated panels (m^2)
CRM	Cost of the remaining materials (i.e., not the main materials) of transformer ($)
CSA	Cross-section area (mm^2)
CSF	Core stacking factor
CTM	Transformer manufacturing cost ($)
D	Width of core leg (mm). See Fig. 2.3
$D13$	Coil equivalent external diameter immediately after the HV winding, including the HV cooling ducts (mm). See Fig. 2.9
$D3$	Coil equivalent external diameter immediately after the tube paper (mm). See Fig. 2.9

$D7$	Coil equivalent external diameter immediately after the LV winding, including the LV cooling ducts (mm). See Fig. 2.9
$D9$	Coil equivalent external diameter immediately after the I_{HV-LV} insulation (mm). See Fig. 2.9
d_{HV}	Diameter of HV conductor (mm). See Fig. 2.5
$D_{HV\text{-}C}$	Distance between HV winding and core (mm). See Fig. 2.6
$D_{LV\text{-}C}$	Distance between LV winding and core (mm). See Fig. 2.6
D_{Panel}	Width of corrugated panel (mm). See Fig. 2.15
$Ducts_{HV}$	Number of ducts of HV winding
$Ducts_{LV}$	Number of ducts of LV winding
D_w	Width of cooling duct (mm)
$DWPG_{HV}$	Width of HV duct strip plus gap (mm)
$DWPG_{LV}$	Width of LV duct strip plus gap (mm)
EdL_{HV}	Eddy current loss of HV winding (W)
EdL_{LV}	Eddy current loss of LV winding (W)
E_u	Thickness of core leg (mm). See Fig. 2.3
f	Frequency (Hz)
$F1$	Window width of small individual core (mm). See Fig. 2.3
$F2$	Window width of large individual core (mm). See Fig. 2.3
FD_{max}	Maximum flux density (Gauss)
G	Height of core window (mm). See Fig. 2.3
g_{CP}	Weight per unit area of corrugated panels (kg/m^2)
g_{DS}	Mass density of duct strips (kg/m^3)
g_{HV}	Mass density of HV conductor (kg/m^3)
g_{LV}	Mass density of LV conductor (kg/m^3)
g_{MM}	Mass density of magnetic material (kg/m^3)
g_O	Mass density of mineral oil (kg/m^3)
HCP	Height of corrugated panel (mm). See Fig. 2.15
HV	High voltage
$HVCC$	Connection of external (HV) winding
$I_{HV\text{-}HV}$	Insulation outside HV winding (mm). See Fig. 2.6
I_{HVL}	Insulation between layers of HV winding (mm). See Fig. 2.5
$I_{HV\text{-}LV}$	Insulation between LV and HV winding (mm). See Fig. 2.6
$I_{LV\text{-}C}$	Insulation between LV winding and core (mm). See Fig. 2.6
I_{LVL}	Insulation between layers of LV winding (mm). See Fig. 2.4
$Impulse_{max}$	Maximum impulse voltage that an insulating paper can withstand (kV)
$Induced_{max}$	Maximum induced voltage that an insulating paper can withstand (kV)
I_{LV}^{p}	Phase current of LV winding (A)
IR	Ohmic (resistive) part of impedance voltage (%)
IX	Inductive part of impedance voltage (%)
K	Distance between two adjacent cores (mm). See Fig. 2.3
$Layers_{HV}$	Number of layers of HV winding

$Layers_{LV}$	Number of layers of LV winding
$LDSP_{HV}$	Layer direction space factor of HV winding
$LDSP_{LV}$	Layer direction space factor of LV winding
LG_{HV}	Dimension of cooling ducts of HV winding (mm). A practical computation formula is given in Example 2.5
LL_1	Transformer load loss (W) at voltage $V^l_{HV,1}$
LL_2	Transformer load loss (W) at minimum voltage of HV winding
LL_g	Guaranteed load loss (W)
$LL_{HV,1}$	Load loss (W) of HV winding at voltage $V^l_{HV,1}$
$LL_{HV,2}$	Load loss (W) of HV winding at minimum voltage of HV winding
LL_{LV}	Load loss (W) of LV winding
LV	Low voltage
$LVCC$	Connection of internal (LV) winding
ML	Length of the mould of the coil. See Fig. 2.10
MS	Margin ($) in the sale of transformer
MT_{HV}	Mean turn length of HV winding (mm). See Fig. 2.10
MT_{LV}	Mean turn length of LV winding (mm). See Fig. 2.10
MW	Width of the mould of the coil (mm). See Fig. 2.10
NCP	Total number of corrugated panels
NLL	Transformer no-load loss (W)
NLL_g	Guaranteed no-load loss (W)
OH	Height of mineral oil (mm)
$Pitch$	Distance between two adjacent corrugated panels (mm). See Fig. 2.15
S_n	Transformer rated power (kVA)
SM	Transformer sales margin (%)
$SNLL_{TF}$	Transformer specific no-load loss (W/kg). See Fig. 2.8
$t_{a,\max}$	Maximum ambient temperature (°C)
$TAOR$	Transformer average oil rise (°C)
$Taps_{HV,\max}$	Upper limit of taps of HV winding (%)
$Taps_{HV,\min}$	Lower limit of taps of HV winding (%)
TD_{HV}	Width of HV layer (mm). See Fig. 2.5
TD_{LV}	Width of LV layer (mm). See Fig. 2.4
TDO	Transformer design optimization
T_{DS}	Thickness of duct strips without insulation (mm)
$TDSP_{HV}$	Turn direction space factor of HV winding
$TDSP_{LV}$	Turn direction space factor of LV winding
TE	Tolerances and elongation of coil (mm)
TH	Tank height (mm). See Fig. 2.11
TL	Tank length (mm). See Fig. 2.11
TLC	Total length of the coil (mm)
TLT_{HV}	Total thickness of the HV leads (mm)

TLT_{LV}	Total thickness of the LV leads (mm)
t_{LV}	Thickness of LV conductor (mm). See Fig. 2.4
$t_{o,\max}$	Maximum oil temperature (°C)
TOC	Transformer total owning cost ($) throughout transformer lifetime
$Turns_{HV,\max}$	Maximum number of turns of HV winding
$turns_{LV}$	Number of turns of LV winding
$TurnsMain_{HV}$	Number of turns of HV winding at voltage $V^{l}_{HV,1}$
$TurnWidth_{HV}$	Width of HV conductor with insulation (mm)
$TurnWidth_{LV}$	Width of LV conductor with insulation (mm)
TW	Tank width (mm). See Fig. 2.11
$t_{w,\max}$	Maximum winding temperature (°C)
TI_{HV}	Insulation of taps of HV winding (mm)
uc_1	Unit cost of LV winding ($/kg)
uc_2	Unit cost of HV winding ($/kg)
uc_3	Unit cost of magnetic material ($/kg)
uc_4	Unit cost of insulating paper ($/kg)
uc_5	Unit cost of duct strips ($/kg)
uc_6	Unit cost of mineral oil ($/kg)
uc_7	Unit cost of sheet steel ($/kg)
uc_8	Unit cost of corrugated panels ($/kg)
U_k	Impedance voltage (%)
$U_{k,g}$	Guaranteed impedance voltage (%)
V_{CT}	Volume of oil conservator (L)
$V^{l}_{HV,1}$	First rated line voltage (V) of HV winding
$V^{l}_{HV,2}$	Second rated line voltage (V) of HV winding
V^{l}_{LV}	Rated line voltage (V) of LV winding
V^{p}_{LV}	Rated phase voltage (V) of LV winding
VPT	Volts per turn (V/turn)
uc_1	Total weight of LV winding (kg)
uc_2	Total weight of HV winding (kg)
uc_3	Total weight of magnetic material (kg)
uc_4	Total weight of insulating paper (kg)
uc_5	Total weight of duct strips (kg)
uc_6	Total weight of mineral oil (kg)
uc_7	Total weight of sheet steel (kg)
uc_8	Total weight of corrugated panels (kg)
Δd_{HV}	Insulation of HV conductor (mm). See Fig. 2.5
ρ_{HV}	Resistivity of HV conductor ($\Omega \cdot \mathrm{mm}^2/\mathrm{m}$)
ρ_{LV}	Resistivity of LV conductor ($\Omega \cdot \mathrm{mm}^2/\mathrm{m}$)

2.2 Introduction

The objective of *transformer design optimization* (TDO) is to design the transformer so as to minimize the transformer manufacturing cost, i.e., the sum of materials cost plus labor cost, subject to constraints imposed by international standards and transformer user specification.

The aim of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. The transformer design should be carried out based on the specification given, using available materials economically in order to achieve low cost, low weight, small size and good operating performance.

The transformer design is worked out using various methods based on accumulated experience realized in different formulas, equations, tables and charts. Transformer design methods vary among transformer manufacturers (Mittle and Mittal 1996).

While designing a transformer, much emphasis should be placed on lowering its cost by saving materials and reducing to a minimum labor-consuming operations in its manufacture. The design should be satisfactory with respect to dielectric strength and mechanical endurance, and windings must withstand dynamic and thermal stresses in the event of short-circuit.

In order to meet the above requirements, the transformer designer should be familiar with the prices of basic materials used in the transformer. He should also be familiar with the amount of labor consumed in the production of transformer parts and assemblies.

This chapter presents a conventional transformer design methodology based on a multiple design technique (Georgilakis et al. 2007) for solution of the TDO problem. This conventional transformer design method is a heuristic technique that assigns many alternative values to the design variables so as to generate a large number of alternative designs and finally to select the design that satisfies all the problem constraints with minimum manufacturing cost.

2.3 Problem Formulation

The TDO problem is formulated as follows: minimize an objective function subject to several constraints.

Among the various objective functions of the TDO problem that are defined in Sect. 2.3.1, the most commonly used objective functions are:

1. The minimization of transformer manufacturing cost. This is mainly used when designing transformers for industrial and commercial users, since these users usually do not evaluate the cost of losses when purchasing transformers.

2. The minimization of transformer total owning cost. This is mainly used when designing transformers for electric utilities, since these users usually evaluate the cost of losses when purchasing transformers.

The constraints of the TDO problem are related to transformer operation, manufacturing capabilities, and transformer user special needs. These constraints are presented in Sect. 2.3.2.

2.3.1 *Objective Function*

In the bibliography of transformer design, several objective functions are optimized:

1. Minimization of active part mass (Jabr 2005)
2. Minimization of active part cost (Rubaai 1994, Amoiralis et al. 2008)
3. Minimization of main materials cost (Amoiralis et al. 2009)
4. Minimization of manufacturing cost (Odessey 1974; Georgilakis et al. 2007; Georgilakis 2008; Georgilakis 2009)
5. Minimization of total owning cost (Andersen 1991; Del Vecchio et al. 2002)
6. Maximization of transformer rated power (Judd and Kressler 1977, Jabr 2005)

These objective functions are analyzed in the following paragraphs.

2.3.1.1 Active Part Mass

The objective is to minimize the active part mass, APM :

$$\min APM = \min \sum_{i=1}^{3} w_i \ , \tag{2.1}$$

where w_1 (kg) is the total weight of the low voltage (LV) winding, w_2 is the total weight of the high voltage (HV) winding, and w_3 is the total weight of the magnetic material.

2.3.1.2 Active Part Cost

The objective is to minimize the active part cost, APC :

$$\min APC = \min \sum_{i=1}^{3} uc_i \cdot w_i \ , \qquad (2.2)$$

where uc_1 ($/kg) is the unit cost of the LV winding, uc_2 is the unit cost of the HV winding, uc_3 is the unit cost of magnetic material, w_1 (kg) is the total weight of the LV winding, w_2 is the total weight of the HV winding, and w_3 is the total weight of magnetic material.

2.3.1.3 Main Materials Cost

The objective is to minimize the cost of transformer main materials, CMM :

$$\min CMM = \min \sum_{i=1}^{8} uc_i \cdot w_i \ , \qquad (2.3)$$

where uc_1 ($/kg) is the unit cost of the LV winding, uc_2 is the unit cost of the HV winding, uc_3 is the unit cost of magnetic material, uc_4 is the unit cost of insulating paper, uc_5 is the unit cost of duct strips, uc_6 is the unit cost of mineral oil, uc_7 is the unit cost of sheet steel, uc_8 is the unit cost of corrugated panels, w_1 (kg) is the total weight of the LV winding, w_2 is the total weight of the HV winding, w_3 is the total weight of magnetic material, w_4 is the total weight of insulating paper, w_5 is the total weight of duct strips, w_6 is the total weight of mineral oil, w_7 is the total weight of sheet steel, and w_8 is the total weight of corrugated panels.

2.3.1.4 Manufacturing Cost

The objective is to minimize the cost of transformer manufacturing, CTM :

$$\min CTM = \min\left[CMM + CRM + C_{Lab}\right], \qquad (2.4)$$

where CMM ($) is the cost of transformer main materials as computed by (2.3), CRM is the cost of the remaining materials (not included in CMM) of the transformer, and C_{Lab} is the labor cost to manufacture the transformer.

2.3.1.5 Total Owning Cost

The objective is to minimize the transformer total owning cost, TOC, which includes the cost to purchase the transformer and the cost of losses throughout the transformer lifetime:

$$\min TOC = \min\left[BP + A\cdot NLL + B\cdot LL\right], \tag{2.5}$$

where A (\$/W) is the no-load loss cost, B (\$/W) is the load loss cost, NLL (W) is the no-load loss, LL (W) is the load loss, and BP (\$) is the transformer purchase cost (also called sales price or bid price) that is computed as follows:

$$BP = \frac{CTM}{1-SM} = \frac{CMM + CRM + C_{Lab}}{1-SM}, \tag{2.6}$$

where CTM (\$) is the transformer manufacturing cost, SM (%) is the transformer sales margin, CMM (\$) is the cost of transformer main materials as computed by (2.3), CRM (\$) is the cost of the remaining materials (not included in CMM) of the transformer, and C_{Lab} (\$) is the labor cost to manufacture the transformer.

The A and B coefficients of (2.5) are computed according to the methodologies of Chap. 8.

2.3.1.6 Rated Power

The objective is to maximize transformer rated power, S_n:

$$\max S_n . \tag{2.7}$$

2.3.2 Constraints

The constraints of the TDO problem are the following:

1. Induced voltage constraint

2. Turns ratio constraint

3. No-load loss constraint

4. Load loss constraint
5. Total loss constraint
6. Impedance voltage constraint
7. Magnetic induction constraint
8. Heat transfer constraint
9. Temperature rise constraint
10. Efficiency constraint
11. No-load current constraint
12. Voltage regulation constraint
13. Induced voltage constraints
14. Impulse voltage constraints
15. Tank dimensions constraints

These constraints are analyzed in the following paragraphs.

2.3.2.1 Induced Voltage Constraint

This expresses the relation between the induced voltage in the secondary winding and the maximum flux density:

$$V_2 = 4.44 \cdot f \cdot N_2 \cdot FD_{\max} \cdot CSF \cdot D \cdot 2 \cdot E_u \,, \tag{2.8}$$

where V_2 is the effective value of the induced phase voltage in the secondary winding, f is the frequency, N_2 is the number of turns of the secondary winding, $FD_{\max}$ is the maximum flux density, CSF is the core stacking factor, D is the width of the core leg, and E_u is the thickness of the core leg. In (2.8), the quantity $CSF \cdot D \cdot 2 \cdot E_u$ expresses the effective core cross-section area of the magnetic flux in the shell-type transformer. Section 2.6.2 explains how (2.8) is obtained.

2.3.2.2 Turns Ratio Constraint

The voltage ratio is equal to the turns ratio:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}, \tag{2.9}$$

where V_1 and V_2 are the phase voltage of the primary and secondary winding, respectively, and N_1 and N_2 are the number of turns of the primary and secondary winding, respectively.

2.3.2.3 No-Load Loss Constraint

The designed no-load loss, NLL, must be smaller than a maximum no-load loss, $NLL_{\max}$:

$$NLL < NLL_{\max}. \tag{2.10}$$

2.3.2.4 Load Loss Constraint

The designed load loss, LL, must be smaller than a maximum load loss, $LL_{\max}$:

$$LL < LL_{\max}. \tag{2.11}$$

2.3.2.5 Total Loss Constraint

The total loss, TTL, of the transformer must be smaller than a maximum total loss, $TTL_{\max}$:

$$TTL < TTL_{\max}. \tag{2.12}$$

It should be noted that the total loss of the transformer is equal to the sum of its no-load loss and load loss, i.e.:

$$TTL = NLL + LL. \tag{2.13}$$

2.3.2.6 Impedance Voltage Constraint

The transformer impedance voltage, U_k, must be between a minimum impedance voltage, $U_{k,\min}$, and a maximum impedance voltage, $U_{k,\max}$:

$$U_{k,\min} < U_k < U_{k,\max} . \tag{2.14}$$

2.3.2.7 Flux Density Constraint

The maximum flux density, $FD_{\max}$, is required to be smaller than a saturation flux density, FD_{sat} (Judd and Kressler 1977):

$$FD_{\max} < FD_{sat} . \tag{2.15}$$

2.3.2.8 Heat Transfer Constraint

The total heat (W) produced by the total loss, TTL, of the transformer must be smaller than the total heat (W), TH_{CCR}, that can be carried away by the combined effects of conduction, convection, and radiation (MIT 1962):

$$TTL < TH_{CCR} . \tag{2.16}$$

2.3.2.9 Temperature Rise Constraint

The transformer temperature rise, ΔT, that is due to the heat generated by the total loss of the transformer must be smaller than a maximum temperature rise, $\Delta T_{\max}$ (Odessey 1974):

$$\Delta T < \Delta T_{\max} . \tag{2.17}$$

2.3.2.10 Efficiency Constraint

The transformer efficiency, n, is sometimes required to be greater than a minimum efficiency, $n_{\min}$:

$$n > n_{\min} . \tag{2.18}$$

2.3.2.11 No-Load Current Constraint

The transformer no-load current, i_φ, is sometimes required to be smaller than a maximum no-load current, $i_{\varphi,\max}$:

$$i_\varphi < i_{\varphi,\max} . \tag{2.19}$$

2.3.2.12 Voltage Regulation Constraint

The transformer voltage regulation, ΔV, is sometimes required to be smaller than a maximum voltage regulation, $\Delta V_{\max}$ (Odessey 1974):

$$\Delta V < \Delta V_{\max} . \tag{2.20}$$

2.3.2.13 Induced Voltage Constraints

The thickness of layer insulation must withstand the induced voltage test. In particular, the induced voltage in the internal winding, $Induced_{LV}$, is required to be smaller than the maximum induced voltage, $Induced_{LV,\max}$, that the insulating paper between the layers of the internal winding can withstand:

