Effect of design parameters on temperature rise of windings of dry type electrical transformer

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Abstract

The hot spot temperature and the average temperature rise of windings have been analyzed for a naturally cooled dry type electrical transformer consisting of low voltage (LV) cross-matic and high voltage (HV) disc type windings using computational fluid dynamics technique. The fluid flow in winding's duct and temperature distribution in windings have been computed by solving continuity, momentum and energy equations using finite volume based CFD code. The CFD model has been compared with experimental results. The CFD model has been used to study the effects of various design parameters influencing winding's temperature for better understanding of its thermal behaviour. The results of parametric studies have been used to develop empirical correlations for predicting average and hot spot temperature rise of windings. The coefficients of empirical correlations for LV and HV windings have been generated using constrained optimization method.

Keywords: Dry type transformer; thermal; CFD simulation; LV; HV; cross-matic; disc windings

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Nomenclature

ATHV	average temperature rise of HV windings, K
ATLV	average temperature rise of LV windings, K
CFD	computational fluid dynamics
HSLV1	hot spot temperature rise of LV layer 1 windings, K
HSLV2	hot spot temperature rise of LV layer 2 windings, K
HSHV	hot spot temperature rise of HV windings, K
HV	high voltage
k_y	thermal conductivity in radial direction, W/(m-K)
k_z	thermal conductivity in axial direction, W/(m-K)
LV	low voltage
PHOENICS	parabolic, hyperbolic or elliptic numerical integration code series
U	vector velocity, m/s
S_ϕ	source term

Greek

ρ	density, kg/m^3
ϕ	general flow variables such as velocity & temperature
Γ_ϕ	diffusive exchange coefficient for flow variable

Abbreviation

Temp	temperature, ^{o}C

1. Introduction

The reliability of a dry type electrical transformer depends on its ability to dissipate the internally generated heat from the windings to the surroundings. The temperature distribution within a transformer depends on its detailed construction, eddy current losses in windings and thermal environment in which the transformer is operating. The transformer usually consists of three limbs (phases), each limb corresponding to one phase is separated by phase barriers as shown in Fig. 1 [1]. It is enclosed in a tank, which is ventilated at the bottom and at the top, as shown in Fig. 2. Each limb consists of a number of concentric cylinders & windings. The inner most part is the core. It is surrounded by a LV cylinder, which is made up of an insulating material such as fibre glass, LV windings, which generally consist of two layers, a HV cylinder, which is an insulating cylinder and HV windings. A schematic diagram of arrangements of core, LV cylinder, LV windings, HV cylinder, and HV windings is shown in Fig. 3. Each part is separated from the other by means of insulated vertical strips, which are located at a particular pitch around the circumference. These strips form vertical ducts for air flow. Each winding (LV or HV) consists of individual discs arranged vertically and separated from each other by means of horizontal spacer blocks. The disc consists of copper insulated by nomex paper on all sides with a specified thickness. The naturally cooled dry type transformer employs air as the cooling medium. The ambient air enters the transformer tank at the bottom, picks up heat from windings, moves up through the vertical ducts because of buoyancy forces and leaves into the atmosphere from the top. The cooling capacity of air is limited due to its low heat capacity, therefore, the hot spot temperature rise of windings and the average windings temperature rise are two important design parameters of a transformer because the life expectancy, safety and permissible over loads depend upon these factors. The hot spot and the average temperature rise of windings depend on many design and construction parameters of a dry type transformer, which a thermal engineer wants to know a priori. The transformer's manufacturers use some standard design curves or thermal network method to estimate temperature rise in the windings. Using the standard curves, the average temperature rise in windings can be estimated, but hot spot and its location cannot be determined for any new design.

There are a few theoretical and experimental studies on hot spot temperature prediction and average temperature calculation of windings for dry type transformer. Halacsy [2] presented a simplified analytical model for predicting average temperature rise of dry type transformer windings. Satterlee [3] conducted experimental studies on dry type air cooled transformers and reported that the hot spot temperature is located at a distance of 10-15% below the top of the windings. Stewart and Whitman [4] conducted a series of thermal tests on a variety of dry type transformer coils and found that the hot spot is located at some points from 75-95% of the windings height, being higher for taller coils. Based on a number thermal tests of ventilated dry type transformers, Whitman [5] reported that the temperature gradient of windings is affected by amount & type of turn, insulation layer, vertical height of the windings, radial build of the windings and ventilating ducts in the windings. Pierce [6, 7] developed a mathematical model to predict hot spot temperature rise in ventilated dry type transformer. The model has been used to study the effects of various parameters on the ratio of hottest spot to average windings temperature rise. The number of conductor layers, insulation thickness and conductor strand size were found to have only a minor effect on the ratio. The windings height was found to be main parameter influencing this ratio. The model predicts hot spot temperature in layer type windings.

Literature reviews reveal that most of the studies are based on analytical or experimental approach or both. There are a very few numerical simulation studies available on dry type transformer, which can provide more detailed information, e.g. location and value of hot spots in LV layer 1, LV layer 2 and HV windings, therefore a CFD model is needed for temperature prediction, which can also be used for parametric simulation studies to evaluate the effects of input design parameters on hot spot and average temperature rise for an efficient thermal design.

2. System configuration and model development

A naturally cooled dry type transformer consisting of cross-matic type LV windings and disc type HV windings has been considered for investigation as shown schematically in Fig. 4. It has 7 discs (turns) in LV windings and 44 discs in HV windings, which are arranged vertically. LV windings consist of two layers and HV windings consist of one layer. LV and HV windings generate heat under operating condition. Heat is transferred in the conductor by conduction and from the conductor surface it is convected and radiated between surfaces. Top few windings radiate heat to ambient air. A finite volume based CFD model has been developed to simulate fluid flow and temperature distribution in the windings using PHOENICS CFD code to identify the location of hot spot as well as to understand heat transfer characteristics of windings for different design specifications and operating conditions. The general conservation equations of continuity, momentum & energy have been solved to compute velocity and temperature field in the geometrical domain. The generalized form of transport equation governing fluid flow and heat transfer can be expressed as follows [8]:

$$\frac{\partial\,(\rho\phi)}{\partial t} + \frac{\partial}{\partial x_k}\left[\rho U\phi - \Gamma_\phi \frac{\partial \phi}{\partial x_k}\right] = S_\phi \qquad (1)$$

2.1 Modeling considerations

The following considerations have been taken into account for modeling dry type transformer under natural convection:

- From symmetry considerations, one quarter of center phase consisting of LV and HV windings is considered in cylindrical-polar co-ordinate, assuming that similar behaviour occurs in all the three phases [1]. Grids have been varied in radial (y-axis) and axial (z-axis) direction. The numbers of grids in radial and axial directions are 30 & 135 respectively. There is no variation of grid in circumferential direction (x-axis).