$$Induced_{LV} < Induced_{LV,\max} . \tag{2.21}$$

The induced voltage in the external winding, $Induced_{HV}$, is required to be smaller than the maximum induced voltage, $Induced_{HV,\max}$, that the insulating paper between the layers of the external winding can withstand:

$$Induced_{HV} < Induced_{HV,\max} . \tag{2.22}$$

2.3.2.14 Impulse Voltage Constraints

The thickness of layer insulation must withstand the impulse voltage test. In particular, the impulse voltage in the internal winding, $Impulse_{LV}$, is required to be smaller than the maximum impulse voltage, $Impulse_{LV,\max}$, that the insulating paper between the layers of the internal winding can withstand:

$$Impulse_{LV} < Impulse_{LV,\max} . \tag{2.23}$$

The impulse voltage in the external winding, $Impulse_{HV}$, is required to be smaller than the maximum impulse voltage, $Impulse_{HV,\max}$, that the insulating paper between the layers of the external winding can withstand:

$$Induced_{HV} < Induced_{HV,\max} . \tag{2.24}$$

2.3.2.15 Tank Dimensions Constraints

The tank length, TL , is sometimes required to be smaller than a maximum tank length, $TL_{\max}$:

$$TL < TL_{\max} , \tag{2.25}$$

the tank width, TW , is sometimes required to be smaller than a maximum tank width, $TW_{\max}$:

$$TW < TW_{\max} , \tag{2.26}$$

and the tank height, TH , is sometimes required to be smaller than a maximum tank height, $TH_{\max}$:

$$TH < TH_{\max} . \tag{2.27}$$

2.3.3 Mathematical Formulation of the TDO Problem

One common formulation of the TDO problem is the minimization of transformer manufacturing cost (Georgilakis et al. 2007):

$$\min CTM = \min\left[CRM + C_{Lab} + \sum_{i=1}^{8} uc_i \cdot w_i\right], \tag{2.28}$$

subject to the following constraints:

$$V_2 = 4.44 \cdot f \cdot N_2 \cdot FD_{\max} \cdot CSF \cdot D \cdot 2 \cdot E_u , \tag{2.29}$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}, \tag{2.30}$$

$$NLL < NLL_{\max} , \tag{2.31}$$

$$LL < LL_{\max} , \tag{2.32}$$

$$TTL < TTL_{\max} , \tag{2.33}$$

$$U_{k,\min} < U_k < U_{k,\max} , \tag{2.34}$$

$$FD_{\max} < FD_{sat} , \tag{2.35}$$

$$TTL < TH_{CCR} , \tag{2.36}$$

$$\Delta T < \Delta T_{\max} , \tag{2.37}$$

$$Induced_{LV} < Induced_{LV,\max} , \tag{2.38}$$

$$Induced_{HV} < Induced_{HV,\max} , \tag{2.39}$$

$$Impulse_{LV} < Impulse_{LV,\max} , \tag{2.40}$$

$$Induced_{HV} < Induced_{HV,\max} , \tag{2.41}$$

$$TL < TL_{\max} , \tag{2.42}$$

$$TW < TW_{\max} , \tag{2.43}$$

$$TH < TH_{\max} . \tag{2.44}$$

2.3.4 Characteristics of the TDO Problem

The TDO problem is a complex constrained mixed-integer nonlinear programming problem. The TDO problem is further complicated by the fact that the objective function is discontinuous (Andersen 1991).

2.4 Conventional Transformer Design Optimization Method

2.4.1 Methodology

This section describes a conventional heuristic methodology for solution of the TDO problem of Sect. 2.3.3. This methodology, also known as multiple design method, is a heuristic technique that assigns many alternative values to the design variables so as to generate a large number of alternative designs and finally to select the design that satisfies all the problem constraints with minimum manufacturing cost.

The methodology concerns the optimization of transformers with the following technical characteristics:

1. Three-phase, oil-immersed distribution transformers

2. Magnetic circuit of shell type and wound cores

3. Foil, round wire, or rectangular wire technology for both low voltage (LV) and high voltage (HV) conductors

The process of finding the optimum transformer is implemented with the help of a suitable computer program, which uses at maximum 134 input parameters in order to make the transformer program as parametric as possible. These 134 input parameters are split into the following seven types (Georgilakis et al. 2007):

1. *Description variables* (e.g., rated power, rated low voltage (LV) and high voltage (HV), frequency, LV and HV connection). Table 2.6 shows an example of description variables.

2. *Special variables* (e.g., core stacking factor, turns direction space factor, mass density of materials used). Table 2.7 shows an example of special variables.

3. *Default variables* (e.g., LV and HV taps, guaranteed no-load loss, load loss, and impedance voltage). Table 2.8 shows an example of default variables.

4. *Cost variables* (e.g., unit cost for LV and HV conductor, magnetic steel, mineral oil, insulating paper, duct strips, corrugated panels). Table 2.9 shows an example of cost variables.

5. *Various variables* (e.g., number of LV and HV ducts). Table 2.10 shows an example of various variables.

6. *Conductor cross-section calculation variables* (LV and HV conductor cross-sections can be defined by the user or can be calculated using current density,

or thermal short-circuit test). Table 2.11 shows an example of conductor cross-section calculation variables.

7. *Design variables* (i.e., number of LV turns, width of core leg, height of core window, magnetic induction, LV and HV cross-section area). It should be noted that the magnetic material properties (e.g., type, grade, thickness, specific no-load loss) are given as input data when defining the values of magnetic induction within the design variables. Table 2.12 shows an example of design variables.

The computer program allows many variations in design variables. These variations permit the investigation of sufficient candidate solutions. For each one of the candidate solutions, it is checked if all the specifications (constraints) are satisfied, and if they are satisfied, the manufacturing cost is estimated and the solution is characterized as *acceptable*. On the other hand, the candidate solutions that violate the specification are characterized as *non-acceptable* solutions. Finally, among the acceptable solutions, the transformer with the minimum manufacturing cost is selected, which is the optimum transformer.

There are six design variables:

1. The number of turns of low voltage coil, $turns_{LV}$
2. The width of core leg, D
3. The magnetic induction, $FD_{\max}$
4. The height of core window, G
5. The cross-section area of the LV conductor, $area_{LV}$
6. The cross-section area of the HV voltage conductor, $area_{HV}$

Giving n_{LV} different values for the number of turns of low voltage coil, n_D values for the width of core leg, n_{FD} tries for the magnetic induction, n_G different values for the height of core window, cs_{LV} different values for the calculation of cross-section area of low voltage coil and cs_{HV} different values for the calculation of cross-section of high voltage coil, the total candidate solutions (loops of the computer program), n_{loops}, are calculated from the following equation:

$$n_{loops} = n_{LV} \cdot n_D \cdot n_{FD} \cdot n_G \cdot cs_{LV} \cdot cs_{HV} \,. \tag{2.45}$$

The search algorithm of the optimum transformer is presented in Table 2.1 (Georgilakis et al. 2007). This methodology is already applied in the transformer manufacturing industry.

Table 2.1 Conventional TDO method

For $i = 1$ to n_{LV}

For $j = 1$ to n_D

For $k = 1$ to n_{FD}

For $l = 1$ to n_G

Calculate the volts per turn and the thickness of core leg based on Sect. 2.6.

For $m = 1$ to cs_{LV}

For $n = 1$ to cs_{HV}

Calculate the layer insulations based on Sect. 2.7.

If one or more of the constraints of (2.38), (2.39), (2.40), and (2.41) is violated, then the solution is rejected and the next loop is executed.

Calculate winding and core dimensions based on Sect. 2.8.

Calculate core weight and no-load loss based on Sect. 2.9.

If the no-load loss constraint of (2.31) is violated, then the solution is rejected and the next loop is executed.

Calculate the inductive part of impedance voltage based on Sect. 2.10.

Calculate the load loss based on Sect. 2.11.

If the load loss constraint of (2.32) is violated, then the solution is rejected and the next loop is executed.

If the total loss constraint of (2.33) is violated, then the solution is rejected and the next loop is executed.

Calculate the impedance voltage based on Sect. 2.12.

If the impedance voltage constraint of (2.34) is violated, then the solution is rejected and the next loop is executed.

Calculate the coil length based on Sect. 2.13.

Calculate the tank dimensions based on Sect. 2.14.

If one or more of tank constraints of (2.42), (2.43), and (2.44) is violated, then the solution is rejected and the next loop is executed.

Calculate the winding gradient (temperature rise) and the oil gradient based on Sect. 2.15.

If the temperature rise constraint of (2.37) is violated, then the solution is rejected and the next loop is executed.

Calculate the heat that can be dissipated based on Sect. 2.16.

If the heat transfer constraint of (2.36) is violated, then the solution is rejected and the next loop is executed.

Calculate the weight of insulating materials based on Sect. 2.17.

Calculate the weight of duct strips based on Sect. 2.18.

Calculate the weight of mineral oil based on Sect. 2.19.

Calculate the weight of sheet steel based on Sect. 2.20.

Calculate the weight of corrugated panels based on Sect. 2.21.

Calculate the cost of transformer main materials based on Sect. 2.22.

Calculate the transformer manufacturing cost based on Sect. 2.23.

The optimum transformer is the one with the minimum manufacturing cost.

2.4.2 Case Study

2.4.2.1 Transformer Design Data

The efficiency of the TDO methodology of Sect. 2.4.1 is presented through an actual design example of a three-phase, 160 kVA, 20/0.4 kV (i.e., primary voltage 20 kV and secondary voltage 0.4 kV), 50 Hz, transformer. The internal (LV) winding is star-connected (Y) and the external (HV) winding is delta-connected (Δ).

The maximum load loss is 2350 W and the maximum no-load loss is 425 W. The impedance voltage is 4% with tolerance ±10%.

Copper sheet is used for the low voltage conductor and copper wire is used for the high voltage conductor.

The calculation of the cross-section area of the conductors is implemented using the current density. More specifically, current density of 3.2 A/mm^2 is chosen for the internal coil and current density of 3.7 A/mm^2 is chosen for the external coil.

2.4.2.2 Selection of the Values of Design Variables

For the number of turns of the low voltage conductor, eight alternative values (i.e., $n_{LV} = 8$) are considered: 28, 29, 30, 31, 32, 33, 34, and 35 turns.

For the width of core leg (*D*), two alternative values (i.e., $n_D = 2$) are selected: 170 and 190 mm.

For the magnetic induction, seven alternative values (i.e., $n_{FD} = 7$) are used: 14000, 14500, 15000, 15500, 16000, 16500, and 17000 Gauss. For each one of these seven different values of the magnetic induction, the respective specific no-load losses (W/kg) of the transformer are given.

For the height of core window (*G*), 10 alternative values (i.e., $n_G = 10$) are considered: 190, 195, 200, 205, 210, 215, 220, 225, 230, and 235 mm.

For each value of *G*, only one cross-section area of the LV conductor is used, i.e., $cs_{LV} = 1$.

Four values for the cross-section area of the external conductor are considered, i.e., $cs_{HV} = 4$.

The total number of candidate solutions is computed using (2.45):

$$n_{loops} = n_{LV} \cdot n_D \cdot n_{FD} \cdot n_G \cdot cs_{LV} \cdot cs_{HV} \Rightarrow$$

$$n_{loops} = 8 \cdot 2 \cdot 7 \cdot 10 \cdot 1 \cdot 4 \Rightarrow n_{loops} = 4480\,.$$

Table 2.2 Acceptable solutions sorted by manufacturing cost (*CTM*)

Number	$turns_{LV}$	D (mm)	$FD_{\max}$ (Gauss)	G (mm)	$area_{LV}$ (mm^2)	$area_{HV}$ (mm^2)	CTM ($)
1	29	190	16500	210	76.80	0.8825	6144.55
2	29	170	16500	205	74.80	0.8825	6148.28
3	29	190	16500	215	78.80	0.8825	6171.58
4	30	170	16500	215	78.80	0.8825	6175.65
5	28	190	16000	200	72.80	0.8825	6186.10
197	28	170	14000	215	78.80	0.9503	6805.78
198	29	170	14000	215	78.80	0.9852	6810.43
199	29	170	14000	220	80.80	0.9852	6812.55
200	28	170	14000	210	76.80	0.9852	6832.53
201	28	170	14000	215	78.80	0.9852	6834.68

Since the maximum load loss is 2350 W, then, among the 4480 candidate solutions, those that have load loss over 2350 W will be rejected.

Since the maximum no-load loss is 425 W, then, among the 4480 candidate solutions, those that have no-load loss over 425 W will be rejected.

Since the impedance voltage is 4% with tolerance ±10%, then, among the 4480 candidate solutions, those that have impedance voltage less than 3.6% or greater than 4.4% will be rejected.

2.4.2.3 Results

A computer program calculates which of the 4480 candidate solutions are acceptable (all the constraints are satisfied) and which are rejected.

For all the acceptable solutions, their technical characteristics are calculated and their manufacturing cost is estimated. The manufacturing cost is equal to the sum of transformer materials cost plus labor cost, given by (2.4).

For all the non-acceptable solutions, the reasons for rejection are recorded to a computer file.

The computer program finds that among the 4480 candidate solutions, 201 are acceptable solutions and the remaining 4279 are rejected. More specifically, 383 are rejected due to violation of the no-load loss (NLL) specification, 3453 are rejected due to violation of the load loss (LL) specification, and 443 are rejected due to violation of the impedance voltage (U_k) specification.

Table 2.2 presents the first five (cheapest) and the last five (most expensive) solutions from the total 201 accepted solutions. It can be seen from Table 2.2 that the manufacturing cost of the cheapest solution (optimum transformer) is $6144.55 and the most expensive solution costs $6834.68. Namely, the optimum solution is 10.1% cheaper in comparison with the most expensive solution. The optimum transformer is the transformer number 1 of Table 2.2, which has the following technical characteristics: $NLL = 415$ W, $LL = 2325$ W, and $U_k = 3.90$ %. As can be seen from Table 2.2, the values of the design variables for the optimum transformer are as follows: $turns_{LV} = 29$, $D = 190$ mm, $FD_{\max} = 16500$ Gauss, $G = 210$ mm, $area_{LV} = 76.80$ mm^2, and $area_{HV} = 0.8825$ mm^2. The LV conductor of the optimum transformer is made of copper sheet with 192 mm width and 0.4 mm thickness, so the cross-section area of the LV conductor is 76.80 mm^2. The HV conductor of the optimum transformer is made of copper wire with 1.06 mm diameter, so the cross-section area of the HV conductor is 0.8825 mm^2.

2.4.2.4 Sensitivity Analysis

2.4.2.4.1 Variation of Magnetic Induction

Table 2.3 presents the values of four output variables, namely, (1) no-load loss (*NLL*), (2) load loss (*LL*), (3) impedance voltage (U_k), and (4) manufacturing cost (*CTM*), when only one of the design variables is varied, and more specifically the magnetic induction $FD_{\max}$, which takes 31 values from 14000 to 17000 Gauss with a step of 100 Gauss. All the remaining design variables ($turns_{LV}$, D, G, $area_{LV}$, and $area_{HV}$) remain constant and equal to the respective values of the optimum transformer (transformer number 1 of Table 2.2). Table 2.3 shows that among the 31 candidate solutions, only seven are accepted. It can be seen from Table 2.3 that the new optimum solution has a manufacturing cost of $6129.68. This means that with specific variation of the magnetic induction, a cheaper solution was found (since the previous optimum solution of Table 2.2 has a manufacturing cost of $6144.55). In Fig. 2.1, the no-load loss versus the magnetic induction is plotted, while Fig. 2.2 plots the load loss versus the magnetic induction. From Figs. 2.1 and 2.2 it can be concluded that, in general, the no-load loss is increased and the load loss is decreased with an increase of magnetic induction $FD_{\max}$.

Table 2.3 Variation of magnetic induction $FD_{\max}$ (accepted solutions sorted by manufacturing cost, *CTM*)

Input variables						Output variables			
$turns_{LV}$	D (mm)	$FD_{\max}$ (Gauss)	G (mm)	$area_{LV}$ (mm^2)	$area_{HV}$ (mm^2)	NLL (W)	LL (W)	U_k (%)	CTM ($)
29	190	16600	210	76.80	0.8825	420	2321	3.90	6129.68
29	190	16500	210	76.80	0.8825	415	2325	3.90	6144.55
29	190	16400	210	76.80	0.8825	409	2329	3.91	6159.20
29	190	16300	210	76.80	0.8825	402	2334	3.92	6174.90
29	190	16200	210	76.80	0.8825	395	2338	3.93	6190.33
29	190	16100	210	76.80	0.8825	388	2342	3.94	6205.53
29	190	16000	210	76.80	0.8825	381	2347	3.94	6212.68

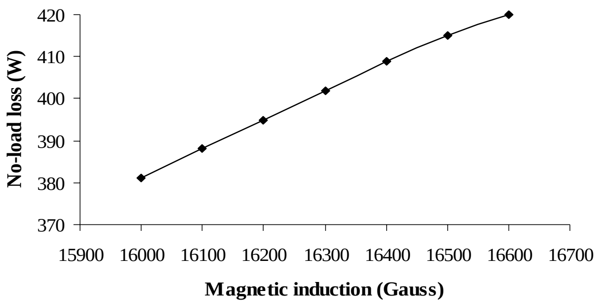

Fig. 2.1 No-load loss versus magnetic induction

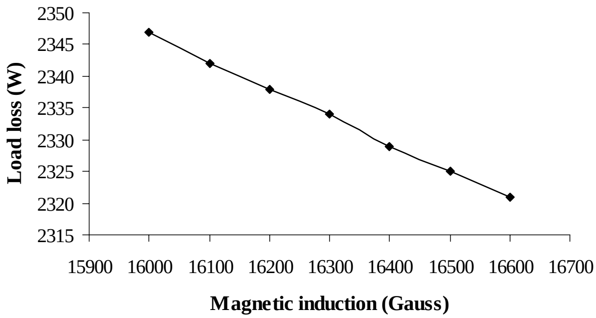

Fig. 2.2 Load loss versus magnetic induction

2.4.2.4.2 Variation of Cross-Section Area of Low Voltage Coil

Table 2.4 presents the values of four output variables, namely, (1) no-load loss (*NLL*), (2) load loss (*LL*), (3) impedance voltage (U_k), and (4) manufacturing cost (*CTM*), when only one of the design variables is varied, and more specifically the cross-section area of the low voltage conductor, which takes nine values: 192×0.36, 192×0.37, 192×0.38, 192×0.39, 192×0.40, 192×0.41, 192×0.42, 192×0.43, and 192×0.44 mm^2. All the remaining design variables remain constant and equal to the respective values of the optimum transformer (transformer number 1 of Table 2.2). Table 2.4 shows that among the nine candidate solutions, only four are accepted. It can be seen from Table 2.4 that the new optimum solution has a manufacturing cost of $6129.58. This means that with the specific variation of the cross-section area of the LV conductor, a marginally cheaper solution was found (since the previous optimum solution of Table 2.3 has a manufacturing cost of $6129.68).

It is concluded that the optimum transformer is the first transformer of Table 2.4, which has the following technical characteristics: $NLL = 415\ \mathrm{W}$, $LL = 2346\ \mathrm{W}$, and $U_k = 3.89\ \%$, while $CTM = \$\ 6129.58$. As can be seen from Table 2.4, the values of the design variables for the optimum transformer are as follows: $turns_{LV} = 29$, $D = 190\ \mathrm{mm}$, $FD_{\max} = 16500\ \mathrm{Gauss}$, $G = 210\ \mathrm{mm}$, $area_{LV} = 74.88\ \mathrm{mm}^2$, and $area_{HV} = 0.8825\ \mathrm{mm}^2$. The LV conductor of the optimum transformer is copper sheet with 192 mm width and 0.39 mm thickness, so $area_{LV} = 192 \times 0.39 = 74.88\ \mathrm{mm}^2$. The HV conductor of the optimum transformer is copper wire with 1.06 mm diameter, so the cross-section area of the HV conductor is $area_{HV} = (\pi / 4) \cdot 1.06^2 = 0.8825\ \mathrm{mm}^2$.

2.4.3 Repetitive Transformer Design Process

Table 2.5 shows how changing core and conductor design can reduce no-load and load losses but also affects the cost of the transformer, when we try to further improve the optimum design.

The optimum design is implemented through the following steps:

1. Initially the input variables are entered in a computer program. Many different values of the design variables are given, so many candidate solutions are considered.

2. A computer program determines which candidate solutions are acceptable and which are rejected (they violate one or more of the constraints).

3. The acceptable solutions are sorted according to their manufacturing cost. The optimum transformer corresponds to the least-cost solution.

Table 2.4 Variation of cross-section area of low voltage conductor (solutions sorted by manufacturing cost, *CTM*)

Input variables						Output variables			
$turns_{LV}$	D (mm)	$FD_{\max}$ (Gauss)	G (mm)	$area_{LV}$ (mm^2)	$area_{HV}$ (mm^2)	NLL (W)	LL (W)	U_k (%)	CTM ($)
29	190	16500	210	74.88	0.8825	415	2346	3.89	6129.58
29	190	16500	210	76.80	0.8825	415	2325	3.90	6144.55
29	190	16500	210	78.72	0.8825	415	2303	3.92	6159.60
29	190	16500	210	80.64	0.8825	415	2283	3.94	6175.48

Table 2.5 Loss reduction alternatives

	No-load loss	Load loss	Cost
To decrease no-load loss			
A. Use lower-loss core material	Lower	No change	Higher
B. Decrease flux density by:			
1. Increasing core cross-section area (CSA)	Lower	Higher	Higher
2. Decreasing volts per turn	Lower	Higher	Higher
C. Decrease flux path length by decreasing conductor CSA	Lower	Higher	Lower
To decrease load loss			
A. Decrease current density by increasing conductor CSA	Higher	Lower	Higher
B. Decrease current path length by:			
1. Decreasing core CSA	Higher	Lower	Lower
2. Increasing volts per turn	Higher	Lower	Lower

It is possible that all the candidate solutions are rejected. Then the computer file of non-acceptable solutions should be studied and the reasons for rejection understood.

Generally, the following cases may appear:

1. Necessity to decrease or increase no-load loss
2. Necessity to decrease or increase load loss
3. Necessity to decrease or increase impedance voltage

The no-load loss is decreased by one of the following methods (linked to design variables):

1. Increasing the number of turns of LV coil
2. Decreasing the magnetic induction, $FD_{\max}$
3. Decreasing the height of core window, G

The no-load loss is increased by one of the following methods (linked to design variables):

1. Decreasing the number of turns of LV coil
2. Increasing the magnetic induction
3. Increasing the height of core window

The load loss is decreased with the following ways (related to design variables):

1. Decreasing the number of turns of LV coil
2. Increasing the magnetic induction
3. Increasing the cross-section area of HV coil
4. Increasing the cross-section area of LV coil
5. Increasing the height of core window

The impedance voltage is decreased as follows:

1. Decreasing the number of turns of LV coil
2. Increasing the height of core window

Generally, the cost of transformer is decreased as follows:

1. Increasing the no-load loss
2. Increasing the load loss

From the above it is seen that there is an interaction between the design and output variables. For example, the no-load loss is decreased with the decrease of magnetic induction (with the remaining design parameters kept constant), but unfortunately the load loss is increased. The optimum solution is derived by selecting values for the design variables such that the transformer satisfies the constraints with minimum manufacturing cost. The selection is implemented through many tries (many different values for the design parameters) and is executed with the help of a suitable computer program.

2.5 Example of Transformer Design Data

This section gives the input data that are necessary for the design of a 630 kVA, three-phase, oil-immersed, distribution transformer. The transformer windings are made of copper. The input data are split into seven types, as already described in Sect. 2.4.1. Sections 2.6 to 2.23 present the design of this transformer.

Table 2.6 Values of description variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	f	50	Hz	Frequency
2	$HVCC$	Δ	-	Connection of HV winding
3	$LVCC$	Y	-	Connection of LV winding
4	S_n	630	kVA	Rated power
5	$V^l_{HV,1}$	20000	V	First rated line voltage of HV winding
6	$V^l_{HV,2}$	6600	V	Second rated line voltage of HV winding
7	V^l_{LV}	400	V	Rated line voltage of LV winding

Table 2.7 Values of special variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	BIL_{HV}	125	kV	Basic insulation level of HV winding
2	BIL_{LV}	10	kV	Basic insulation level of LV winding
3	CSF	0.965	-	Core stacking factor
4	g_{CP}	9.87	kg/m^2	Weight per unit area of corrugated panels
5	g_{DS}	1.25	kg/m^3	Mass density of duct strips
6	g_{HV}	8856	kg/m^3	Mass density of HV winding
7	g_{LV}	8856	kg/m^3	Mass density of LV winding
8	g_{MM}	7650	kg/m^3	Mass density of magnetic steel
9	g_O	870	kg/m^3	Mass density of mineral oil
10	$LDSP_{HV}$	1	-	Layer direction space factor of HV winding
11	$LDSP_{LV}$	0.909	-	Layer direction space factor of LV winding
12	$t_{a,max}$	45	°C	Maximum ambient temperature
13	$TDSP_{HV}$	0.98	-	Turns direction space factor of HV winding
14	$TDSP_{LV}$	1	-	Turns direction space factor of LV winding
15	$t_{o,max}$	100	°C	Maximum oil temperature
16	$t_{w,max}$	105	°C	Maximum winding temperature
17	ρ_{HV}	0.020968	$\Omega \cdot mm^2/m$	Resistivity of HV winding
18	ρ_{LV}	0.020968	$\Omega \cdot mm^2/m$	Resistivity of LV winding

2.5.1 Values of Description Variables

The values of description variables are given in Table 2.6. Internal winding is the low voltage winding, while external winding is the high voltage winding.

2.5.2 Values of Special Variables

The values of special variables are given in Table 2.7.

2.5.3 Values of Default Variables

The values of default variables are given in Table 2.8. The tolerance for no-load loss, load-loss and impedance voltage are according to IEC 60076-1 (Table 1.6). There are ±2.5% and ±5% voltage taps at the HV winding. There are no voltage taps at the LV winding.

2.5.4 Values of Cost Variables

The values of cost variables are given in Table 2.9.

Table 2.8 Values of default variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	EdL_{HV}	266	W	Eddy current loss of HV winding
2	EdL_{LV}	399	W	Eddy current loss of LV winding
3	LL_g	8900	W	Guaranteed load loss
4	NLL_g	1100	W	Guaranteed no-load loss
5	$Taps_{HV,\max}$	5	%	Upper limit of taps of HV winding
6	$Taps_{HV,\min}$	5	%	Lower limit of taps of HV winding
7	$U_{k,g}$	6	%	Guaranteed impedance voltage

Table 2.9 Values of cost variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	A	13.39	\$/W	No-load loss factor (cost rate)
2	B	2.09	\$/W	Load loss factor (cost rate)
3	C_{Lab}	4541	\$	Labor cost
4	CRM	1236	\$	Cost of the rest materials
5	SM	35	%	Sales margin
6	uc_1	12.01	\$/kg	Unit cost of LV winding
7	uc_2	12.01	\$/kg	Unit cost of HV winding
8	uc_3	6.01	\$/kg	Unit cost of magnetic steel
9	uc_4	7.72	\$/kg	Unit cost of insulating paper
10	uc_5	8.58	\$/kg	Unit cost of duct strips
11	uc_6	1.72	\$/kg	Unit cost of mineral oil
12	uc_7	1.03	\$/kg	Unit cost of sheet steel
13	uc_8	1.20	\$/kg	Unit cost of corrugated panels

2.5.5 Values of Various Variables

The values of various variables are given in Table 2.10.

2.5.6 Values of Conductor Cross-Section Calculation Variables

The values of conductor cross-section calculation variables are given in Table 2.11.

2.5.7 Values of Design Variables

The values of design variables are given in Table 2.12. Using (2.45), we can see that the number of loops to solve this design problem is:

$$n_{loops} = n_{LV} \cdot n_D \cdot n_{FD} \cdot n_G \cdot cs_{LV} \cdot cs_{HV} \Rightarrow$$

$$n_{loops} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \Rightarrow n_{loops} = 1 \, .$$

This one iteration (loop) of calculations will be presented in Example 2.1 to Example 2.18.

Table 2.10 Values of various variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	$CCEE$	3	mm	Core to coil each end
2	$D_{HV\text{-}C}$	39	mm	Distance between HV winding and core
3	$D_{LV\text{-}C}$	6.5	mm	Distance between LV winding and core
4	D_{Panel}	220	mm	Width of corrugated panel
5	$Ducts_{HV}$	12	-	Number of ducts of HV winding
6	$Ducts_{LV}$	10	-	Number of ducts of LV winding
7	Dw	15	mm	Width of cooling ducts
8	$DWPG_{HV}$	35	mm	Width of HV winding duct strip plus gap
9	$DWPG_{LV}$	25	mm	Width of LV winding duct strip plus gap
10	HCP	800	mm	Height of corrugated panel
11	$I_{HV\text{-}HV}$	6.64	mm	Insulation outside external winding
12	$I_{HV\text{-}LV}$	6.92	mm	Insulation between LV winding and HV winding
13	$I_{LV\text{-}C}$	1.5	mm	Insulation between LV winding and core
14	K	9	mm	Distance between two adjacent cores
15	$Pitch$	44	mm	Distance between two adjacent fins
16	T_{DS}	3	mm	Thickness of duct strips (without insulation)
17	TE	38.1	mm	Tolerances and elongation of coil
18	TI_{HV}	1.4	mm	Insulation of HV taps
19	TLT_{HV}	14.2	mm	Total thickness of the HV leads
20	TLT_{LV}	12.48	mm	Total thickness of the LV leads
21	V_{CT}	25	L	Volume of oil conservator

Table 2.11 Values of conductor cross-section calculation variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	$area_{LV}$	191.18	mm^2	Cross-section area of LV winding
2	d_{HV}	1.8	mm	Diameter of HV conductor (without insulation Δd)
3	$HVCM$	Copper	-	Material of HV conductor
4	$LVCM$	Copper	-	Material of LV conductor
5	t_{LV}	0.79	mm	Thickness of LV conductor
6	$Type_{HV}$	Round wire	-	Type of HV conductor
7	$Type_{LV}$	Foil	-	Type of LV conductor
8	w_{LV}	242	mm	Width of LV conductor
9	Δd_{HV}	0.111	mm	Insulation of HV conductor

Table 2.12 Values of design variables for the 630 kVA transformer designed in Example 2.1 to Example 2.18

#	Symbol	Value	Unit	Description
1	cs_{HV}	1	-	Number of iterations for calculation of the cross-section area of the HV conductor
2	cs_{LV}	1	-	Number of iterations for calculation of the cross-section area of the LV conductor
3	D	220	mm	Width of core leg
4	$FD_{\max}$	17000	Gauss	Magnetic induction
5	G	261	mm	Height of core window
6	n_D	1	-	Number of iterations for the width of core leg
7	n_{FD}	1	-	Number of iterations for the magnetic induction
8	n_G	1	-	Number of iterations for the height of core window
9	n_{LV}	1	-	Number of iterations for the number of LV turns
10	$SNLL_{TF}$	1.87	W/kg	Specific no-load loss
11	$turns_{LV}$	15	-	Number of turns of LV winding

2.6 Calculation of Volts per Turn and Thickness of Core Leg

2.6.1 Calculation of Volts per Turn

The volts per turn, *VPT*, are calculated from the following equation:

$$VPT = \frac{V_{LV}^{p}}{turns_{LV}} \tag{2.46}$$

where V_{LV}^{p} (V) is the rated phase voltage of the LV winding and $turns_{LV}$ is the number of turns of the LV winding.

2.6.2 Calculation of Thickness of Core Leg

Let us suppose that the *magnetic flux* ϕ is sinusoidal:

$$\phi = \Phi_{\max} \cdot \sin(\omega \cdot t)\,, \tag{2.47}$$

where $\Phi_{\max}$ is the maximum flux and ω (rad/s) is the angular frequency.

The induced voltage e is:

$$e = N \cdot \frac{d\phi}{dt}\,, \tag{2.48}$$

where *N* is the number of turns of the winding.

By combining (2.47) and (2.48), the induced voltage e is computed from the following equation:

$$e = \omega \cdot N \cdot \Phi_{\max} \cdot \cos(\omega \cdot t)\,. \tag{2.49}$$

The effective value *E* of the induced voltage e is:

$$E = \frac{\omega \cdot N \cdot \Phi_{\max}}{\sqrt{2}} = \frac{2 \cdot \pi \cdot f \cdot N \cdot \Phi_{\max}}{\sqrt{2}} \Rightarrow$$

$$E = 4.44 \cdot f \cdot N \cdot \Phi_{\max}\,, \tag{2.50}$$

where *f* (Hz) is the frequency.

Based on (2.50), the maximum flux $\Phi_{\max}$ is computed as follows:

$$\Phi_{\max} = \frac{E}{4.44 \cdot f \cdot N} . \tag{2.51}$$

The maximum flux $\Phi_{\max}$ is also computed as follows:

$$\Phi_{\max} = FD_{\max} \cdot A_{eff} , \tag{2.52}$$

where $FD_{\max}$ is the maximum magnetic induction and A_{eff} is the effective core cross-section area of the magnetic flux.

Based on Fig. 2.3, the effective core cross-section area A_{eff} of the magnetic flux is computed as follows:

$$A_{eff} = CSF \cdot 2 \cdot A_C = CSF \cdot 2 \cdot (D \cdot E_u) , \tag{2.53}$$

where *CSF* is the core stacking factor, *D* (mm) is the width of core leg and E_u (mm) is the thickness of the core leg. The core stacking factor expresses the net cross-section area of the magnetic flux, i.e., the insulation of the magnetic material is subtracted.

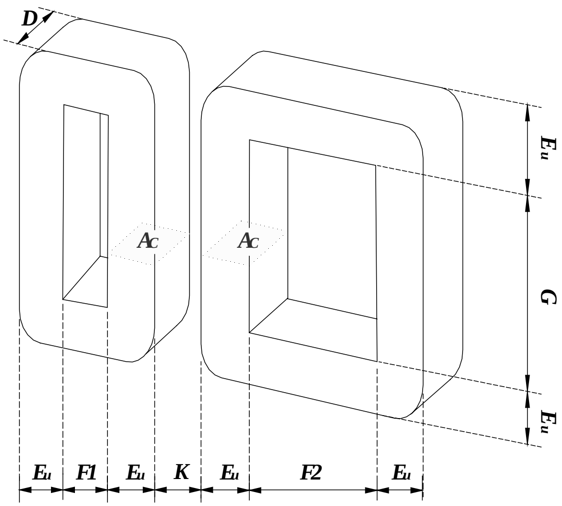

Fig. 2.3 Geometrical characteristics of the small and the large individual core. The magnetic flux passes throught the cross-section area A_c of the small and the large individual core

The volts per turn, *VPT*, can be computed as follows:

$$VPT = \frac{E}{N} . \tag{2.54}$$

By combining (2.51) to (2.54), an analytical expression for the calculation of the thickness of core leg, E_u, is derived as follows:

$$\Phi_{\max} = \frac{VPT}{4.44 \cdot f} \Rightarrow FD_{\max} \cdot A_{eff} = \frac{VPT}{4.44 \cdot f} \Rightarrow FD_{\max} \cdot CSF \cdot 2 \cdot D \cdot E_u = \frac{VPT}{4.44 \cdot f} \Rightarrow$$

$$E_u = \frac{VPT}{8.88 \cdot CSF \cdot D \cdot FD_{\max} \cdot f} . \tag{2.55}$$

2.6.3 Example 2.1

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the volts per turn and thickness of the core leg.

Solution

Since the LV winding is star-connected (Table 2.6), the rated phase voltage of the LV winding is:

$$V_{LV}^{p} = \frac{V_{LV}^{l}}{\sqrt{3}} = \frac{400\ \text{V}}{\sqrt{3}} \Rightarrow V_{LV}^{p} = 230.94\ \text{V} .$$

The volts per turn are computed using (2.46):

$$VPT = \frac{V_{LV}^{p}}{turns_{LV}} = \frac{230.94}{15} \Rightarrow VPT = 15.396\ \frac{\text{V}}{\text{turn}} .$$

The thickness of the core leg is computed using (2.55):

$$E_u = \frac{VPT}{8.88 \cdot CSF \cdot D \cdot FD_{\max} \cdot f} = \frac{15.396}{8.88 \cdot 0.965 \cdot (220 \cdot 10^{-3}) \cdot 1.7 \cdot 50} = 0.096\ \text{m} \Rightarrow$$

$$E_u = 96\ \text{mm} .$$

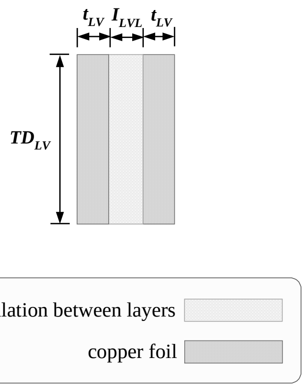

Fig. 2.4 Insulation between two layers of the LV winding. Each LV layer has one turn made of copper foil

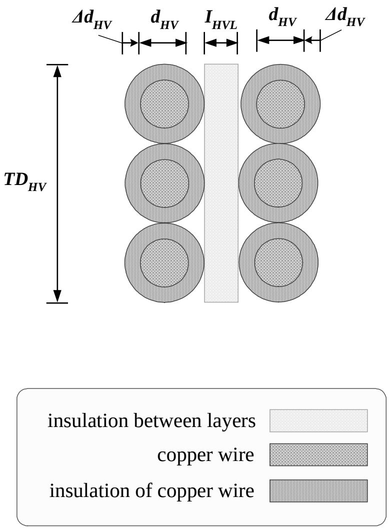

Fig. 2.5 Insulation between two layers of the HV winding. Each layer has three turns made of copper wire

2.7 Calculation of Layer Insulation

The thickness of the insulation between the layers of the LV winding must be sufficient to withstand the induced voltage as well as the impulse voltage of the LV winding. Similarly, the thickness of the insulation between the layers of the HV winding must be sufficient to withstand the induced voltage as well as the impulse voltage of the HV winding.