- The phase barrier is ignored to reduce the domain size and computation time.
- The windings have been modeled as a blockage obstructing flow path and generating heat source. Irrespective of the construction and type of the windings, all the windings are considered to be discontinuous discs. The effect of construction of the windings is taken care of by incorporating appropriate value of equivalent thermal conductivity in radial and axial directions, based on electrical analogy [6].
- Heat transfer by conduction, convection, and radiation has been considered in addition to buoyancy effect. The radiation model solves energy transport in solids by conduction and that within the space between solids by radiation. Emissivity has been assumed to be 0.3 for mild steel wall placed at the edge of the domain to incorporate the enclosure effect of tank wall and it is 0.9 on all other surfaces. The enclosure wall loses heat by convection and radiation.
- Air properties have varied according to ideal gas law, in which density & viscosity vary with temperature and specific heat and conductivity are constant.
- Various simulation studies were conducted with core losses taken into account and it was observed that due to core losses, surrounding air temperature increases. To simplify the model, air inlet temperature at the entrance of transformer has been considered 5 ^{o}C higher than ambient temperature.

3. Simulation and experimental study

The simulation study reveals that the air flow is more predominant in the vertical duct as compared to the horizontal duct. Fig. 5 shows axial temperature variation along its height at the centre of windings in LV layer 1 and air temperature at the midpoint of the vertical duct located between the two layers of LV windings. The temperature curve of windings is staircase in nature due to horizontal air ducts between windings. The winding temperature increases as the vertical height increases which is due to rise in the temperature of air because it picks up heat from lower windings and moves up at higher temperature due to buoyancy forces. The similar thermal behaviour has been observed in LV layer 2 winding. Fig. 6 shows temperature variation at the centre of HV windings along its height. The staircase effect is not predominant in the temperature curve as observed in LV windings because the radial depth of HV windings is approximately 4 times more than that of the radial depth of LV windings and the air entrapped between windings remain at nearly windings temperature. The temperature of windings increases gradually along its height and it starts decreasing after reaching first peak because there is no heat flux in 21st to 24th conductor due to minimum tapping condition which is used for voltage regulation, again it starts increasing from 25th conductor and reaches a second peak (maximum value) and at the end it starts decreasing as few windings located at the top are cooled by convection and radiation under ambient condition. The location of hot spot in LV windings was found to be at 89 % of windings height and that of HV windings at 67.80 % of windings height, which are approximately close to the locations reported by Satterlee [3] and Stewart et al [4].

A comparison of hot spot temperature rise and average winding temperature rise predicted from CFD simulation and that of obtained from experiment for naturally cooled dry type transformer is presented in Table 1. The hot spot temperature rise of LV windings and the average temperature rise of HV windings predicted from CFD simulation were found to be 133.1 K & 94.3 K and the corresponding experimental results obtained from heat run test were found to be 128.2 K and 93.9 K, respectively. There was a deviation of 3.8 % in the case of hot spot temperature rise of LV windings and 0.45 % in the case of average temperature rise of HV windings.

Using the CFD model, the following constructional and operating parameters of LV and HV windings have been varied to understand the heat transfer behaviour of dry type transformer:

- Radial depth
- Heat load
- Inner radius
- Thermal conductivity

The following assumptions have been considered in the parametric studies:

i. Total number of discs in each layer is constant
ii. The number of layers (turns) in a single disc is constant
iii. Heat losses in all the discs of both LV and HV windings are varied in the same proportion to ensure that distribution of the losses remain the same, if the heat loss in LV winding has been increased by 5 %, the heat loss in HV winding has been also been increased by 5 %.

4. Results & discussions

Various simulation studies have been conducted using the CFD model to study the effects of variation in input design parameters on hot spot temperature and average temperature rise of LV and HV windings. The results of parametric studies have been used for developing empirical correlations for temperature prediction of windings.

4.1 Effect of radial depth of LV windings

Fig. 7 shows effect of variation of thickness of LV windings on windings temperature. As the radial build up of LV windings increases, the average and hot spot temperature rise of LV windings increases, which may be due to increase in thermal resistance of windings as well as reduction in vertical duct width, which reduces mass flux of cooling fluid. Increase in the radial depth of LV windings from 5 mm to 13 mm has resulted in increase of average temperature of LV windings by 10.7 % and that of hot spot temperature of LV layer1 & LV layer 2 in the range of 12.2 to 12.7 %. The hot spot and average temperature rise of HV windings increases marginally as the LV windings shift towards HV windings.

4.2 Effect of radial depth of HV windings

With the increase in the radial depth of HV windings it has been observed that the average temperature rise of HV windings remains more or less the same, however its hot spot temperature rise increases gradually. The result obtained is shown in Fig. 8, which reveals that the increase in the surface area of windings in horizontal direction does not help in cooling but the increase in the radial depth of HV windings may increase its thermal resistance due to which hot spot temperature increases. Increase in radial depth of HV windings from 25 mm to 60 mm has resulted in the increase of hot spot temperature rise from 121.5 K to 130.6 K, whereas the average temperature rise remained around 96 K.

Increase in the radial depth of HV windings decreased the average temperature rise and hot spot temperature rise of LV windings in the range of 2.5 to 3 %. The decrease in temperature of LV windings may be attributed to the reduction in radiation heat flux of HV cylinder radiated towards surrounding of LV windings.

4.3 Effect of heat load

It has been observed that there is a direct effect of heat load on LV and HV windings, i.e., with the increase in heat load of LV or HV windings, the average temperature and the hot spot temperature rise of corresponding windings increase. There is marginal effect of heat load on one winding on other, i.e., increase in the heat load of HV windings (e.g. 10 %) keeping the heat load of LV windings constant, results in the marginal increase of hot spot temperature rise (e.g. 1 %) and average temperature rise (0.7-0.8 %) of LV windings. Fig. 9 & Fig. 10 show effects of heat load on LV and HV windings, respectively.