2.7.1 Layer Insulation of LV Winding

The thickness of the insulation between the layers of the LV winding, I_{LVL}, is computed using appropriate tables. Such a table contains, for example, the empirical rule that if the LV winding is made of copper foil with thickness between 0.4 and 1 mm, then $I_{LVL} = 0.28\,\text{mm}$. Figure 2.4 shows the insulation between two layers of the LV winding, where each layer has one turn made of copper foil.

2.7.2 Layer Insulation of HV Winding

The thickness of the insulation between the layers of the HV winding, I_{HVL}, is typically computed using appropriate tables. Such a table contains, for example, the empirical rule that if the HV winding is made of copper wire with diameter less than 2 mm, then $I_{HVL} = 0.28\,\text{mm}$. Figure 2.5 shows the insulation between two layers of the HV winding, where each layer has three turns made of copper wire.

2.7.3 Example 2.2

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the layer insulations.

Solution

As can be seen from Table 2.11, the LV winding is made of copper foil with 0.79 mm thickness, so, using the empirical rule of Sect. 2.7.1, $I_{LVL} = 0.28\,\text{mm}$, since the thickness of the copper foil is between 0.4 and 1 mm.

The HV winding is made of copper wire with 1.8 mm diameter (Table 2.11), so, using the empirical rule of Sect. 2.7.2, $I_{HVL} = 0.28\,\text{mm}$, since the diameter of the copper wire is less than 2 mm.

2.8 Calculation of Winding and Core Dimensions

During this step, the following technical characteristics are computed:

1. The width of the LV and the HV layer, TD_{LV} and TD_{HV}, respectively.

2. The width of the LV and the HV conductor with insulation, $TurnWidth_{LV}$ and $TurnWidth_{HV}$, respectively.

3. The thickness of the LV and the HV winding, BLD_{LV} and BLD_{HV}, respectively.

4. The window width of the small and the large individual core, $F1$ and $F2$, respectively.

5. The number of layers of the LV and the HV winding, $Layers_{LV}$ and $Layers_{HV}$, respectively.

6. The number of turns of the HV winding, $TurnsMain_{HV}$, at voltage $V^{l}_{HV,1}$.

7. The maximum number of turns of the HV winding, $Turns_{HV,\max}$.

Moreover, it is checked if the layer insulations I_{LVL} and I_{HVL} can withstand the induced and impulse voltage.

The sequence of calculations is illustrated in Example 2.3.

The above-mentioned dimensions (TD_{LV}, TD_{HV}, BLD_{LV}, BLD_{HV}, $F1$, $F2$) can be seen in Fig. 2.6.

2.8.1 *Example 2.3*

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. The layer insulation of 0.28 mm can withstand 6 kV maximum induced voltage and 23.5 kV maximum impulse voltage.

1. Compute the dimensions of the LV winding.

2. Compute the dimensions of the HV winding.

3. Calculate the window width of the small and large individual core.

4. Check if the layer insulations are correctly selected.

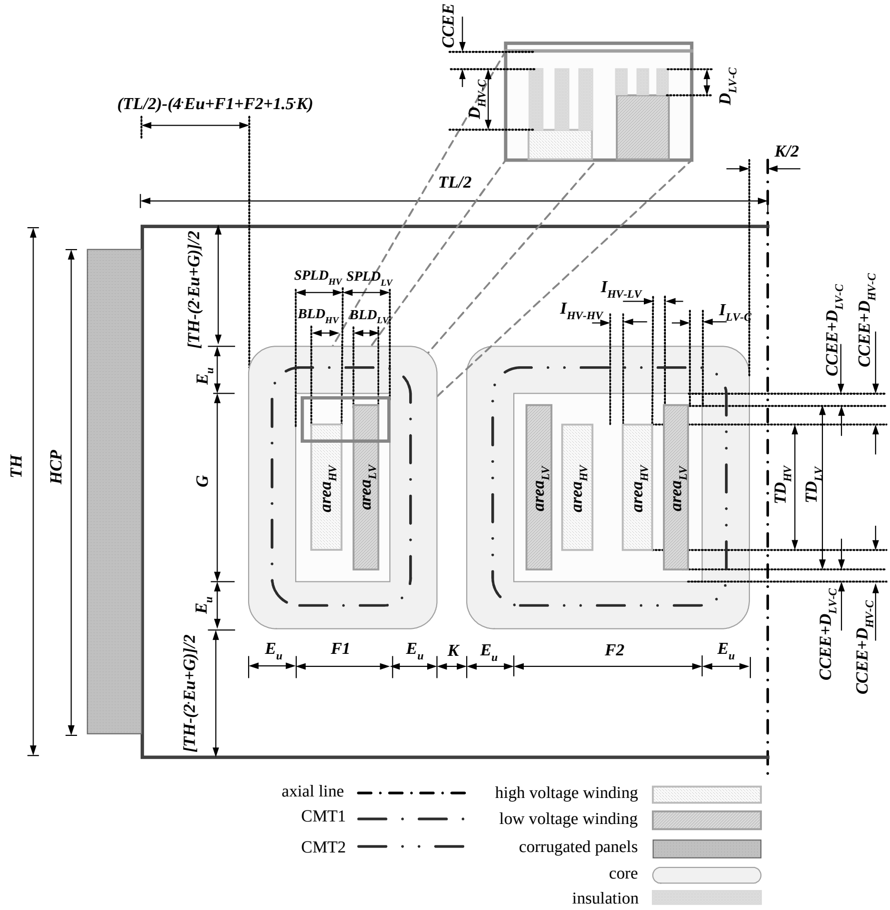

Fig. 2.6 Geometrical dimensions of transformer intersection

Solution

1. Since there are no taps at the LV winding, the number of turns of the LV winding is:

$$TurnsMain_{LV} = turns_{LV} \Rightarrow TurnsMain_{LV} = 15\,.$$

Since the LV winding is made of foil, each layer has one turn, so the number of layers of the LV winding is equal to the number of LV turns:

$$Layers_{LV} = TurnsMain_{LV} \Rightarrow Layers_{LV} = 15 .$$

It can be seen from Fig. 2.6 that the width of the LV layer is:

$$TD_{LV} = G - 2 \cdot CCEE - 2 \cdot D_{LV-C} = 261 - 2 \cdot 3 - 2 \cdot 6.5 \Rightarrow TD_{LV} = 242 \text{ mm} .$$

The width of the LV conductor with the insulation, $TurnWidth_{LV}$, is:

$$TurnWidth_{LV} = TD_{LV} \Rightarrow TurnWidth_{LV} = 242 \text{ mm} .$$

The thickness of the LV winding is:

$$BLD_{LV} = (t_{LV} + I_{LVL}) \cdot \frac{Layers_{LV}}{LDSP_{LV}} = (0.79 + 0.28) \cdot \frac{15}{0.909} \Rightarrow$$

$$BLD_{LV} = 17.66 \text{ mm} .$$

It can be seen from Fig. 2.6 that the total thickness of the LV winding is:

$$SPLD_{LV} = BLD_{LV} + I_{LV-C} + I_{HV-LV} = 17.66 + 1.5 + 6.92 \Rightarrow SPLD_{LV} = 26.08 \text{ mm} .$$

2. The HV winding is delta-connected, so the phase voltages are equal to the respective line voltages:

$$V^{p}_{HV,1} = V^{l}_{HV,1} = 20000 \text{ V} \text{ and } V^{p}_{HV,2} = V^{l}_{HV,2} = 6600 \text{ V} .$$

Since the maximum voltage tap at the HV winding is +5% (Table 2.8), the maximum HV winding phase voltage at the maximum tap is:

$$V^{p}_{HV,\max tap} = V^{p}_{HV,1} \cdot (1 + 0.05) = 20000 \cdot (1 + 0.05) \Rightarrow V^{p}_{HV,\max tap} = 21000 \text{ V} .$$

At the maximum primary voltage of 21 kV, the maximum number of turns of the HV winding is:

$$Turns_{HV,\max} = \frac{V^{p}_{HV,\max tap}}{VPT} = \frac{21000}{15.396} \Rightarrow Turns_{HV,\max} = 1364 .$$

At the rated primary voltage of 20 kV, the rated number of turns of the HV winding is:

$$TurnsMain_{HV} = Turns_{HV,\max} \cdot \frac{V^{p}_{HV,1}}{V^{p}_{HV,\max tap}} = 1364 \cdot \frac{20000}{21000} \Rightarrow$$

$$TurnsMain_{HV} = 1299\ .$$

It can be seen from Fig. 2.6 that the width of the HV layer is:

$$TD_{HV} = G - 2 \cdot CCEE - 2 \cdot D_{HV-C} = 261 - 2 \cdot 3 - 2 \cdot 39 \Rightarrow TD_{HV} = 177\ \text{mm}\ .$$

The width of the HV conductor with the insulation, $TurnWidth_{HV}$, is:

$$TurnWidth_{HV} = d_{HV} + \Delta d_{HV} = 1.8 + 0.111 \Rightarrow TurnWidth_{HV} = 1.911\ \text{mm}\ .$$

The turns per layer of the HV winding are:

$$TurnsPerLayer_{HV} = \left[\frac{TD_{HV}}{TurnWidth_{HV}} - 1\right] \cdot TDSP_{HV} = \left[\frac{177}{1.911} - 1\right] \cdot 0.98 \Rightarrow$$

$$TurnsPerLayer_{HV} = 89.79\ .$$

The external winding is composed of three sub-coils, because the second primary voltage of 6.6 kV is obtained from the first primary voltage of 20 kV divided by three:

$$6.6\ \text{kV} \approx \frac{20\ \text{kV}}{3}\ .$$

In particular, if the three sub-coils are connected in series, a voltage of 20 kV is obtained. On the other hand, if the three sub-coils are connected in parallel, a voltage of 6.6 kV is obtained.

The number of turns per layer for each one of the three sub-coils is:

$$TurnsPerLayer_{HV,\,sub-coil} = \frac{TurnsPerLayer_{HV}}{3} = \frac{89.79}{3} \Rightarrow$$
$$TurnsPerLayer_{HV,\,sub-coil} = 29.93\ .$$

After rounding off:

$$TurnsPerLayer_{HV,\,sub-coil} = 29\text{, and}$$

$$TurnsPerLayer_{HV} = 3 \cdot TurnsPerLayer_{HV,\,sub-coil} = 3 \cdot 29 \Rightarrow TurnsPerLayer_{HV} = 87\ .$$

The number of layers of the HV winding is:

$$Layers_{HV} = \frac{Turns_{HV,\max}}{TurnsPerLayer_{HV}} = \frac{1364}{87} \Rightarrow Layers_{HV} = 15.68 \, .$$

After rounding off, $Layers_{HV} = 16$.

The thickness of the HV winding is:

$$BLD_{HV} = (TurnWidth_{HV} + I_{HVL}) \cdot \frac{Layers_{HV}}{LDSP_{HV}} + TI_{HV} = (1.911 + 0.28) \cdot \frac{16}{1} + 1.4 \Rightarrow$$

$$BLD_{HV} = 36.47 \text{ mm} \, .$$

It can be seen from Fig. 2.6 that the total thickness of the HV winding is:

$$SPLD_{HV} = BLD_{HV} + I_{HV-HV} = 36.47 + 6.64 \Rightarrow SPLD_{HV} = 43.11 \text{ mm} \, .$$

3. It can be seen from Fig. 2.6 that the window width of the small individual core is:

$$F1 = SPLD_{LV} + SPLD_{HV} = 26.08 + 43.11 \Rightarrow F1 = 69.19 \text{ mm} \, .$$

After rounding off, $F1 = 69$ mm .

The window width of the large individual core is:

$$F2 = 2 \cdot F1 = 2 \cdot 69 \Rightarrow F2 = 138 \text{ mm} \, .$$

4. The layer insulation of 0.28 mm can withstand 6 kV maximum induced voltage and 23.5 kV maximum impulse voltage, i.e.:

$$Induced_{\max} = 6 \text{ kV} \text{ and } Impulse_{\max} = 23.5 \text{ kV} \, .$$

The layer insulation $I_{LVL} = 0.28$ mm of the LV winding can withstand the induced voltage, since:

$$Induced_{LV} = VPT \cdot 2 \cdot 2 \cdot 10^{-3} = 15.396 \cdot 2 \cdot 2 \cdot 10^{-3} \Rightarrow$$

$$Induced_{LV} = 0.062 \text{ kV} < Induced_{\max} = 6 \text{ kV} \, .$$

The layer insulation $I_{LVL} = 0.28\,\text{mm}$ of the LV winding can also withstand the impulse voltage, since:

$$Impulse_{LV} = \frac{2 \cdot BIL_{LV}}{turns_{LV}} = \frac{2 \cdot 10}{15} \Rightarrow$$

$$Impulse_{LV} = 1.33\,\text{kV} < Impulse_{\max} = 23.5\,\text{kV} .$$

The layer insulation $I_{HVL} = 0.28\,\text{mm}$ of the HV winding can withstand the induced voltage, since:

$$Induced_{HV} = VPT \cdot 2 \cdot TurnsPerLayer_{HV} \cdot 2 \cdot 10^{-3} = 15.396 \cdot 2 \cdot 87 \cdot 2 \cdot 10^{-3} \Rightarrow$$

$$Induced_{HV} = 5.36\,\text{kV} < Induced_{\max} = 6\,\text{kV} .$$

Since the minimum voltage tap at the HV winding is 5% (Table 2.8), the minimum HV winding phase voltage at the minimum tap is:

$$V^{p}_{HV,\,\min tap} = V^{p}_{HV,1} \cdot (1 - 0.05) = 20000 \cdot (1 - 0.05) \Rightarrow V^{p}_{HV,\,\min tap} = 19000\ \text{V} .$$

The layer insulation $I_{HVL} = 0.28\,\text{mm}$ of the HV winding can also withstand the impulse voltage, since:

$$Impulse_{HV} = \frac{2 \cdot BIL_{HV} \cdot TurnsPerLayer_{HV}}{TurnsMain_{HV} \cdot \dfrac{V^{p}_{HV,\,\min tap}}{V^{p}_{HV,1}}} = \frac{2 \cdot 125 \cdot 87}{1299 \cdot \dfrac{19000}{20000}} \Rightarrow$$

$$Impulse_{HV} = 17.62\,\text{kV} < Impulse_{\max} = 23.5\,\text{kV} .$$

Consequently, the insulation between the layers of the LV winding can withstand the induced and the impulse voltage. Similarly, the insulation between the layers of the HV winding can withstand the induced and the impulse voltage.

2.9 Calculation of Core Weight and No-Load Loss

The core constructional parameters are shown in Figs. 2.3 and 2.7. The mean turn length of the small individual core is (Hatziargyriou et al. 1998):

$$CMT1 = 2 \cdot (F1 + G) + 2 \cdot \pi \cdot \left[\frac{E_u}{2} + 3.5 \right] - 8 \cdot 3.5 . \tag{2.56}$$

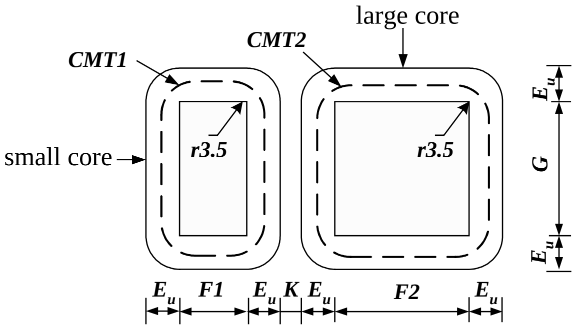

Fig. 2.7 Constructional parameters of the small and large individual core

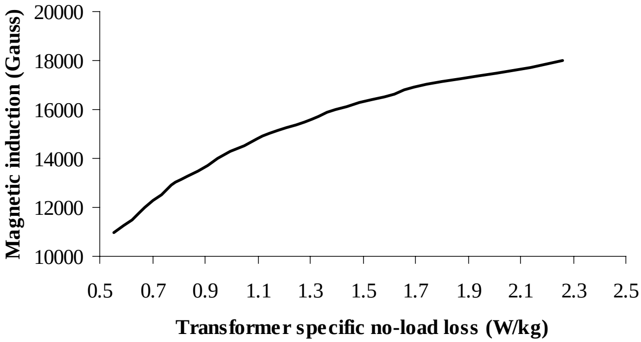

Fig. 2.8 Typical no-load loss curve

The weight of the small individual core is:

$$SCW = CMT1 \cdot D \cdot E_u \cdot CSF \cdot g_{MM} . \tag{2.57}$$

The mean turn length of the large individual core is (Hatziargyriou et al. 1998):

$$CMT2 = 2 \cdot (F2 + G) + 2 \cdot \pi \cdot \left[\frac{E_u}{2} + 3.5 \right] - 8 \cdot 3.5 . \tag{2.58}$$

The weight of the large individual core is:

$$LCW = CMT2 \cdot D \cdot E_u \cdot CSF \cdot g_{MM} . \tag{2.59}$$

The total weight of transformer magnetic material is equal to the sum of the weight of the two small and the two large individual cores:

$$w_3 = 2 \cdot (SCW + LCW)\,. \tag{2.60}$$

The transformer no-load loss is (Hatziargyriou et al. 1998):

$$NLL = w_3 \cdot SNLL_{TF}\,, \tag{2.61}$$

where $SNLL_{TF}$ is the transformer specific no-load loss (W/kg) obtained from the no-load loss curve for a given magnetic induction $FD_{\max}$. Different no-load loss curves correspond to different magnetic materials. A typical no-load loss curve is shown in Fig. 2.8 (Hatziargyriou et al. 1998).

2.9.1 Example 2.4

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Calculate the weight of the small individual core.
2. Compute the weight of the large individual core.
3. Calculate the total weight of transformer magnetic material.
4. Compute the transformer no-load loss. Check if the no-load loss tolerance of IEC 60076-1 is satisfied.

Solution

1. The mean turn length of the small individual core is computed from (2.56):

$$CMT1 = 2 \cdot (F1 + G) + 2 \cdot \pi \cdot \left[\frac{E_u}{2} + 3.5\right] - 8 \cdot 3.5 \Rightarrow$$

$$CMT1 = 2 \cdot (69 + 261) + 2 \cdot \pi \cdot \left[\frac{96}{2} + 3.5\right] - 8 \cdot 3.5 \Rightarrow CMT1 = 955.6 \text{ mm}\,.$$

The weight of the small individual core is calculated using (2.57):

$$SCW = CMT1 \cdot D \cdot E_u \cdot CSF \cdot g_{MM} \Rightarrow$$

$$SCW = (955.6 \cdot 10^{-3}) \cdot (220 \cdot 10^{-3}) \cdot (96 \cdot 10^{-3}) \cdot 0.965 \cdot 7650 \Rightarrow SCW = 149 \text{ kg} .$$

2. The mean turn length of the large individual core is:

$$CMT2 = 2 \cdot (F2 + G) + 2 \cdot \pi \cdot \left[\frac{E_u}{2} + 3.5 \right] - 8 \cdot 3.5 \Rightarrow$$

$$CMT2 = 2 \cdot (138 + 261) + 2 \cdot \pi \cdot \left[\frac{96}{2} + 3.5 \right] - 8 \cdot 3.5 \Rightarrow CMT2 = 1093.6 \text{ mm} .$$

The weight of the large individual core is:

$$LCW = CMT2 \cdot D \cdot E_u \cdot CSF \cdot g_{MM} \Rightarrow$$

$$LCW = (1093.6 \cdot 10^{-3}) \cdot (220 \cdot 10^{-3}) \cdot (96 \cdot 10^{-3}) \cdot 0.965 \cdot 7650 \Rightarrow LCW = 170.5 \text{ kg} .$$

3. The total weight of transformer magnetic material is computed from (2.60):

$$w_3 = 2 \cdot (SCW + LCW) = 2 \cdot (149 + 170.5) \Rightarrow w_3 = 639 \text{ kg} .$$

4. The transformer no-load loss is calculated using (2.61):

$$NLL = w_3 \cdot SNLL_{TF} = 639 \cdot 1.87 \Rightarrow NLL = 1195 \text{ W} .$$

In order for the no-load loss tolerance of IEC 60076-1 to be satisfied, the following constraint must be met:

$$NLL < 1.15 \cdot NLL_g \Rightarrow 1195 < 1.15 \cdot 1100 \Rightarrow 1195 < 1265 ,$$

which is fulfilled.

2.10 Calculation of Inductive Part of Impedance Voltage

During this step, the following technical characteristics are computed:

1. The equivalent diameters $D3$, $D7$, $D9$, and $D13$ of the coil. These diameters are shown in Fig. 2.9.

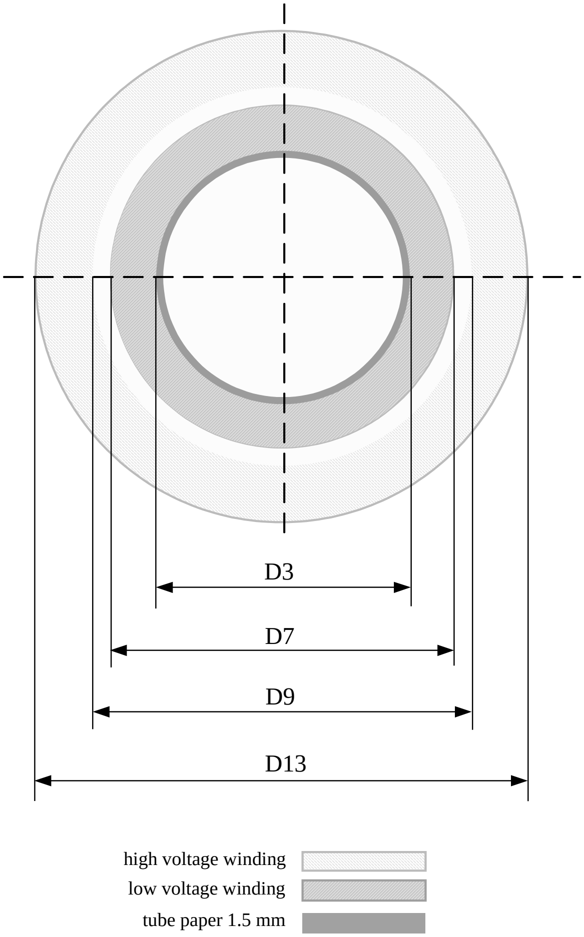

Fig. 2.9 Equivalent diameters of coil

2. The length *ML* and width *MW* of the coil former. These dimensions are shown in Fig. 2.10.

3. The inductive part of impedance voltage, *IX* .

   The necessary calculations are illustrated in Example 2.5.

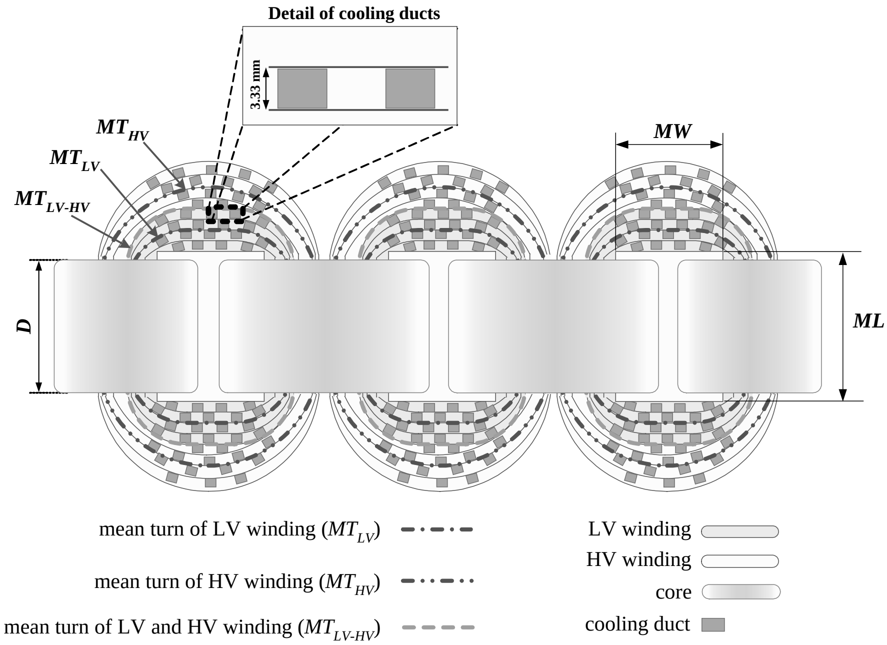

Fig. 2.10 Transformer active part

2.10.1 Example 2.5

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Calculate the inductive part of the impedance voltage.

Solution

The length *ML* and width *MW* of the coil former are:

$$ML = D + 2 \cdot CCEE = 220 + 2 \cdot 3 \Rightarrow ML = 226\,\text{mm}\,,$$

$$MW = 2 \cdot E_u + K = 2 \cdot 96 + 9 \Rightarrow MW = 201\,\text{mm}\,.$$

The equivalent diameter *DMC* of coil former is:

$$DMC = \frac{2 \cdot (ML + MW) - 10.992}{\pi} = \frac{2 \cdot (226 + 201) - 10.992}{\pi} \Rightarrow DMC = 268.34\,\text{mm}\,.$$

The equivalent external diameter $D3$ including the tube paper of thickness $I_{LV-C} = 1.5\text{ mm}$ is:

$$D3 = DMC + 2 \cdot I_{LV-C} = 268.34 + 2 \cdot 1.5 \Rightarrow D3 = 271.34\text{ mm}.$$

The area $A3$ corresponding to diameter $D3$ is:

$$A3 = \frac{\pi \cdot D3^2}{4} = \frac{\pi \cdot 271.34^2}{4} \Rightarrow A3 = 57825\text{ mm}^2.$$

The equivalent external diameter $D5$ of the LV winding (without taking into account the cooling ducts of the LV winding) is:

$$D5 = D3 + 2 \cdot BLD_{LV} = 271.34 + 2 \cdot 17.66 \Rightarrow D5 = 306.66\text{ mm}.$$

The area $A5$ corresponding to diameter $D5$ is:

$$A5 = \frac{\pi \cdot D5^2}{4} = \frac{\pi \cdot 306.66^2}{4} \Rightarrow A5 = 73859\text{ mm}^2.$$

The dimension LG_{LV} of the cooling ducts of the LV winding is:

$$LG_{LV} = MW \Rightarrow LG_{LV} = 201\text{ mm}.$$

The thickness of the LV cooling ducts is 3.33 mm, so the area $A6$ of the cooling ducts of the LV winding is:

$$A6 = Ducts_{LV} \cdot 3.33 \cdot LG_{LV} \cdot 2 = 10 \cdot 3.33 \cdot 201 \cdot 2 \Rightarrow A6 = 13387\text{ mm}^2.$$

The area $A7$ of the LV winding, including the area of the cooling ducts of the LV winding, is:

$$A7 = A5 + A6 = 73859 + 13387 \Rightarrow A7 = 87246\text{ mm}^2.$$

The diameter $D7$ corresponding to area $D7$ is:

$$D7 = \sqrt{\frac{4 \cdot A7}{\pi}} = \sqrt{\frac{4 \cdot 87246}{\pi}} \Rightarrow D7 = 333.29\text{ mm}.$$

The diameter $D9$ over the insulation I_{HV-LV} is:

$$D9 = D7 + 2 \cdot I_{HV-LV} = 333.29 + 2 \cdot 6.92 \Rightarrow D9 = 347.13 \text{ mm} .$$

The area $A9$ corresponding to diameter $D9$ is:

$$A9 = \frac{\pi \cdot D9^2}{4} = \frac{\pi \cdot 347.13^2}{4} \Rightarrow A9 = 94640 \text{ mm}^2 .$$

The equivalent external diameter $D11$ of the HV winding (without taking into account the cooling ducts of the HV winding) is:

$$D11 = D9 + 2 \cdot BLD_{HV} = 347.13 + 2 \cdot 36.47 \Rightarrow D11 = 420.07 \text{ mm} .$$

The area $A11$ corresponding to diameter $D11$ is:

$$A11 = \frac{\pi \cdot D11^2}{4} = \frac{\pi \cdot 420.07^2}{4} \Rightarrow A11 = 138590 \text{ mm}^2 .$$

The dimension LG_{HV} of the cooling ducts of the HV winding is:

$$LG_{HV} = A + 2 \cdot BLD_{LV} + 2 \cdot I_{HV-LV} = 201 + 2 \cdot 17.66 + 2 \cdot 6.92 \Rightarrow$$

$$LG_{HV} = 250.16 \text{ mm} .$$

The thickness of the HV cooling ducts is 3.33 mm, so the area $A12$ of the cooling ducts of the HV winding is:

$$A12 = Ducts_{HV} \cdot 3.33 \cdot LG_{HV} \cdot 2 = 12 \cdot 3.33 \cdot 250.16 \cdot 2 \Rightarrow A12 = 19993 \text{ mm}^2 .$$

The area $A13$ of the HV winding, including the area of the cooling ducts of the HV winding, is:

$$A13 = A11 + A12 = 138590 + 19993 \Rightarrow A13 = 158583 \text{ mm}^2 .$$

The diameter $D13$ corresponding to area $D13$ is:

$$D13 = \sqrt{\frac{4 \cdot A13}{\pi}} = \sqrt{\frac{4 \cdot 158583}{\pi}} \Rightarrow D13 = 449.35 \text{ mm} .$$

The factor k_L is computed as follows:

$$k_L = \frac{-2\cdot\sqrt{A3}+\sqrt{A7}+\sqrt{A9}}{3.54\cdot TD_{LV}} = \frac{-2\cdot\sqrt{57825}+\sqrt{87246}+\sqrt{94640}}{3.54\cdot 242} \Rightarrow k_L = 0.142\,.$$

The dimension $L17$ is computed as follows:

$$L17 = (k_L^2 + k_L + 1)\cdot TD_{LV} = (0.142^2 + 0.142 + 1)\cdot 242 \Rightarrow L17 = 281.24\ \text{mm}\,.$$

The factor k_P is computed as follows:

$$k_P = \frac{2\cdot\sqrt{A13}-\sqrt{A7}-\sqrt{A9}}{3.54\cdot TD_{HV}} = \frac{2\cdot\sqrt{158583}-\sqrt{87246}-\sqrt{94640}}{3.54\cdot 177} \Rightarrow k_P = 0.309\,.$$

The dimension $L21$ is computed as follows:

$$L21 = (k_P^2 + k_P + 1)\cdot TD_{HV} = (0.309^2 + 0.309 + 1)\cdot 177 \Rightarrow L21 = 248.59\ \text{mm}\,.$$

The dimension $LH23$ is computed as follows:

$$LH23 = L17 + L21 = 281.24 + 248.59 \Rightarrow LH23 = 529.83\ \text{mm}\,.$$

The inductance $L25$ is computed as follows:

$$L25 = \frac{(A5 - A3)\cdot 0.396}{L17}\cdot\mu_0 \Rightarrow$$

$$L25 = \left[\frac{(73859-57825)\cdot 10^{-6}\ \text{m}^2}{281.24\cdot 10^{-3}\ \text{m}}\right]\cdot 0.396\cdot\left[4\cdot\pi\cdot 10^{-7}\ \frac{\text{H}}{\text{m}}\right] \Rightarrow$$

$$L25 = 2.84\cdot 10^{-8}\ \text{H}\,.$$

The inductance $L26$ is computed as follows:

$$L26 = \frac{(A11 - A9)\cdot 0.396}{L21}\cdot\mu_0 \Rightarrow$$

$$L26 = \left[\frac{(138590-94640)\cdot 10^{-6}\ \text{m}^2}{248.59\cdot 10^{-3}\ \text{m}}\right]\cdot 0.396\cdot\left[4\cdot\pi\cdot 10^{-7}\ \frac{\text{H}}{\text{m}}\right] \Rightarrow$$

$$L26 = 8.80\cdot 10^{-8}\ \text{H}\,.$$

The inductance $L27$ is computed as follows:

$$L27 = \frac{(A9 - A7) \cdot 2}{LH23} \cdot \mu_0 \Rightarrow$$

$$L27 = \left[\frac{(94640 - 87246) \cdot 10^{-6} \text{ m}^2}{529.83 \cdot 10^{-3} \text{ m}} \right] \cdot 2 \cdot \left[4 \cdot \pi \cdot 10^{-7} \frac{\text{H}}{\text{m}} \right] \Rightarrow$$

$$L27 = 3.51 \cdot 10^{-8} \text{ H} .$$

The inductance $L28$ is computed as follows:

$$L28 = \frac{A6 \cdot FN(Ducts_{LV})}{L17} \cdot \mu_0 \Rightarrow$$

$$L28 = \left[\frac{13387 \cdot 10^{-6} \text{ m}^2}{281.24 \cdot 10^{-3} \text{ m}} \right] \cdot 0.318 \cdot \left[4 \cdot \pi \cdot 10^{-7} \frac{\text{H}}{\text{m}} \right] \Rightarrow L28 = 1.90 \cdot 10^{-8} \text{ H} ,$$

where the value of parameter $FN(Ducts_{LV}) = FN(10) = 0.318$ is obtained from tables.

The inductance $L29$ is computed as follows:

$$L29 = \frac{A12 \cdot FN(Ducts_{HV})}{L21} \cdot \mu_0 \Rightarrow$$

$$L29 = \left[\frac{19993 \cdot 10^{-6} \text{ m}^2}{248.59 \cdot 10^{-3} \text{ m}} \right] \cdot 0.320 \cdot \left[4 \cdot \pi \cdot 10^{-7} \frac{\text{H}}{\text{m}} \right] \Rightarrow L29 = 3.23 \cdot 10^{-8} \text{ H} ,$$

where the value of parameter $FN(Ducts_{HV}) = FN(12) = 0.320$ is obtained from tables.

The total inductance, L_{tot}, is computed as follows:

$$L_{tot} = L25 + L26 + L27 + L28 + L29 \Rightarrow$$

$$L_{tot} = (2.84 + 8.80 + 3.51 + 1.90 + 3.23) \cdot 10^{-8} \Rightarrow L_{tot} = 2.03 \cdot 10^{-7} \text{ H} .$$

The phase current I_{LV}^{p} that flows through the star-connected LV winding is:

$$I_{LV}^{p} = \frac{S}{3 \cdot V_{LV}^{p}} = \frac{630000 \text{ VA}}{3 \cdot (230.94 \text{ V})} \Rightarrow I_{LV}^{p} = 909.33 \text{ A} .$$

The inductive part IX of the impedance voltage is calculated as follows:

$$IX = \frac{I_{LV}^{p} \cdot 2 \cdot \pi \cdot f \cdot turns_{LV}^{2} \cdot L_{tot}}{V_{LV}^{p}} \Rightarrow$$

$$IX = \frac{(909.33\ \text{A}) \cdot 2 \cdot \pi \cdot (50\ \text{Hz}) \cdot 15^{2} \cdot (2.03 \cdot 10^{-7}\ \text{H})}{230.94\ \text{V}} = 0.0565 \Rightarrow IX = 5.65\ \%\ .$$

2.11 Calculation of Load Loss

During this step, the following technical characteristics are computed:

1. The mean turn length of LV winding
2. The load loss of LV winding
3. The weight of LV winding
4. The mean turn length of HV winding
5. The load loss of HV winding
6. The weight of HV winding
7. The transformer load loss
8. The transformer total loss

The sequence of calculations is illustrated in Example 2.6.

2.11.1 Example 2.6

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Calculate the load loss of the LV winding.
2. Calculate the load loss of the HV winding at voltage $V_{HV,1}^{l}$.
3. Compute the transformer load loss at voltage $V_{HV,1}^{l}$. Check if the IEC 60076-1 tolerance for load loss at voltage $V_{HV,1}^{l}$ is satisfied.