4.4 Effect of thermal conductivity

Table 2 shows effect of thermal conductivity on temperature rise of windings. With the increase in thermal conductivity of HV windings, the hot spot and average winding temperature rise decreases due to reduction of thermal gradient in the windings. The simulation study reveals that that by increasing thermal conductivity 25 % in radial direction, the hot spot temperature rise of HV windings has been decreased by 2.5 % and the average winding temperature rise has been decreased by 0.85 %.

4.5 Effect of inner radius

Fig. 11 shows effect of inner radius on windings temperature. With the increase in the inner radius, the hot spot and the average temperature rise of LV and HV windings temperature decrease. Increase in inner radius from 130.5 mm to 160.5 mm has resulted in reduction of temperature of HV windings by around 8 % and that of LV windings by around 12 %. As the inner radius increases, the surface area of winding increases which in turn enhances heat transfer rate from windings.

4.6 Empirical correlations for LV and HV windings

Based on various simulation studies, empirical correlations have been developed for predicting temperature rise of windings. The general characteristics equation for LV windings is determined as:

$$Y = C0 + C1X1 + C2X2 + C3X3 + C4X4 + C5X5 + C6X6 + C7X7 + C8X8 + C9X9 + C10X10 \qquad (2)$$

Where Y is the output (hot spot/average windings temperature rise), X1, X2, X3,....X10 are the input design parameters and C0, C1, C2, C3, C4, C5, ... C10 are the coefficients.

The input design parameters for LV windings of dry type transformer are as follows:

X1 = Radial depth of LV windings [mm]
X2 = Mean radius of LV layer 1 [mm]
X3 = Mean radius of LV layer 2 [mm]
X4 = Height of LV windings [mm]
X5 = k_z/k_y
X6 = Horizontal duct width in LV windings [mm]
X7 = Inner duct width of LV layer 1 [mm]
X8 = Outer duct width of LV layer 1 [mm]
X9 = Outer duct width of LV layer 2 [mm]
X10 = Heat loss (LV) [W]

The above mentioned design parameters have been varied in simulation studies to get the hot spot and average temperature rise of windings under various design conditions. Based on the simulation results, the coefficients of design parameters have been generated using NPSOL, a set of FORTRAN subroutine designed to minimize a smooth nonlinear function (objective function) with constraints [9]. The objective function (Φ) is taken as the sum of square of error terms, i.e.

$$\Phi = \sum\{(C0 + C1X1i + C2X2i + \ldots\ldots.CnXni) - Yi\}^2$$

All the coefficients (C0, C1, C2, …. Cn) are determined such that the value of Φ is minimum. The coefficients of LV windings determined from constrained optimization method are given in Table 3.

For HV windings the characteristics equation is determined as:

$$Y = C0 + C1X1 + C2X2 + C3X3 + C4X4 + C5X5 + C6X6 + C7X7 + C8X8 \qquad (3)$$

Where Y is the output (hot spot/average windings temperature rise), X1, X2, X3,....X8 are the input design parameters and C0, C1, C2, C3, C4, C5, ... C8 are the coefficients.

The input design parameters for HV windings are as follows:

X1 = Mean radius of HV windings [mm]

X2 = Radial depth of HV windings [mm]

X3 = k_z/k_y

X4 = Horizontal duct width in HV windings [mm]

X5 = Inner duct width of HV windings [mm]

X6 = Outer duct width of HV windings [mm]

X7 = Height of HV windings [mm]

X8 = Heat loss (HV) [W]

The coefficients of HV windings determined from constrained optimization method are given in Table 4.

The empirical correlations for LV and HV windings serve as design tool for quick estimation of hot spot and average temperature rise of dry type transformer having LV as crossmatic type windings and HV as disc type windings.

5. Conclusions

A CFD model has been developed to determine hot spot and average winding temperature rise of LV and HV windings of a dry type transformer. The hot spot temperature has been found in first layer of LV windings. The location and value of hot spot temperature and average temperature rise are in agreement with the literature and experiment. The CFD model has been used for parametric studies for better understanding of heat transfer characteristics of windings under different design and operating conditions. From parametric studies empirical correlations have been developed to compute average and hot spot temperature rise of LV and HV windings, which can be used as a design tool for thermal engineer. The accuracy of CFD model can be further improved by including core losses and heat load in windings varying with temperature, which is suggested as future work.

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References

1. Foster Derek R., Dry-Type disc wound transformers in medium voltage applications, http://www.olsun.com/Disc%20Wound%20Transformers.pdf.

2. Halacsy A. A., Temperature rise of dry type transformers, AIEE Transactions, Vol. 77, Part III, (1958) 456-462.

3. Satterlee W.W., Design and operating characteristics of modern dry type air cooled transformers, AIEE Transactions, Vol. 63, (1944) 701-704.

4. Stewart H. C. and Whitman L. C., Hot spot temperatures in dry type transformer windings, AIEE Transactions, Vol. 63, (1944) 763-768.

5. Whitman L. C., Coordination of dry type transformer models with transformer geometry, AIEE Transactions, Vol. 75, part III, (1956) 328-332.

6. Pierce Linden W., Predicting hottest spot temperatures in ventilated dry type transformer windings, IEEE Transactions on Power Delivery, Vol. 9, No. 2, (1994) 1160-1172.

7. Pierce Linden W., Hottest spot temperatures in ventilated dry type transformers, IEEE Transactions on Power Delivery, Vol. 9, No. 1, (1994) 257-264.

8. Spalding D.B., The mathematical basis of PHOENICS, PHOENICS 3.5 manual, CHAM, UK , http://www.cham.co.uk/phoenics/d_polis/d_lecs/general/maths.htm, 2003.