4. Check if the IEC 60076-1 tolerance for total loss at voltage $V_{HV,1}^{l}$ is satisfied.

5. Calculate the load loss of the HV winding at the minimum high voltage.

6. Compute the transformer load loss at the minimum high voltage. Check if the IEC 60076-1 tolerance for load loss at the minimum high voltage is satisfied.

7. Check if the IEC 60076-1 tolerance for total loss at the minimum high voltage is satisfied.

8. Calculate the weight of the LV winding.

9. Calculate the weight of the HV winding.

Solution

1. The mean turn length of the LV winding is:

$$MT_{LV} = \left[\frac{D3 + D7}{2}\right] \cdot \pi = \left[\frac{271.34 + 333.29}{2}\right] \cdot \pi \Rightarrow MT_{LV} = 949.75 \text{ mm} .$$

The length of the LV winding is:

$$CL_{LV} = MT_{LV} \cdot Layers_{LV} \cdot 3 = (949.75 \cdot 10^{-3} \text{ m}) \cdot 15 \cdot 3 \Rightarrow CL_{LV} = 42.74 \text{ m} .$$

The cross-section area of the LV winding is:

$$area_{LV} = TurnWidth_{LV} \cdot t_{LV} = (242 \text{ mm}) \cdot (0.79 \text{ mm}) \Rightarrow$$

$$area_{LV} = 191.18 \text{ mm}^2 .$$

The resistance of the LV winding is:

$$R_{LV} = \frac{\rho_{LV} \cdot \frac{CL_{LV}}{3}}{area_{LV}} = \frac{\left[0.020968 \frac{\Omega \cdot \text{mm}^2}{\text{m}}\right] \cdot \frac{(42.74 \text{ m})}{3}}{191.18 \text{ mm}^2} \Rightarrow R_{LV} = 1.56 \cdot 10^{-3} \ \Omega .$$

The load loss of the LV winding is:

$$LL_{LV} = 3 \cdot R_{LV} \cdot (I_{LV}^{p})^2 \cdot 1.04 = 3 \cdot (1.56 \cdot 10^{-3} \ \Omega) \cdot (909.33 \text{ A})^2 \cdot 1.04 \Rightarrow$$

$$LL_{LV} = 4025 \text{ W} .$$

2. The mean turn length of the HV winding is:

$$MT_{HV} = \left[\frac{D9 + D13}{2}\right] \cdot \pi = \left[\frac{347.13 + 449.35}{2}\right] \cdot \pi \Rightarrow MT_{HV} = 1251.11\,\text{mm}\,.$$

The length of the HV winding at the rated voltage $V_{HV,1}^{l} = 20\,\text{kV}$ is:

$$CL_{HV,1} = MT_{HV} \cdot TurnsMain_{HV} \cdot 3 = (1251.11 \cdot 10^{-3}\,\text{m}) \cdot 1299 \cdot 3 \Rightarrow$$

$$CL_{HV,1} = 4875.6\,\text{m}\,.$$

The cross-section area of the HV winding is:

$$area_{HV} = \frac{\pi \cdot d_{HV}^2}{4} = \frac{\pi \cdot (1.8\,\text{mm})^2}{4} \Rightarrow area_{HV} = 2.54\,\text{mm}^2\,.$$

The phase current $I_{HV,1}^{p}$ that flows through the delta-connected HV winding at the rated voltage $V_{HV,1}^{p} = V_{HV,1}^{l} = 20\,\text{kV}$ is:

$$I_{HV,1}^{p} = \frac{S_n}{3 \cdot V_{HV,1}^{p}} = \frac{630000\,\text{VA}}{3 \cdot (20000\,\text{V})} \Rightarrow I_{HV,1}^{p} = 10.5\,\text{A}\,.$$

The resistance of the HV winding at the rated voltage $V_{HV,1}^{l} = 20\,\text{kV}$ is:

$$R_{HV,1} = \frac{\rho_{HV} \cdot \frac{CL_{HV,1}}{3}}{area_{HV}} = \frac{\left[0.020968\,\frac{\Omega \cdot \text{mm}^2}{\text{m}}\right] \cdot \frac{(4875.6\,\text{m})}{3}}{2.54\,\text{mm}^2} \Rightarrow R_{HV,1} = 13.4\,\Omega\,.$$

The load loss of the HV winding at the rated voltage $V_{HV,1}^{l} = 20\,\text{kV}$ is:

$$LL_{HV,1} = 3 \cdot R_{HV,1} \cdot (I_{HV,1}^{p})^2 \cdot 1.06 = 3 \cdot (13.4\,\Omega) \cdot (10.5\,\text{A})^2 \cdot 1.06 \Rightarrow$$

$$LL_{HV,1} = 4698\,\text{W}\,.$$

3. The transformer load loss at the rated voltage $V_{HV,1}^{l} = 20\,\text{kV}$ is:

$$LL_1 = LL_{LV} + LL_{HV,1} + EdL_{LV} + EdL_{HV} = 4025 + 4698 + 399 + 266 \Rightarrow$$

$$LL_1 = 9388 \text{ W} .$$

In order for the IEC 60076-1 tolerance on the load loss at the rated voltage $V_{HV,1}^{l} = 20 \text{ kV}$ to be satisfied, the following constraint must be met:

$$LL_1 < 1.15 \cdot LL_g \Rightarrow 9388 < 1.15 \cdot 8900 \Rightarrow 9388 < 10235 ,$$

which is fulfilled.

4. In order for the IEC 60076-1 tolerance on the total loss at the rated voltage $V_{HV,1}^{l} = 20 \text{ kV}$ to be satisfied, the following constraint must be met:

$$(NLL + LL_1) < 1.1 \cdot (NLL_g + LL_g) \Rightarrow$$

$$(1195 + 9388) < 1.1 \cdot (1100 + 8900) \Rightarrow 10583 < 11000 ,$$

which is fulfilled.

5. The transformer operates with 20 kV or with 6.6 kV primary voltages, while the minimum tap is 5% for both primary voltages. This means that the minimum high voltage is:

$$HV_{\min}^{p} = V_{HV,2}^{p} \cdot (1 - Taps_{HV,\min}) = 6600 \cdot (1 - 0.05) \Rightarrow HV_{\min}^{p} = 6270 \text{ V} .$$

The number of turns that give the minimum high voltage of 6270 V is:

$$Turns_{HV,\min} = TurnsMain_{HV} \cdot \frac{HV_{\min}^{p}}{V_{HV,1}^{p}} = 1299 \cdot \left[\frac{6270 \text{ V}}{20000 \text{ V}} \right] \Rightarrow Turns_{HV,\min} = 407 .$$

The length of the external winding at the minimum high voltage of 6270 V is:

$$CL_{HV,2} = MT_{HV} \cdot Turns_{HV,\min} \cdot 3 = (1251.11 \cdot 10^{-3} \text{ m}) \cdot 407 \cdot 3 \Rightarrow$$

$$CL_{HV,2} = 1527.6 \text{ m} .$$

The phase current $I_{HV,2}^{p}$ that flows through the delta-connected HV winding at the minimum high voltage of 6270 V is:

$$I_{HV,2}^{p} = \frac{S}{3 \cdot HV_{\min}^{p}} = \frac{630000 \text{ VA}}{3 \cdot (6270 \text{ V})} \Rightarrow I_{HV,2}^{p} = 33.5 \text{ A} .$$

Since there are three sub-coils connected in parallel, the current that flows in each sub-coil is:

$$I_{HV,2,sub-coil}^{p} = \frac{I_{HV,2}^{p}}{3} = \frac{33.5 \text{ A}}{3} \Rightarrow I_{HV,2,sub-coil}^{p} = 11.17 \text{ A} .$$

The resistance of the HV winding at the minimum high voltage of 6270 V is:

$$R_{HV,2} = \frac{\rho_{HV} \cdot \frac{CL_{HV,2}}{3}}{area_{HV}} = \frac{\left[0.020968 \frac{\Omega \cdot \text{mm}^2}{\text{m}}\right] \cdot \frac{(1527.6 \text{ m})}{3}}{2.54 \text{ mm}^2} \Rightarrow R_{HV,2} = 4.2\, \Omega .$$

The load loss of each sub-coil of the HV winding at the minimum high voltage of 6270 V is:

$$LL_{HV,2,sub-coil} = 3 \cdot R_{HV,2} \cdot (I_{HV,2,sub-coil}^{p})^2 \cdot 1.06 = 3 \cdot (4.2\, \Omega) \cdot (11.17 \text{ A})^2 \cdot 1.06 \Rightarrow$$

$$LL_{HV,2,sub-coil} = 1666 \text{ W} .$$

The load loss (of the three sub-coils) of the HV winding at the minimum high voltage of 6270 V is:

$$LL_{HV,2} = 3 \cdot LL_{HV,2,sub-coil} = 3 \cdot 1666 \Rightarrow LL_{HV,2} = 4998 \text{ W} .$$

6. The transformer load loss at the minimum high voltage of 6270 V is:

$$LL_2 = LL_{LV} + LL_{HV,2} + EdL_{LV} + EdL_{HV} = 4025 + 4998 + 399 + 266 \Rightarrow$$

$$LL_2 = 9688 \text{ W} .$$

In order for the IEC 60076-1 tolerance on the load loss at the minimum high voltage of 6270 V to be satisfied, the following constraint must be met:

$$LL_2 < 1.15 \cdot LL_g \Rightarrow 9688 < 1.15 \cdot 8900 \Rightarrow 9688 < 10235 ,$$

which is fulfilled.

7. In order for the IEC 60076-1 tolerance on the total loss at the minimum high voltage of 6270 V to be satisfied, the following constraint must be met:

$$(NLL + LL_2) < 1.1 \cdot (NLL_g + LL_g) \Rightarrow$$

$$(1195 + 9688) < 1.1 \cdot (1100 + 8900) \Rightarrow 10883 < 11000 ,$$

which is fulfilled.

8. The total weight of the LV winding is:

$$w_1 = CL_{LV} \cdot area_{LV} \cdot g_{LV} \cdot 1.05 \Rightarrow$$

$$w_1 = (42.74\ m) \cdot (191.18 \cdot 10^{-6}\ \mathrm{m}^2) \cdot (8856\ \mathrm{kg/m}^3) \cdot 1.05 \Rightarrow w_1 = 76\ \mathrm{kg}\ .$$

9. The total weight of the HV winding is:

$$w_2 = CL_{HV,1} \cdot \left[1 + Taps_{HV,\max}\right] \cdot area_{HV} \cdot g_{HV} \cdot 1.08 \Rightarrow$$

$$w_2 = (4875.6\ \mathrm{m}) \cdot (1 + 0.05) \cdot (2.54 \cdot 10^{-6}\ \mathrm{m}^2) \cdot (8856\ \mathrm{kg/m}^3) \cdot 1.08 \Rightarrow$$

$$w_2 = 124.4\ \mathrm{kg}\ .$$

2.12 Calculation of Impedance Voltage

The ohmic part of the impedance voltage is:

$$IR = \frac{LL_1}{S_n}\ . \tag{2.62}$$

The impedance voltage is computed as follows:

$$U_k = \sqrt{IR^2 + IX^2}\ . \tag{2.63}$$

2.12.1 Example 2.7

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Compute the ohmic part of the impedance voltage.

2. Compute the impedance voltage.

3. Check if the IEC 60076-1 tolerance on the impedance voltage is satisfied.

Solution

1. The ohmic part of the impedance voltage is:

$$IR = \frac{LL_1}{S_n} = \frac{9388\ \text{W}}{630000\ \text{VA}} = 0.0149 \Rightarrow IR = 1.49\ \%\ .$$

2. The impedance voltage is:

$$U_k = \sqrt{IR^2 + IX^2} = \sqrt{0.0149^2 + 0.0565^2} = 0.0584 \Rightarrow U_k = 5.84\ \%\ .$$

3. In order for the impedance voltage tolerance given in IEC 60076-1 to be satisfied, the following constraint must be met:

$$0.9 \cdot U_{k,g} < U_k < 1.1 \cdot U_{k,g} \Rightarrow$$

$$0.9 \cdot (6\ \%) < 5.84\ \% < 1.1 \cdot (6\ \%) \Rightarrow 5.4\ \% < 5.84\ \% < 6.6\ \%\ ,$$

which is fulfilled.

2.13 Calculation of Coil Length

Example 2.8 shows how the coil length is computed.

2.13.1 Example 2.8

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the coil length.

Solution

The total thickness of the cooling ducts, *TCD*, is:

$$TCD = 2 \cdot (Ducts_{LV} + Ducts_{HV}) \cdot 3.33 = 2 \cdot (10 + 12) \cdot 3.33 \Rightarrow TCD = 146.52 \text{ mm} .$$

The overlap of the tube paper (thickness 1.5 mm) plus the LV layer insulation is:

$$OLI_{LV} = 1.5 + I_{LVL} = 1.5 + 0.28 \Rightarrow OLI_{LV} = 1.78 \text{ mm} .$$

The overlap of the layer insulation of the HV winding, OLI_{HV}, is:

$$OLI_{HV} = Layers_{HV} \cdot I_{HVL} = 16 \cdot 0.28 \Rightarrow OLI_{HV} = 4.48 \text{ mm} .$$

The total length of the coil, *LTC*, is calculated as follows:

$$TLC = ML + 2 \cdot F1 + TCD + TLT_{LV} + TLT_{HV} + OLI_{LV} + OLI_{HV} + TE \Rightarrow$$

$$TLC = 226 + 2 \cdot 69 + 146.52 + 12.48 + 14.2 + 1.78 + 4.48 + 38.1 \Rightarrow TLC = 582 \text{ mm} .$$

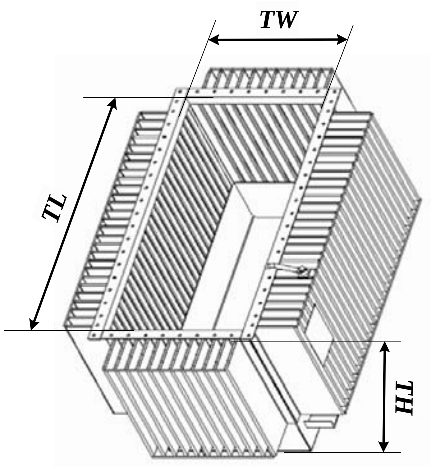

Fig. 2.11 Tank dimensions

2.14 Calculation of Tank Dimensions

The tank dimensions are shown in Fig. 2.11. Example 2.9 shows how the tank dimensions are computed.

2.14.1 Example 2.9

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Compute the tank length.
2. Compute the tank width.
3. Calculate the tank height and the oil height.

Solution

1. The tank length, *TL*, is:

$$TL = 2 \cdot (4 \cdot E_u + 3 \cdot F1 + K) + K + 108 = 2 \cdot (4 \cdot 96 + 3 \cdot 69 + 9) + 9 + 108 \Rightarrow$$

$$TL = 1317 \text{ mm} .$$

2. The tank width, *TW*, is:

$$TW = TLC + 38 = 582 + 38 \Rightarrow TW = 620 \text{ mm} .$$

3. The minimum tank height, $TH_{\min}$, is:

$$TH_{\min} = G + 2 \cdot E_u + 350 = 261 + 2 \cdot 96 + 350 \Rightarrow TH_{\min} = 803 \text{ mm} .$$

Since a triple tap changer and a triple voltage regulator will be used, for constructional reasons, the tank height is selected to be:

$$TH = 1015 \text{ mm} .$$

This transformer has an oil conservator (a cylindrical tank that undergoes the oil volume fluctuation due to oil temperature variation), so the mineral oil height, *OH*, is:

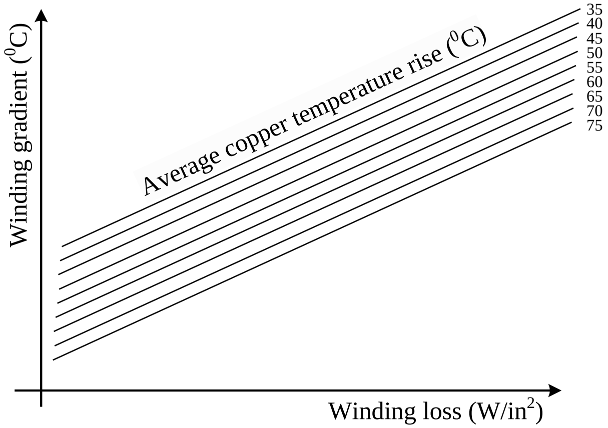

Fig. 2.12 Gradient curves based on average copper temperature rise

$$OH = TH \Rightarrow OH = 1015\ \text{mm}\ .$$

2.15 Calculation of Winding Gradient and Oil Gradient

The gradient (temperature rise) of the LV winding and the gradient of the HV winding are computed using gradient curves of the form shown in Fig. 2.12. The sequence of calculations is presented in Example 2.10.

2.15.1 Example 2.10

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Compute the average gradient between the oil and the LV winding.