9. NPSOL, http://www.sbsi-sol-optimize.com/asp/sol_product_npsol.htm.

Figure Caption:

Fig.1: Windings of a dry type transformer

Fig. 2: A schematic diagram of dry type transformer

Fig. 3: A schematic diagram of windings arrangement in dry type transformer

Fig. 4: A schematic diagram of LV & HV windings

Fig. 5: Temperature distribution in LV layer 1 winding and vertical duct

Fig. 6: Temperature distribution in HV windings

Fig. 7: Effect of radial depth of LV winding on windings temperature

Fig. 8: Effect of radial depth of HV winding on windings temperature

Fig. 9: Effect of heat load on temperature rise of LV windings

Fig. 10: Effect of heat load on temperature rise of HV windings

Fig. 11: Effect of inner radius on windings temperature

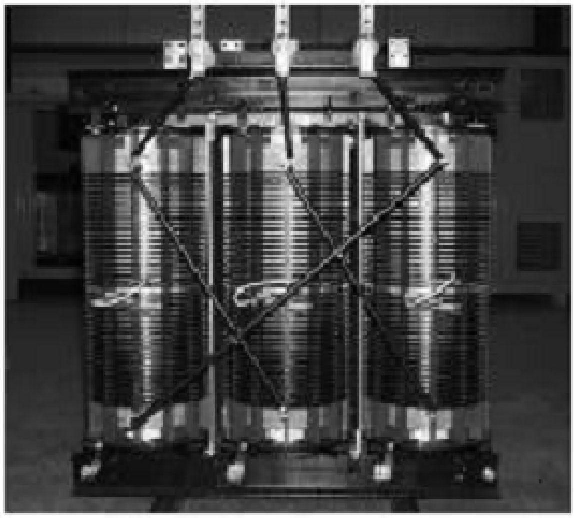


Fig. 1: Windings of a dry type transformer [1]

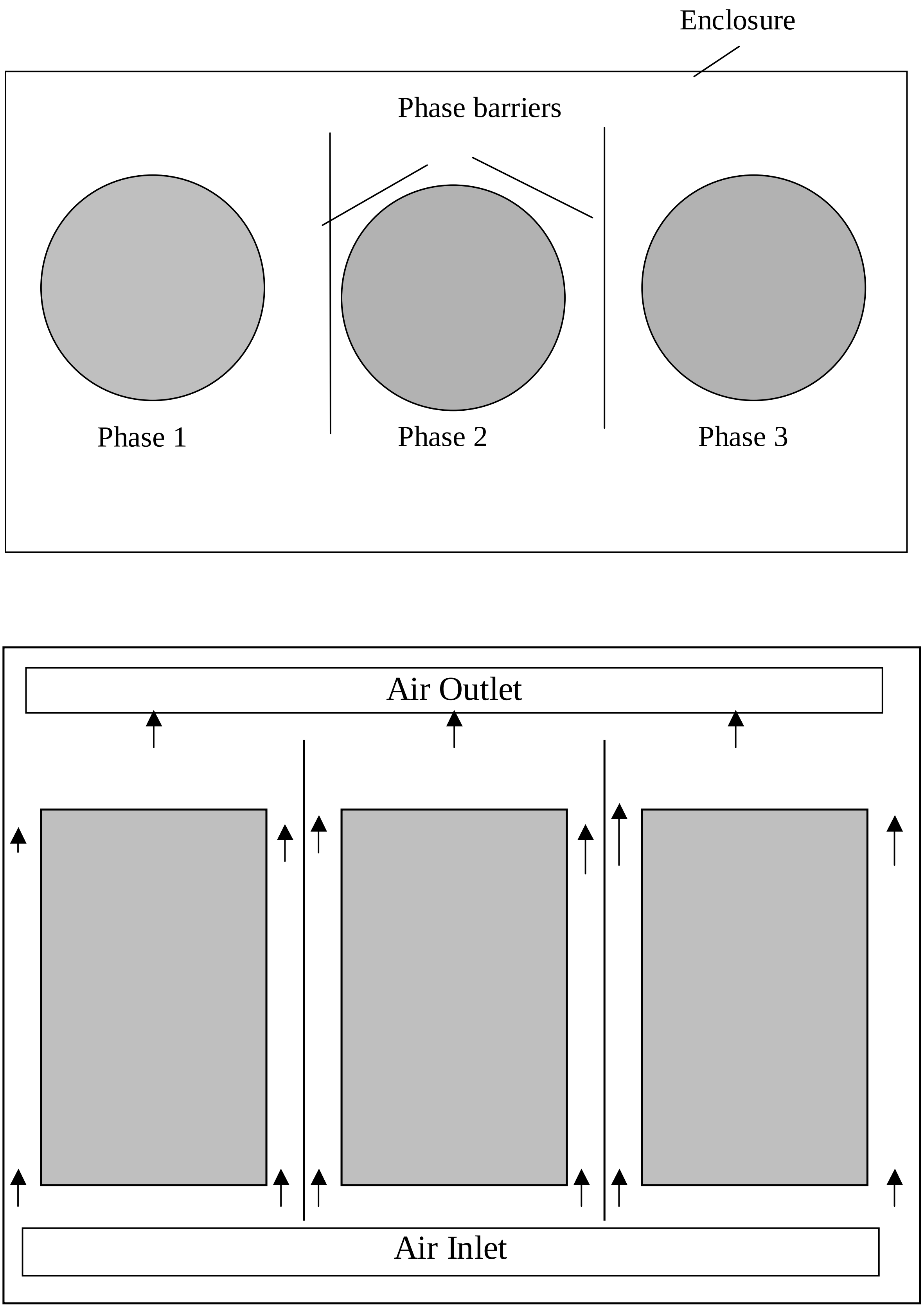
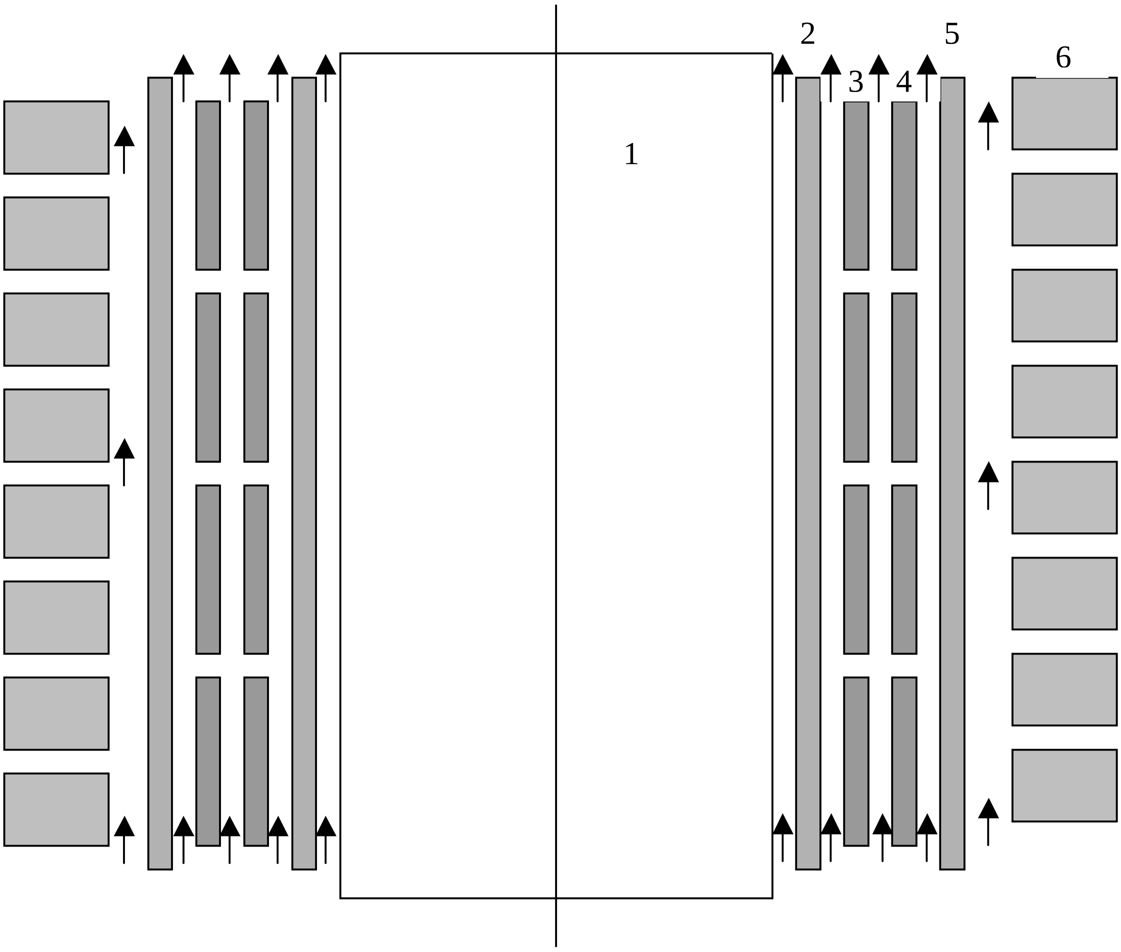