2. Compute the average gradient between the oil and the HV winding.

3. Calculate the average oil temperature rise.

Solution

1. The area of the cooling ducts of the LV winding is:

$$DuctArea_{LV} = Ducts_{LV} \cdot 2 \cdot 2 \cdot MW \cdot TD_{LV} = 10 \cdot 2 \cdot 2 \cdot 201 \cdot 242 \Rightarrow$$

$$DuctArea_{LV} = 1945680 \text{ mm}^2 = \frac{1945680 \text{ mm}^2}{25.4^2 \ \frac{\text{mm}^2}{\text{in}^2}} \Rightarrow DuctArea_{LV} = 3016 \text{ in}^2 .$$

The area of the cooling ducts of the LV gap is:

$$GapDuctArea_{LV} = D7 \cdot \pi \cdot TD_{LV} = 333.29 \cdot \pi \cdot 242 = 253389 \text{ mm}^2 \Rightarrow$$

$$GapDuctArea_{LV} = \frac{253389 \text{ mm}^2}{25.4^2 \ \frac{\text{mm}^2}{\text{in}^2}} \Rightarrow GapDuctArea_{LV} = 393 \text{ in}^2 .$$

The total area of the cooling ducts of the LV winding is:

$$TotalDuctArea_{LV} = DuctArea_{LV} + GapDuctArea_{LV} = 3016 + 393 \Rightarrow$$

$$TotalDuctArea_{LV} = 3409 \text{ in}^2 .$$

The loss in each one of the three LV windings is:

$$CoilLoss_{LV} = \frac{LL_{LV} + EdL_{LV}}{3} = \frac{4025 + 399}{3} \Rightarrow CoilLoss_{LV} = 1475 \text{ W} .$$

The LV winding loss per surface of the cooling ducts is:

$$LPS_{LV} = \frac{CoilLoss_{LV}}{TotalDuctArea_{LV}} = \frac{1475 \text{ W}}{3409 \text{ in}^2} \Rightarrow LPS_{LV} = 0.43 \frac{\text{W}}{\text{in}^2} .$$

The average copper temperature rise, *ACR*, is:

$$ACR = t_{w,\max} - t_{a,\max} = 105 - 45 \Rightarrow ACR = 60 \ ^\circ C .$$

Since $ACR = 60 \ ^\circ C$ and $LPS_{LV} = 0.43 \text{ W/in}^2$, from gradient curves it is found that the gradient of the LV winding, Gra_{LV}, is:

$$Gra_{LV} = 5.2 \ ^\circ C .$$

The average gradient between the oil and the LV winding, $AvGra_{LV}$, is:

$$AvGra_{LV} = 2.09 \cdot Gra_{LV} = 2.09 \cdot 5.2 \Rightarrow AvGra_{LV} = 10.9 \ ^\circ C .$$

2. The area of the cooling ducts of the HV winding is:

$$DuctArea_{HV} = Ducts_{HV} \cdot 2 \cdot 2 \cdot LG_{HV} \cdot TD_{HV} = 12 \cdot 2 \cdot 2 \cdot 250.16 \cdot 177 \Rightarrow$$

$$DuctArea_{HV} = 2125359\ \text{mm}^2 = \frac{2125359\ \text{mm}^2}{25.4^2\ \frac{\text{mm}^2}{\text{in}^2}} \Rightarrow DuctArea_{HV} = 3294\ \text{in}^2 .$$

The area of the cooling ducts of the HV gap is:

$$GapDuctArea_{HV} = D7 \cdot \pi \cdot TD_{HV} = 333.29 \cdot \pi \cdot 177 = 185330\ \text{mm}^2 \Rightarrow$$

$$GapDuctArea_{HV} = \frac{185330\ \text{mm}^2}{25.4^2\ \frac{\text{mm}^2}{\text{in}^2}} \Rightarrow GapDuctArea_{HV} = 287\ \text{in}^2 .$$

The total area of the cooling ducts of the HV winding is:

$$TotalDuctArea_{HV} = DuctArea_{HV} + GapDuctArea_{HV} = 3294 + 287 \Rightarrow$$

$$TotalDuctArea_{HV} = 3581\ \text{in}^2 .$$

The loss in each one of the three HV windings, at the minimum high voltage of 6270 V, is:

$$CoilLoss_{HV} = \frac{LL_{HV,2} + EdL_{HV}}{3} = \frac{4998 + 266}{3} \Rightarrow CoilLoss_{HV} = 1755\ \text{W} .$$

The HV winding loss per surface of the cooling ducts is:

$$LPS_{HV} = \frac{CoilLoss_{HV}}{TotalDuctArea_{HV}} = \frac{1755\ \text{W}}{3581\ \text{in}^2} \Rightarrow LPS_{HV} = 0.49\ \frac{\text{W}}{\text{in}^2} .$$

Since $ACR = 60\ ^0C$ and $LPS_{HV} = 0.49\ \text{W}/\text{in}^2$, from gradient curves it is found that the gradient of the HV winding, Gra_{HV}, is:

$$Gra_{HV} = 5.8\ ^\circ C .$$

The average gradient between the oil and the HV winding, $AvGra_{HV}$, is:

$$AvGra_{HV} = 2.09 \cdot Gra_{HV} = 2.09 \cdot 5.8 \Rightarrow AvGra_{HV} = 12.1\ ^\circ C .$$

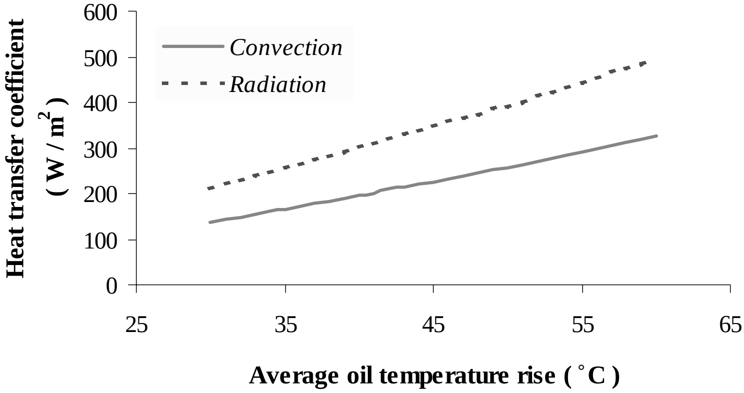

Fig. 2.13 Coefficients (W/m^2) of heat transfer by convection and radiation by transformer tank as a function of average oil temperature rise

3. The maximum gradient is:

$$MaxGra = \max(AvGra_{LV},\ AvGra_{HV}) = \max(10.9,\ 12.1) \Rightarrow MaxGra = 12.1\ ^{\circ}C\ .$$

The average oil temperature rise is:

$$AOR = ACR - MaxGra = 60 - 12.1 \Rightarrow AOR = 47.9\ ^{\circ}C\ .$$

2.16 Calculation of Heat Transfer

The transformer losses appear as heat in the core and coils. This heat must be dissipated without allowing the windings to reach a temperature that will cause excessive deterioration of the insulation (Bean et al. 1959). Rigorous mathematical treatment for expressing transformer heat transfer is quite difficult and hence designers mostly rely on empirical formulas (Flanagan 1993; Kulkarni and Khaparde 2004).

The heat transfer due to transformer tank convection is computed as follows:

$$TCL = TCA \cdot TCC\ , \tag{2.64}$$

where TCA is the tank convection area (m^2) and TCC is the tank convection coefficient (W/m^2), which is derived using Fig. 2.13.

The heat transfer due to transformer tank radiation is:

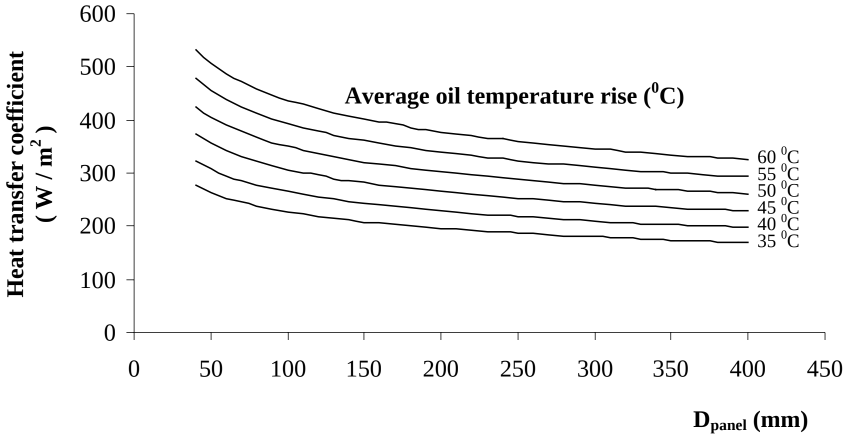

Fig. 2.14 Coefficients (W/m^2) of heat transfer by corrugated panels as a function of D_{panel} as well as a function of average oil temperature rise

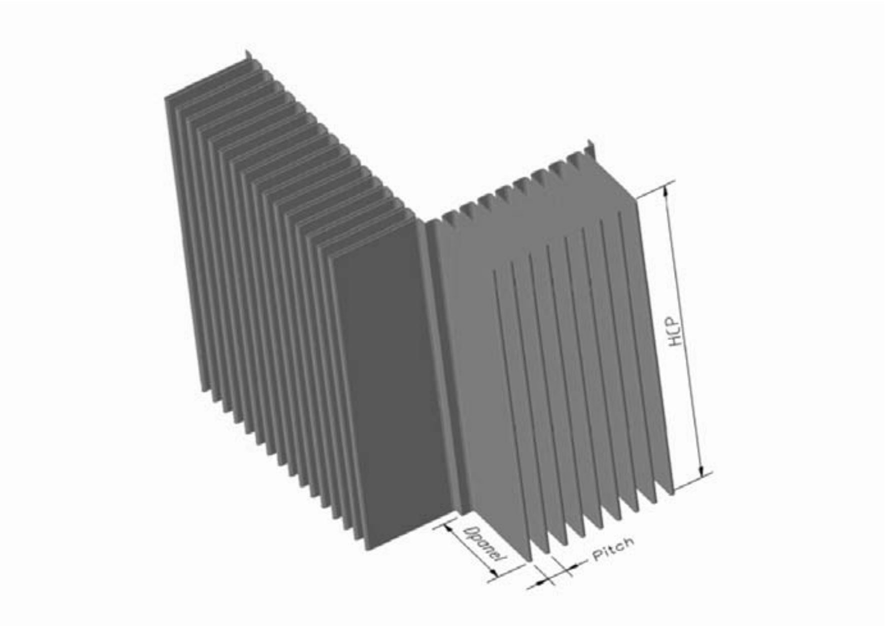

Fig. 2.15 Dimensions of corrugated panels

$$TRL = TRA \cdot TRC\ , \tag{2.65}$$

where *TRA* is the tank radiation area (m^2) and *TRC* is the tank radiation coefficient (W/m^2), which is derived using Fig. 2.13.

The heat transfer through the corrugated panels is computed as follows:

$$CPL = CPA \cdot CPC\ , \tag{2.66}$$

where *CPA* is the corrugated panels area (m^2) and *CPC* is the corrugated panels coefficient (W/m^2), which is derived using Fig. 2.14. The dimensions of the corrugated panels are shown in Fig. 2.15.

The total heat that the transformer can safely transfer is computed as follows:

$$TLRTT = TCL + TRL + CPL\ . \tag{2.67}$$

2.16.1 Example 2.11

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Compute the total heat that can be transferred by the transformer tank.
2. Check if the transformer tank is appropriate for transferring the heat arising from transformer total losses.

Solution

1. Since $AOR = 47.9\ ^0C$, Fig. 2.13 gives $TCC = 244.34\ \mathrm{W/m^2}$ and $TRC = 371.32\ \mathrm{W/m^2}$. Since $AOR = 47.9\ ^0C$ and $D_{Panel} = 220\ \mathrm{mm}$, Fig. 2.14 gives that $CPC = 280.88\ \mathrm{W/m^2}$. Please note that the two digits accuracy of *TCC*, *TRC* and *CPC* is coming from computer simulation.

   The tank convection area is:

$$TCA = 2 \cdot (TL + TW) \cdot TH + 2 \cdot TL \cdot TW = 2 \cdot (1317 + 620) \cdot 1015 + 2 \cdot 1317 \cdot 620 \Rightarrow$$

$$TCA = 5565190\ \mathrm{mm^2} \Rightarrow TCA = 5.57\ \mathrm{m^2}\ .$$

   The heat transfer due to transformer tank convection is computed using (2.64):

$$TCL = TCA \cdot TCC = 5.57 \cdot 244.34 \Rightarrow TCL = 1361\ \mathrm{W}\ .$$

The tank radiation area is computed as follows:

$$TRA = \left[2 \cdot (TL + TW) + 4 \cdot D_{Panel} \cdot \sqrt{2}\right] \cdot OH \Rightarrow$$

$$TRA = \left[2 \cdot (1317 + 620) + 4 \cdot 220 \cdot \sqrt{2}\right] \cdot 1015 = 5195286 \text{ mm}^2 \Rightarrow TRA = 5.2 \text{ m}^2 .$$

The heat transfer due to transformer tank radiation is calculated using (2.65):

$$TRL = TRA \cdot TRC = 5.2 \cdot 371.32 \Rightarrow TRL = 1931 \text{ W} .$$

The transformer is constructed with corrugated panels around the four sides, i.e., across the tank length and tank width. The number of corrugated panels across the tank length, *NCPTL*, is:

$$NCPTL = \text{int}\left[\frac{TL - 60}{Pitch}\right] + 1 = \text{int}\left[\frac{1317 - 60}{44}\right] + 1 = \text{int}[28.57] + 1 \Rightarrow NCPTL = 29 ,$$

where int[*x*] is the integer part of *x*.

The number of corrugated panels across the tank width, *NCPTW*, is:

$$NCPTW = \text{int}\left[\frac{TW - 60}{Pitch}\right] + 1 = \text{int}\left[\frac{620 - 60}{44}\right] + 1 = \text{int}[12.73] + 1 \Rightarrow NCPTW = 13 .$$

The total number of corrugated panels, *NCP*, is:

$$NCP = 2 \cdot (NCPTL + NCPTW) = 2 \cdot (29 + 13) \Rightarrow NCP = 84 .$$

The corrugated panels area, *CPA*, is computed as follows:

$$CPA = 2 \cdot D_{Panel} \cdot HCP \cdot NCP = 2 \cdot 220 \cdot 800 \cdot 84 = 29568000 \Rightarrow CPA = 29.57 \text{ m}^2 .$$

The heat transfer through the corrugated panels is calculated using (2.66):

$$CPL = CPA \cdot CPC = 29.57 \cdot 280.88 \Rightarrow CPL = 8306 \text{ W} .$$

The total heat that the transformer can safely transfer is computed using (2.67):

$$TLRTT = TCL + TRL + CPL = 1361 + 1931 + 8306 \Rightarrow TLRTT = 11598 \text{ W} .$$

2. The transformer total loss, TTL_2, at the minimum high voltage of 6270 V is:

$$TTL_2 = NLL + LL_2 = 1195 + 9688 \Rightarrow TTL_2 = 10883\ \text{W}\ .$$

The transformer tank is appropriate for safely transferring the transformer total losses because:

$$TLRTT > TTL_2 \Rightarrow 11598\ \text{W} > 10883\ \text{W}\ .$$

2.17 Calculation of the Weight of Insulating Materials

Example 2.12 shows how the weight of insulating materials is computed.

2.17.1 Example 2.12

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Compute the total area of each item of insulating material of the LV winding.
2. Compute the total area of each item of insulating material of the HV winding.
3. Calculate the total weight of insulating materials.

Solution

1. The LV winding has the following six insulating materials:
   - Tube paper with thickness 1.5 mm
   - Layer insulation with thickness 0.28 mm
   - End ducts insulation with thickness 0.15 mm
   - Perimetric duct insulation with thickness 0.15 mm
   - Extension paper insulation with thickness 0.41 mm
   - Gap insulation with thickness 0.28 mm

   The area of the tube paper (thickness 1.5 mm), $S_{LV,TP}$, is:

$$S_{LV,TP} = MW \cdot (G - 2 \cdot CCEE) + D3 \cdot \pi \cdot (G - 2 \cdot CCEE) \Rightarrow$$

$$S_{LV,TP} = 201 \cdot (261 - 2 \cdot 3) + 271.34 \cdot \pi \cdot (261 - 2 \cdot 3) = 268627\ \text{mm}^2 \Rightarrow$$

$$S_{LV,TP} = 0.27 \text{ m}^2 .$$

The area of the layer insulation (thickness 0.28 mm), $S_{LV,LI}$, is:

$$S_{LV,LI} = MT_{LV} \cdot (G - 2 \cdot CCEE) \cdot Layers_{LV} = 949.75 \cdot (261 - 2 \cdot 3) \cdot 15 \Rightarrow$$

$$S_{LV,LI} = 3632793 \text{ mm}^2 \Rightarrow S_{LV,LI} = 3.63 \text{ m}^2 .$$

The area of the end ducts insulation (thickness 0.15 mm), $S_{LV,EDI}$, is:

$$S_{LV,EDI} = MW \cdot (G - 2 \cdot CCEE) \cdot Ducts_{LV} \cdot 2 = 201 \cdot (261 - 2 \cdot 3) \cdot 10 \cdot 2 \Rightarrow$$

$$S_{LV,EDI} = 1025100 \text{ mm}^2 \Rightarrow S_{LV,EDI} = 1.03 \text{ m}^2 .$$

The area of perimetric ducts insulation (thickness 0.15 mm), $S_{LV,PDI}$, is:

$$S_{LV,PDI} = D7 \cdot \pi \cdot (G - 2 \cdot CCEE) = 333.29 \cdot \pi \cdot (261 - 2 \cdot 3) \Rightarrow$$

$$S_{LV,PDI} = 267001 \text{ mm}^2 \Rightarrow S_{LV,PDI} = 0.27 \text{ m}^2 .$$

Two extension papers are used. The area of extension paper insulation (thickness 0.41 mm), $S_{LV,EPI}$, is:

$$S_{LV,EPI} = 2 \cdot 2 \cdot \pi \cdot D13 \cdot \left[(G - 2 \cdot CCEE) + 1.8 \cdot BLD_{HV} \right] \Rightarrow$$

$$S_{LV,EPI} = 2 \cdot 2 \cdot \pi \cdot 449.35 \cdot \left[(261 - 2 \cdot 3) + 1.8 \cdot 36.47 \right] = 1810591 \text{ mm}^2 \Rightarrow$$

$$S_{LV,EPI} = 1.81 \text{ m}^2 .$$

Two extension papers with 0.41 mm thickness are used, so the number of papers with thickness 0.28 mm that are used for gap insulation, *NPGI*, is:

$$NPGI = \frac{I_{HV-LV} - 3.3 - 2 \cdot 0.41}{I_{HVL}} = \frac{6.92 - 3.3 - 2 \cdot 0.41}{0.28} \Rightarrow NPGI = 10 .$$

The area of gap insulation (thickness 0.28 mm), $S_{LV,GI}$, is:

$$S_{LV,GI} = D7 \cdot \pi \cdot (G - 2 \cdot CCEE) \cdot NPGI = 333.29 \cdot \pi \cdot (261 - 2 \cdot 3) \cdot 10 \Rightarrow$$

$$S_{LV,GI} = 2670007 \text{ mm}^2 \Rightarrow S_{LV,GI} = 2.67 \text{ m}^2.$$

2. The HV winding has the following six insulating materials:
   – Layer insulation with thickness 0.28 mm
   – End ducts insulation with thickness 0.15 mm
   – Perimetric duct insulation with thickness 0.15 mm
   – Insulation between HV sub-coils with thickness 0.28 mm
   – External gap insulation with thickness 0.28 mm
   – Insulating board paper with thickness 1.5 mm