Fig. 2: A schematic diagram of dry type transformer



1	Core
2	LV cylinder (insulating)
3	LV windings layer 1
4	LV windings layer 2
5	HV cylinder (insulating)
6	HV windings

Fig. 3: A schematic diagram of windings arrangement in dry type transformer

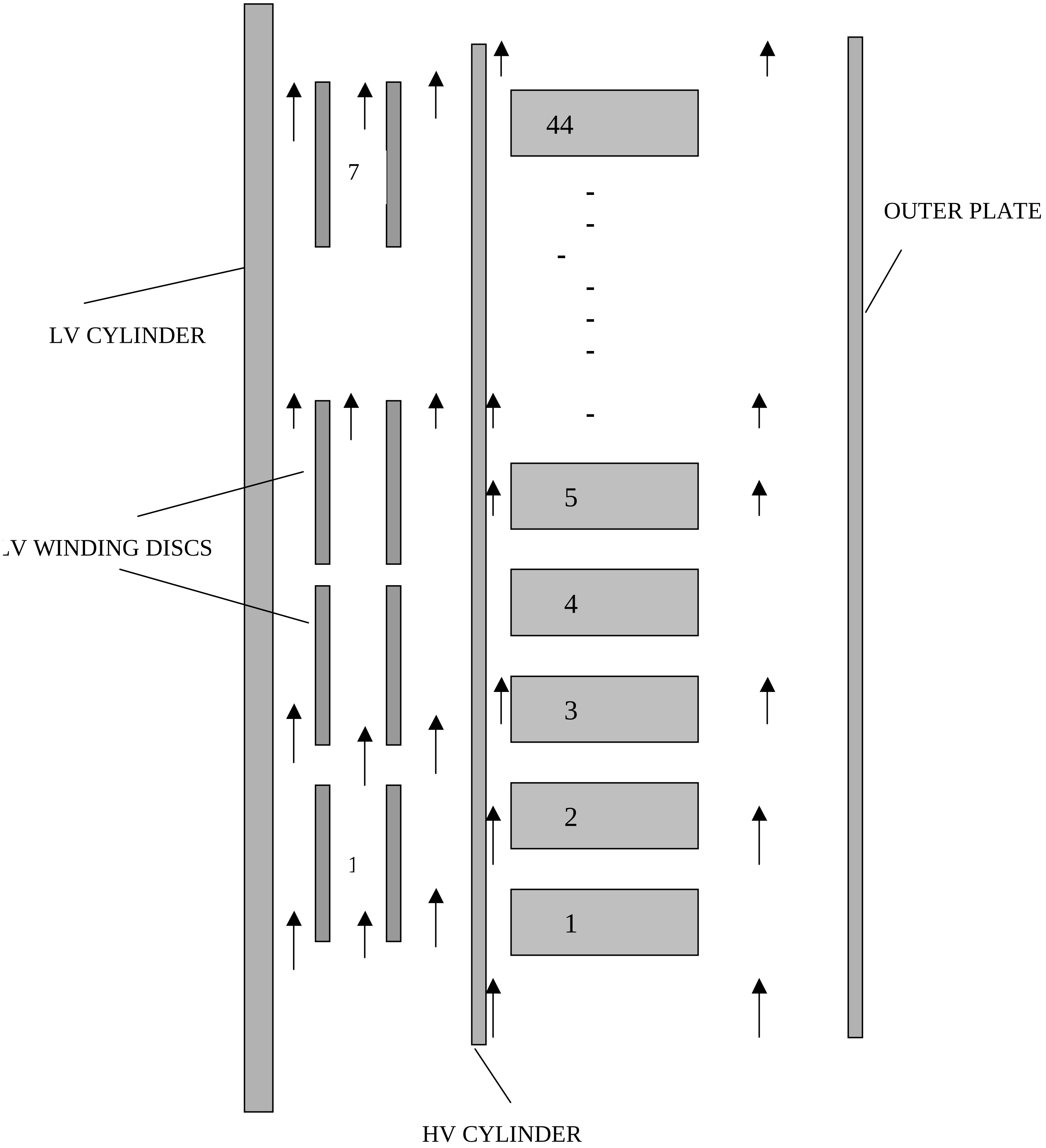


Fig. 4: A schematic diagram of LV & HV windings

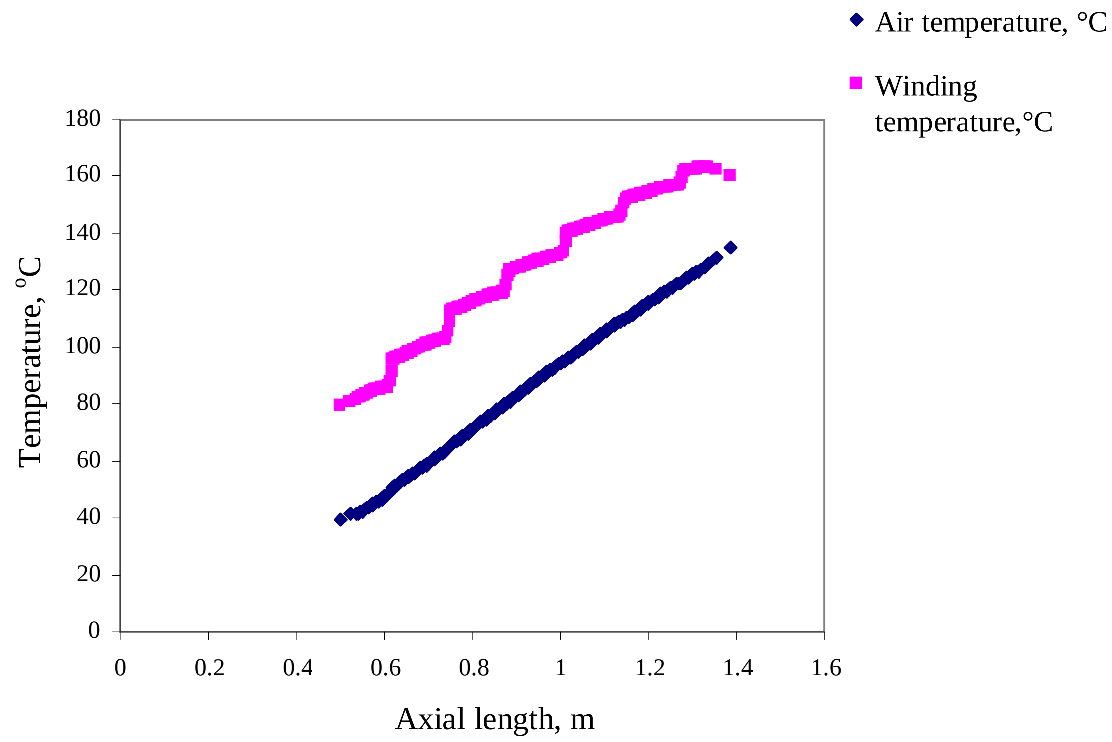


Fig. 5: Temperature distribution in LV layer1 winding and vertical duct

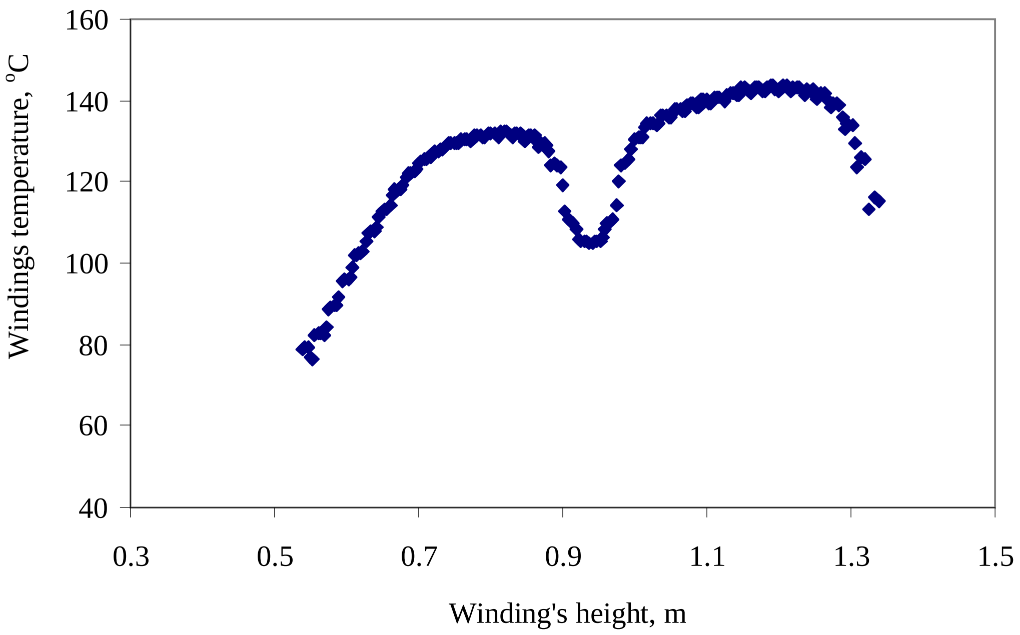


Fig. 6: Temperature distribution in HV windings

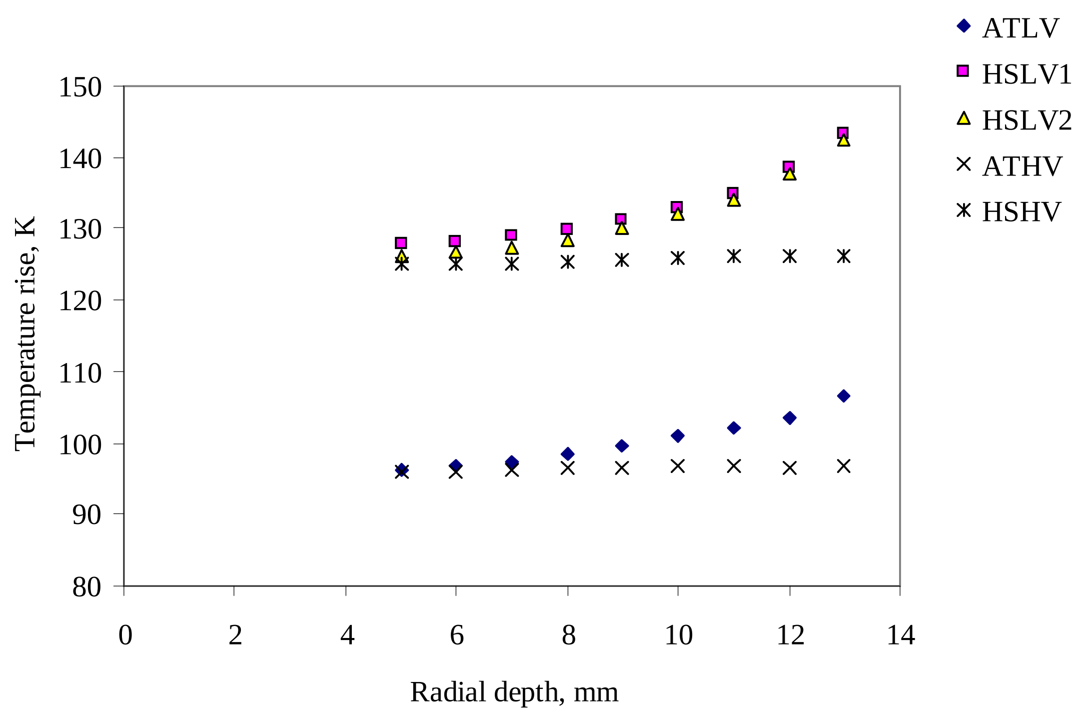


Fig. 7: Effect of radial depth of LV winding on windings temperature

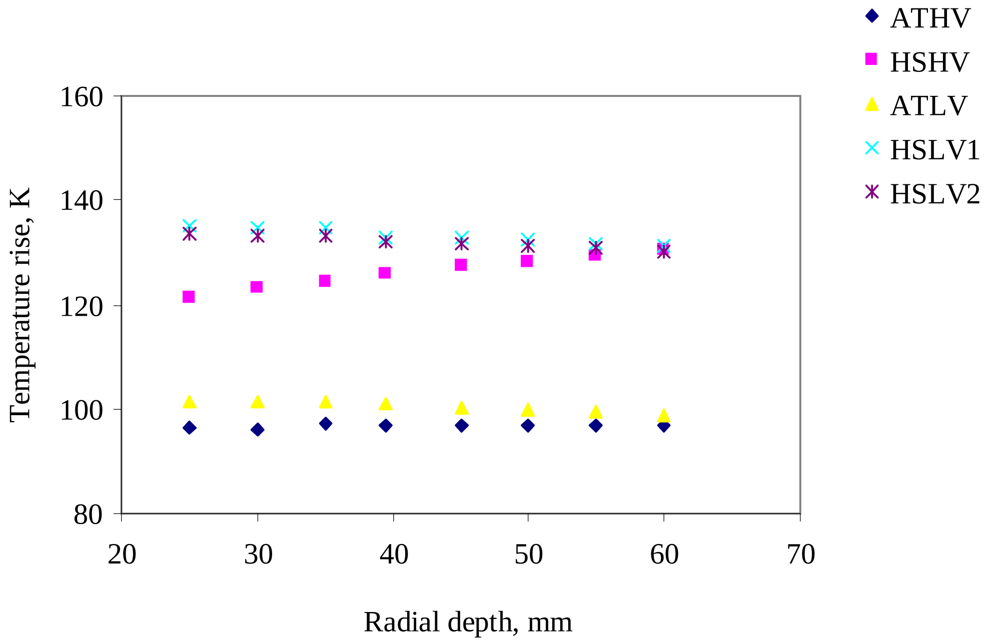


Fig. 8: Effect of radial depth of HV winding on windings temperature

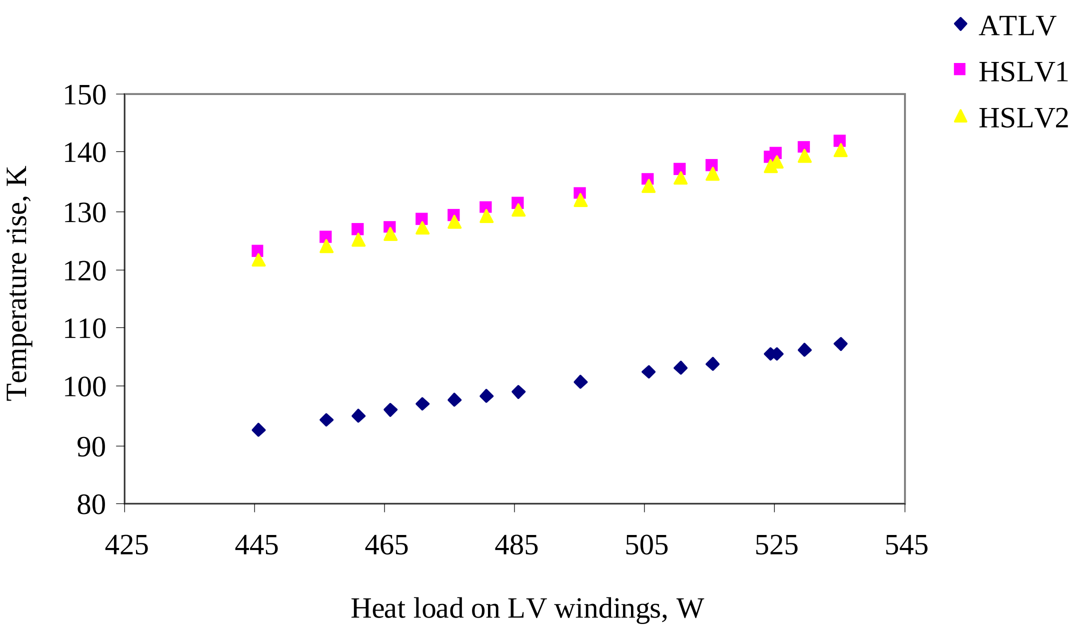


Fig. 9: Effect of heat load on temperature rise of LV windings

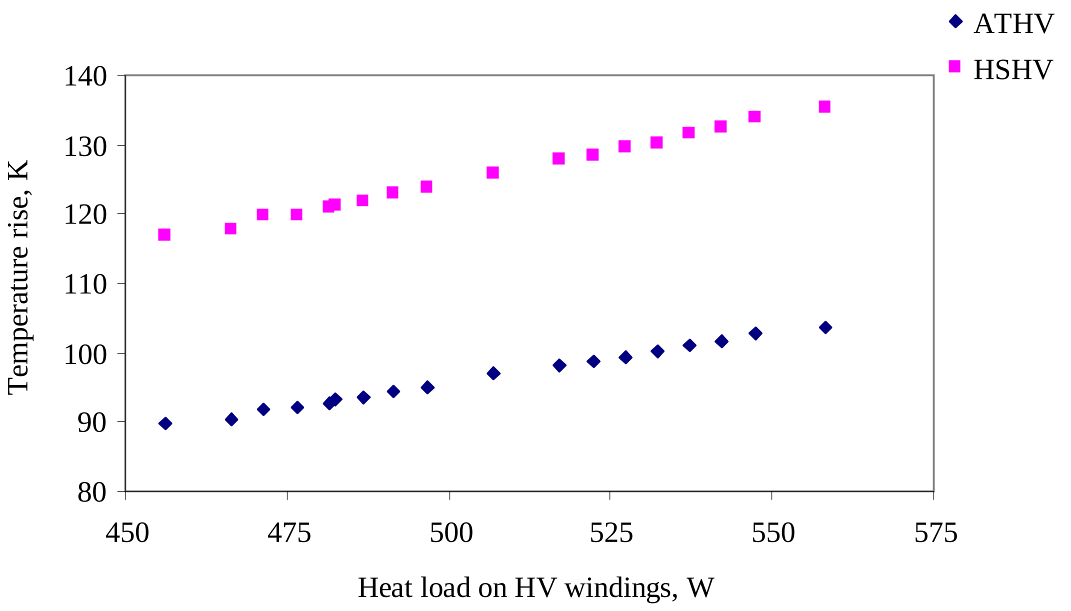


Fig. 10: Effect of heat load on temperature rise of HV windings

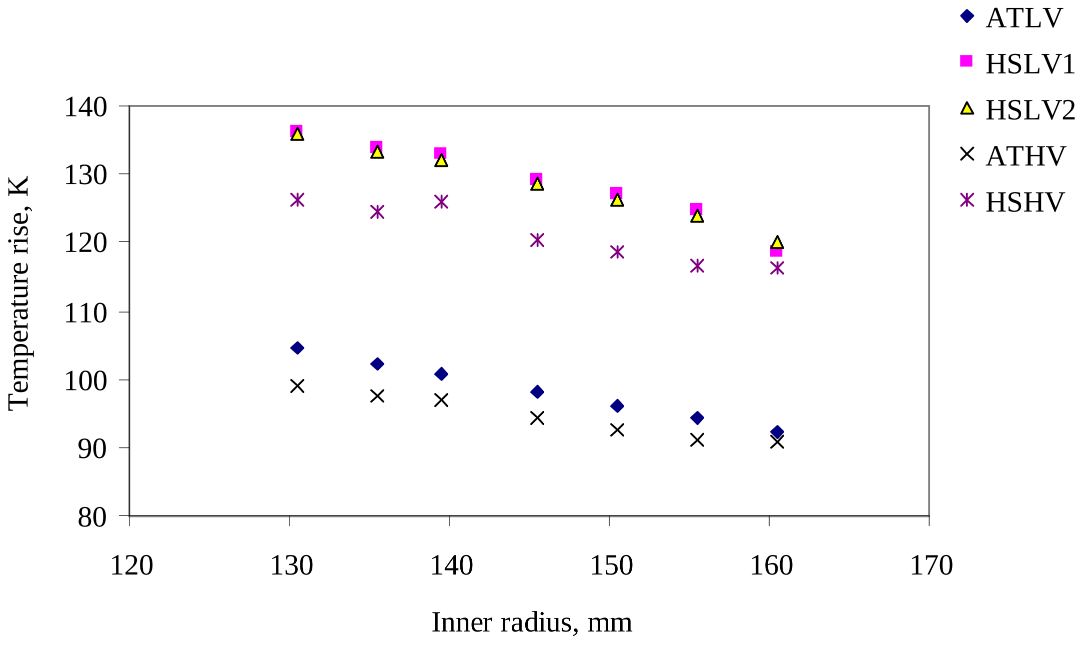


Fig. 11: Effect of inner radius on windings temperature

Table 1: A comparison of CFD simulation with experimental value

Sl. No.	Winding's temperature	LV Windings		HV Windings	
		CFD Simulation	Experimental	CFD Simulation	Experimental
1.	Average temperature rise, K	99.8	-	94.3	93.9
2.	Hot spot temperature rise in layer 1, K	133.1	128.2	119.7	-
3.	Hot spot temperature rise in layer 2, K	132.3	-	-	-

- Average/hot spot temperature rise is obtained by subtracting ambient temperature (35 K)

Table 2: Effect of thermal conductivity on temperature rise of HV windings

Sl. No.	Parameters	Parametric case	
		1	2
1.	Thermal conductivity of HV windings in axial direction, W/(m-K), k_z	3.47	3.47