   The area of the layer insulation (thickness 0.28 mm), $S_{HV,LI}$, is:

$$S_{HV,LI} = MT_{HV} \cdot \left[(G - 2 \cdot CCEE) + 4 \cdot 19\right] \cdot Layers_{HV} \cdot 1.25 \Rightarrow$$

$$S_{HV,LI} = 1251.11 \cdot \left[(261 - 2 \cdot 3) + 4 \cdot 19\right] \cdot 16 \cdot 1.25 = 8282348 \text{ mm}^2 \Rightarrow$$

$$S_{HV,LI} = 8.28 \text{ m}^2.$$

The area of the end ducts insulation (thickness 0.15 mm), $S_{HV,EDI}$, is:

$$S_{HV,EDI} = LG_{HV} \cdot (G - 2 \cdot CCEE) \cdot Ducts_{HV} \cdot 2 = 250.16 \cdot (261 - 2 \cdot 3) \cdot 12 \cdot 2 \Rightarrow$$

$$S_{HV,EDI} = 1530979 \text{ mm}^2 \Rightarrow S_{HV,EDI} = 1.53 \text{ m}^2.$$

The area of perimetric ducts insulation (thickness 0.15 mm), $S_{HV,PDI}$, is:

$$S_{HV,PDI} = D13 \cdot \pi \cdot (G - 2 \cdot CCEE) = 449.35 \cdot \pi \cdot (261 - 2 \cdot 3) \Rightarrow$$

$$S_{HV,PDI} = 359977 \text{ mm}^2 \Rightarrow S_{HV,PDI} = 0.36 \text{ m}^2.$$

Five insulating papers with thickness 0.28 mm are used for insulation between HV sub-coils, so the area of these insulating papers, $S_{HV,Sub}$, is:

$$S_{HV,Sub} = MT_{HV} \cdot (G - 2 \cdot CCEE) \cdot 5 = 1251.11 \cdot (261 - 2 \cdot 3) \cdot 5 = 1595165 \text{ mm}^2 \Rightarrow$$

$$S_{HV,Sub} = 1.60 \text{ m}^2.$$

Two extension papers with 0.41 mm thickness are used, so the number of papers with thickness 0.28 mm that are used for HV gap insulation, *NPEGI*, is:

$$NPEGI = \frac{I_{HV-HV} - 3.3 - 2 \cdot 0.41}{I_{HVL}} = \frac{6.64 - 3.3 - 2 \cdot 0.41}{0.28} \Rightarrow NPEGI = 9 .$$

The area of HV gap insulation (thickness 0.28 mm), $S_{HV,GI}$, is:

$$S_{HV,GI} = D13 \cdot \pi \cdot (G - 2 \cdot CCEE) \cdot NPEGI = 449.35 \cdot \pi \cdot (261 - 2 \cdot 3) \cdot 9 \Rightarrow$$

$$S_{HV,GI} = 3239793 \text{ mm}^2 \Rightarrow S_{HV,GI} = 3.24 \text{ m}^2 .$$

The area of the insulating board paper, $S_{HV,IBP}$, with thickness 1.5 mm that covers a total space of 40 mm is:

$$S_{HV,IBP} = MT_{HV} \cdot 40 \cdot Layers_{HV} = 1251.11 \cdot 40 \cdot 16 = 800710 \text{ mm}^2 \Rightarrow$$

$$S_{HV,IBP} = 0.80 \text{ m}^2 .$$

3. Insulating materials with four different thicknesses are used for the insulation of the LV and HV windings:
   - Insulating material with thickness 1.5 mm
   - Insulating material with thickness 0.41 mm
   - Insulating material with thickness 0.28 mm
   - Insulating material with thickness 0.15 mm

   The weight of the insulating material with thickness 1.5 mm, $WIM_{1.5}$, is:

$$WIM_{1.5} = 3 \cdot 1.1 \cdot 1.95 \cdot (S_{LV,TP} + S_{HV,IBP}) = 3 \cdot 1.1 \cdot \left[1.95 \frac{\text{kg}}{\text{m}^2}\right] \cdot \left[(0.27 + 0.80) \text{ m}^2\right] \Rightarrow$$

$$WIM_{1.5} = 6.89 \text{ kg} .$$

The weight of the insulating material with thickness 0.41 mm, $WIM_{0.41}$, is:

$$WIM_{0.41} = 3 \cdot 1.1 \cdot 0.37 \cdot S_{LV,EPI} = 3 \cdot 1.1 \cdot \left[0.37 \frac{\text{kg}}{\text{m}^2}\right] \cdot (1.81 \text{ m}^2) \Rightarrow WIM_{0.41} = 2.21 \text{ kg} .$$

The weight of the insulating material with thickness 0.28 mm, $WIM_{0.28}$, is:

$$WIM_{0.28} = 3 \cdot 1.1 \cdot 0.26 \cdot (S_{LV,LI} + S_{LV,GI} + S_{HV,LI} + S_{HV,Sub} + S_{HV,GI}) \Rightarrow$$

$$WIM_{0.28} = 3 \cdot 1.1 \cdot \left[0.26 \frac{\text{kg}}{\text{m}^2} \right] \cdot \left[(3.63 + 2.67 + 8.28 + 1.60 + 3.24)\ \text{m}^2 \right] \Rightarrow$$

$$WIM_{0.28} = 16.66\ \text{kg}\ .$$

The weight of the insulating material with thickness 0.15 mm, $WIM_{0.15}$, is:

$$WIM_{0.15} = 3 \cdot 1.1 \cdot 0.13 \cdot (S_{LV,EDI} + S_{LV,PDI} + S_{HV,EDI} + S_{HV,PDI}) \Rightarrow$$

$$WIM_{0.15} = 3 \cdot 1.1 \cdot \left[0.13 \frac{\text{kg}}{\text{m}^2} \right] \cdot \left[(1.03 + 0.27 + 1.53 + 0.36)\ \text{m}^2 \right] \Rightarrow WIM_{0.15} = 1.37\ \text{kg}\ .$$

The total weight of the insulating materials, w_4, is:

$$w_4 = WIM_{1.5} + WIM_{0.41} + WIM_{0.28} + WIM_{0.15} = 6.89 + 2.21 + 16.66 + 1.37 \Rightarrow$$

$$w_4 = 27.13\ \text{kg}\ .$$

2.18 Calculation of the Weight of Ducts

Example 2.13 shows how the weight of the ducts is computed.

2.18.1 Example 2.13

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the weight of duct strips.

Solution

The number of duct strips for the LV winding, N_1, is:

$$N_1 = \frac{MW}{DWPG_{LV}} \cdot Ducts_{LV} \cdot 2 = \frac{201}{25} \cdot 10 \cdot 2 \Rightarrow N_1 = 161\ .$$

The number of perimetric duct strips for the LV winding, N_2, is:

$$N_2 = \frac{\pi \cdot D7}{DWPG_{LV}} = \frac{\pi \cdot 333.29}{25} \Rightarrow N_2 = 42 .$$

The number of duct strips for the HV winding, N_3, is:

$$N_3 = \frac{(MW + 2 \cdot BLD_{LV})}{DWPG_{HV}} \cdot Ducts_{HV} \cdot 2 = \frac{(201 + 2 \cdot 17.66)}{35} \cdot 12 \cdot 2 \Rightarrow N_3 = 162 .$$

The number of perimetric duct strips for the HV winding, N_4, is:

$$N_4 = \frac{\pi \cdot D13}{DWPG_{HV}} = \frac{\pi \cdot 449.35}{35} \Rightarrow N_4 = 40 .$$

The total weight of duct strips, w_5, is:

$$w_5 = 3 \cdot 1.1 \cdot g_{DS} \cdot \left[(N_1 + N_2 + N_3 + N_4) \cdot (G - 2 \cdot CCEE) \cdot D_W \cdot T_{DS} \right] \Rightarrow$$

$$w_5 = 3 \cdot 1.1 \cdot \left[1.25 \frac{\text{kg}}{\text{m}^3} \right] \cdot \left[(161 + 42 + 162 + 40) \cdot (261 - 2 \cdot 3) \cdot 15 \cdot 3 \right] \Rightarrow$$

$$w_5 = 3 \cdot 1.1 \cdot \left[1.25 \frac{\text{kg}}{\text{m}^3} \right] \cdot \left[4647375 \text{ mm}^3 \right] = 3 \cdot 1.1 \cdot \left[1.25 \frac{\text{kg}}{\text{m}^3} \right] \cdot \left[4.65 \text{ m}^3 \right] \Rightarrow$$

$$w_5 = 19.18 \text{ kg} .$$

2.19 Calculation of the Weight of Oil

Example 2.14 shows how the weight of the oil is computed.

2.19.1 Example 2.14

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the weight of the mineral oil.

Solution

The volume of corrugated panels, V_{CP}, is:

$$V_{CP} = 8 \cdot HCP \cdot D_{Panel} \cdot NCP = 8 \cdot 800 \cdot 220 \cdot 84 = 118272000 \text{ mm}^3 \Rightarrow V_{CP} = 118.27 \text{ L} .$$

The volume of the LV and HV windings, V_{Wd}, is:

$$V_{Wd} = \frac{w_1 + w_2}{g_{LV}} = \frac{(76 + 124.4)\ \text{kg}}{8856\ \frac{\text{kg}}{\text{m}^3}} = 0.02263\ \text{m}^3 \Rightarrow V_{Wd} = 22.63\ \text{L}\ .$$

The volume of magnetic material, V_{MM}, is:

$$V_{MM} = \frac{w_3}{g_{MM}} = \frac{639\ \text{kg}}{7650\ \frac{\text{kg}}{\text{m}^3}} = 0.08353\ \text{m}^3 \Rightarrow V_{MM} = 83.53\ \text{L}\ .$$

The volume of the tank, V_T, is:

$$V_T = TL \cdot TW \cdot OH = 1317 \cdot 620 \cdot 1015 = 828788100\ \text{mm}^3 \Rightarrow V_T = 828.79\ \text{L}\ .$$

The volume of mineral oil, V_O, is:

$$V_O = V_T + V_{CT} + V_{CP} - V_{Wd} - V_{MM} = 828.79 + 25 + 118.27 - 22.63 - 83.53 \Rightarrow$$

$$V_O = 865.9\ \text{L} \Rightarrow V_O = 0.866\ \text{m}^3\ .$$

The total weight of mineral oil, w_6, is:

$$w_6 = 0.95 \cdot g_O \cdot V_O = 0.95 \cdot \left[870\ \frac{\text{kg}}{\text{m}^3}\right] \cdot (0.866\ \text{m}^3) \Rightarrow w_6 = 715.75\ \text{kg}\ .$$

2.20 Calculation of the Weight of Sheet Steel

Sheet steel is used for the construction of:

1. The tank
2. The oil conservator
3. The frame that supports the active part of the transformer

An accurate estimate of the weight of the sheet steel can be obtained only after completion of the transformer constructional drawings. However, during the transformer design phase, approximate formulas are used to compute the total weight of the sheet steel.

2.20.1 Example 2.15

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the weight of the sheet steel.

Solution

Using approximate formulas, the total weight of the sheet steel, w_7, is:

$$w_7 = 217.2\ \text{kg}\ .$$

2.21 Calculation of the Weight of Corrugated Panels

Example 2.16 shows how the weight of the corrugated panels is computed.

2.21.1 Example 2.16

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the weight of the corrugated panels.

Solution

The total weight of corrugated panels, w_8, is:

$$w_8 = g_{CP} \cdot CPA = \left[9.87\ \frac{\text{kg}}{\text{m}^2} \right] \cdot (29.57\ \text{m}^2) \Rightarrow w_8 = 291.86\ \text{kg}\ .$$

2.22 Calculation of the Cost of Transformer Main Materials

The cost of transformer main materials is computed as follows:

$$CMM = \sum_{i=1}^{8} uc_i \cdot w_i\ . \tag{2.68}$$

2.22.1 Example 2.17

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12. Compute the cost of transformer main materials.

Solution

The cost of the LV winding, C_1, is:

$$C_1 = uc_1 \cdot w_1 = \left[12.01 \frac{\$}{\text{kg}}\right] \cdot (76 \text{ kg}) \Rightarrow C_1 = \$\,912.76\,.$$

The cost of the HV winding, C_2, is:

$$C_2 = uc_2 \cdot w_2 = \left[12.01 \frac{\$}{\text{kg}}\right] \cdot (124.4 \text{ kg}) \Rightarrow C_2 = \$\,1494.04\,.$$

The cost of magnetic material, C_3, is:

$$C_3 = uc_3 \cdot w_3 = \left[6.01 \frac{\$}{\text{kg}}\right] \cdot (639 \text{ kg}) \Rightarrow C_3 = \$\,3840.39\,.$$

The cost of insulating materials, C_4, is:

$$C_4 = uc_4 \cdot w_4 = \left[7.72 \frac{\$}{\text{kg}}\right] \cdot (27.13 \text{ kg}) \Rightarrow C_4 = \$\,209.44\,.$$

The cost of duct strips, C_5, is:

$$C_5 = uc_5 \cdot w_5 = \left[8.58 \frac{\$}{\text{kg}}\right] \cdot (19.18 \text{ kg}) \Rightarrow C_5 = \$\,164.56\,.$$

The cost of mineral oil, C_6, is:

$$C_6 = uc_6 \cdot w_6 = \left[1.72 \frac{\$}{\text{kg}}\right] \cdot (715.75 \text{ kg}) \Rightarrow C_6 = \$\,1231.09\,.$$

The cost of sheet steel, C_7, is:

$$C_7 = uc_7 \cdot w_7 = \left[1.03 \frac{\$}{\text{kg}}\right] \cdot (217.2 \text{ kg}) \Rightarrow C_7 = \$\,223.72\,.$$

The cost of corrugated panels, C_8, is:

$$C_8 = uc_8 \cdot w_8 = \left[1.20\ \frac{\$}{\text{kg}}\right] \cdot (291.86\ \text{kg}) \Rightarrow C_8 = \$\,350.23\,.$$

The cost of transformer main materials, *CMM*, is:

$$CMM = \sum_{i=1}^{8} C_i \Rightarrow$$

$$CMM = 912.76 + 1494.04 + 3840.39 + 209.44 + 164.56 + 1231.09 + 223.72 + 350.23 \Rightarrow$$

$$CMM = \$\,8426.23\,.$$

2.23 Calculation of Transformer Manufacturing Cost

The transformer materials cost is:

$$CM = CMM + CRM\,. \tag{2.69}$$

The transformer manufacturing cost is:

$$CTM = CM + C_{Lab}\,. \tag{2.70}$$

The transformer bid price (also called sales price or purchasing price) is:

$$BP = \frac{CTM}{1 - SM}\,. \tag{2.71}$$

The sales margin of the transformer is:

$$MS = BP - CTM\,. \tag{2.72}$$

The transformer total owning cost is:

$$TOC = BP + A \cdot NLL + B \cdot LL\,, \tag{2.73}$$

where LL is the transformer load loss.

2.23.1 Example 2.18

It is desired to design a 630 kVA distribution transformer having the input data shown in Tables 2.6 to 2.12.

1. Compute the cost of transformer materials.
2. Compute the transformer manufacturing cost.
3. Compute the transformer sales price.
4. Calculate the transformer total owning cost.

Solution

1. The cost of transformer materials, *CM*, is computed using (2.69):

$$CM = CMM + CRM = 8426.23 + 1236 \Rightarrow CM = \$\,9662.23\,.$$

2. The transformer manufacturing cost, *CTM*, is computed using (2.70):

$$CTM = CM + C_{Lab} = 9662.23 + 4541 \Rightarrow CTM = \$\,14203.23\,.$$

3. The transformer bid price, *BP*, is calculated using (2.71):

$$BP = \frac{CTM}{1 - SM} = \frac{14203.23}{1 - 0.35} \Rightarrow BP = \$\,21851.12\,.$$

The sales margin of the transformer, *MS*, is:

$$MS = BP - CTM = 21851.12 - 14203.23 \Rightarrow MS = \$\,7647.89\,.$$

4. The transformer total owning cost, *TOC*, is:

$$TOC = BP + A \cdot NLL + B \cdot LL_1 = 21851.12 + 13.39 \cdot 1195 + 2.09 \cdot 9388 \Rightarrow$$

$$TOC = \$\,57473.09\,.$$

Figure 2.16 shows the transformer cost components and the transformer bid price.

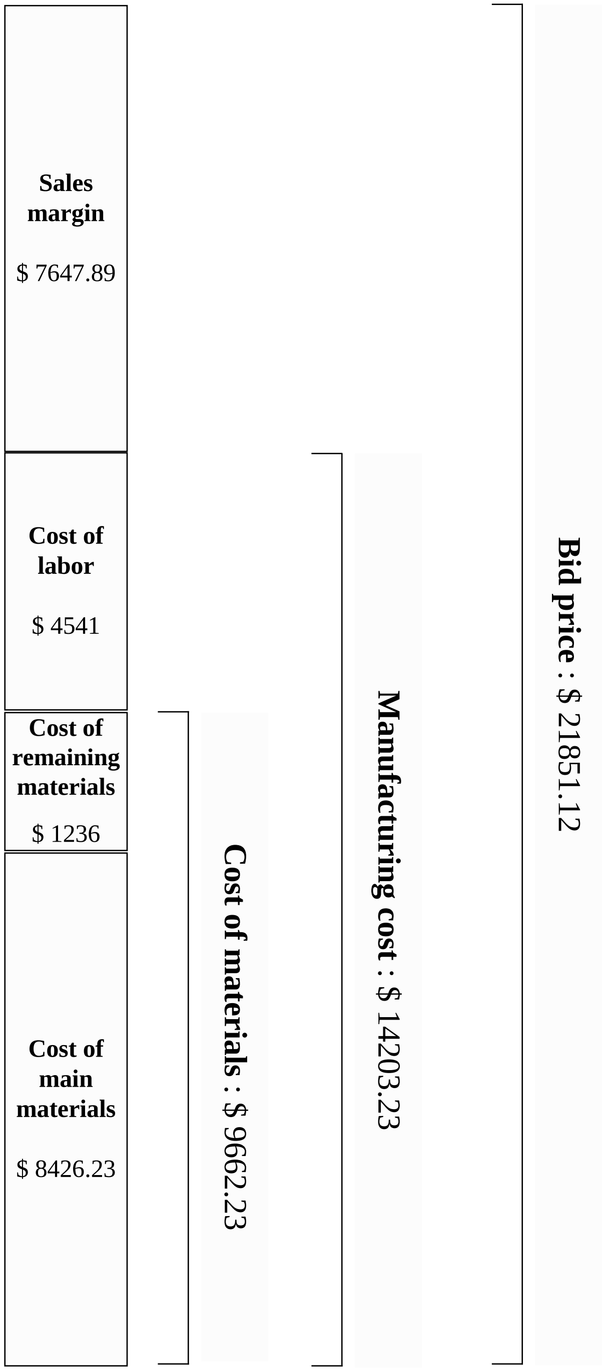

Fig. 2.16 Transformer cost components and bid price

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