2.	Thermal conductivity of HV windings in radial direction, W/(m-K), k_y	1.002	1.26
3.	Thermal conductivity ratio (k_z / k_y)	3.46	2.73
4.	Heat load on HV windings, W	507	507
5.	Heat load on LV windings, W	495	495
6.	ATHV, K	96.87	96.04
7.	HSHV, K	125.94	122.81
8.	ATLV, K	100.89	100.67
9.	HSLV1, K	132.98	132.84
10.	HSLV2, K	132.08	131.74

Table 3: Coefficients for computing temperature rise of LV windings

Sl. No.	Parameters	Average temperature rise	Hot spot temperature rise of LV layer 1	Hot spot temperature rise of LV layer 2
1.	C0	57.8879	132.509	239.4796
2.	Radial depth of LV windings [mm]	2.3292	4.9145	2.116
3.	Mean radius of LV layer 1 [mm]	-0.5254	-0.51089	-0.385
4.	Mean radius of LV layer 2 [mm]	0.2911	-0.3	-0.4596
5.	Height of LV windings [mm]	-0.1257	-0.1404	-0.08503
6.	k_z/k_y	8.09896	9.13885	-0.5896
7.	Horizontal duct width in LV windings [mm]	3.0356	-1.2276	-3.9263
8.	Inner duct width of LV layer 1 [mm]	-0.74424	4.2453	5.1175
9.	Outer duct width of LV layer 1 [mm]	4.1721	8.7585	2.69
10.	Outer duct width of LV layer 2 [mm]	-2.7499	-5.3396	-2.529
11.	Heat loss (LV) [W]	0.14554	0.15978	0.175

Table 4: Coefficients for computing temperature rise of HV windings

Sl. No.	Parameters	Average temperature rise	Hot spot temperature rise of HV
1.	C0	114.81	147.68
2.	Mean radius of HV windings [mm]	-0.5461	-0.6936
3.	Radial depth of HV windings [mm]	0.3325	0.7025
4.	k_z/k_y	6.044	12.299
5.	Horizontal duct width in HV windings [mm]	4.109	7.858
6.	Inner duct width of HV windings [mm]	0.0635	0.7935
7.	Outer duct width of HV windings	0.0454	0.0755
8.	Height of HV windings [mm]	-0.0231	-0.0971
9.	Heat loss (HV) [W]	0.1235	0.1582