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Design Calculation of Voltage Transformer 66kV Line in 230/66/11kV Substation

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Abstract: The main purpose of the substation is to provide reliable and continuous electric power supply related to the distributive network for consumers .when a fault in the distributive network occurs, it is necessary to interrupt the power supply until the fault is removed. For these reasons, distributive substation has to be provided with different protective systems. Among them, voltage transformers are important components of the power system protection. This supply the protection system with scale-down values of current and voltage which are safe and practical to operate. Voltage transformer (50VA, 66/ $\sqrt{3}$ kV:0.11/ $\sqrt{3}$ kV) is designed.

Keywords: Voltage Transformer, Substation, Electric Power Supply, Distributive Network.

I. INTRODUCTION

A voltage transformer is a type of instrument transformer. This is used in conjunction with measuring instruments, protective relays and control circuits. Instrument transformers are designed to transform voltage or current from the high values in the transmission and distribution systems to low values that can be utilized by low voltage metering devices. Instrument transformers are used; metering, protection control and load survey. It is the most common and economic way to detect a disturbance. Voltage transformer connected in parallel with the circuit to be monitored. They operate under the same principles as power transformer significant differences being power capability, size, operating flux levels and compensation. Two types of VT used for protection equipment are; electromagnetic VT and capacitive VT. Electromagnetic VT is a step down transformer whose primary HV and secondary LV winding. These types are used in voltage circuits upto 110/132 KV. The size of electromagnetic VT for higher voltages is largely proportional to the rated voltage; the cost tends to increase at disproportionate rate. Electromagnetic unit contains an inductive voltage transformer, a turning reactance and a protection against ferro-resonance. Capacitor voltage transformer is the most used voltage transformer for high voltage>100KV. CVTs are more economical than inductive VTs. CVT can also be used for line carrier purposes for communication, data transformer and remote control. In HV and EHV systems CVT is free standing device with its own supporting insulator.

II. TYPE OF VOLTAGE TRANSFORMER

There are basically two type of voltage transformers used for protection equipment.

1. Electromagnetic type (commonly refer to as a voltage transformer).
2. Capacitor type (refer to as capacitor voltage transformer).

A. Electromagnetic Voltage Transformer

The electromagnetic wound-type VT is similar in construction to that of the power transformer. The magnetic circuit is a core-type or shell-type arrangement, with the windings concentrically wound on one leg of the core. A barrier is placed between the primary and secondary winding(s) to provide adequate insulation for its voltage class. In low-voltage applications it is usually a two-winding arrangement, but in medium-voltage and high-voltage transformers, a third (tertiary) winding is often added, isolated from the other windings. This provides more flexibility for using the same VT in metering and protective purposes simultaneously. As mentioned previously, the VT is available in single-bushing or dual-bushing arrangements. A single bushing has one lead accessible for connection to the high-voltage conductor, while the other side of the winding is grounded. The grounded terminal (H2) may be accessible somewhere on the VT body near the base plate. The dual-bushing arrangement has two live terminal connections, and both are fully rated for the voltage to which it is to be connected.

B. Capacitor Voltage Transformer

Capacitor voltage transformers (CVTs) use a series string of capacitors to provide a voltage divider network. The capacitor voltage transformer is the most used voltage transformer for high voltages > 100 kV. The application for capacitor voltage transformers, CVTs are the same as for inductive voltage transformers. In addition to those, the CVT can also be used as a coupling capacitor in combination with power line carrier PLC equipment for telecommunication, remote control etc. The dual function voltage transformer and coupling capacitor makes the CVT to an economic alternative also for voltages <100 kV. The CVT consists of two parts, the capacitive voltage divider CVD with the two capacitances C1 and C2 and the electromagnetic unit EMU. The size of the capacitances C1 and C2 determines the voltage ratio of the CVD. The EMU contains an inductive voltage transformer, a tuning reactance and a protection against ferro-resonance. The basic theory regarding accuracy classes, ratio and phase errors etc are the same for CVTs as for inductive voltage transformers.

Figure1. Voltage Transformer used for 66kV in 230/66/ 11kV Substation.

III. OVERVOLTAGE RATING OF VOLTAGE TRANSFORMER

The operating flux density is much lower than in a power transformer. This is to help minimize the losses and to prevent the VT from possible overheating during overvoltage conditions. VTs are normally designed to withstand 110% rated voltage continuously unless otherwise designated. IEEE C57.13 divides VTs into groups based on voltage and application. Group 1 includes those intended for line-to-line or line-to-ground connection and are rated 125%. Group 3 is for units with line-to-ground connection only and with two secondary windings. They are designed to withstand 173% of rated voltage for 1 min, except for those rated 230 kV and above, which must withstand 140% for the same duration. Group 4 is for line-to-ground connections with 125% in emergency conditions. Group 5 is for line-to-ground connections with 140% rating for 1 min.

IV. CONNECTION OF VOLTAGE TRANSFORMER

VTs are provided in two arrangements: dual or two-bushing type and single-bushing type. Two-bushing types are designed for line-to-line connection, but in most cases can be connected line-to-ground with reduced output voltage. Single-bushing types are strictly for line-to-ground connection. The VT should never be connected to a system that is higher than its rated terminal voltage. As for the connection between phases, polarity must always be observed. Low- and medium-voltage VTs may be configured in delta or wye. As the system voltages exceed 69 kV, only single-bushing types are available. Precautions must be taken when connecting VT primaries in wye on an ungrounded system.

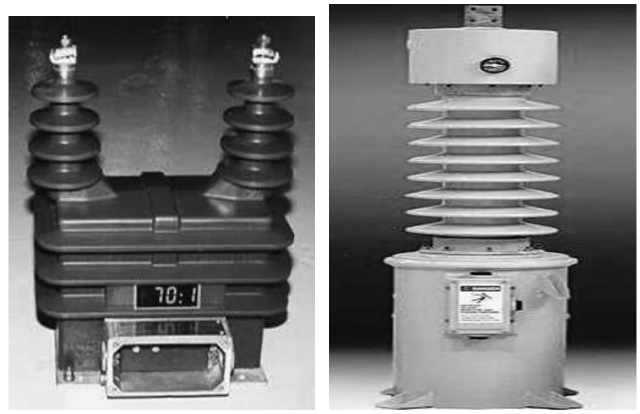

Figure2. Dual Bushing Type and Single Bushing Type Voltage Transformers

V. EQUATIONS USED IN DESIGN CALCULATION

The e.m.f per turn, $E_t = 4.44f\, B_m A_i$ (or) (1)

The e.m.f per turn, $E_t = 4.44f\, \varphi_m$ (2)

Where, B_m= Maximum value of flux density in the core, Tesla, f = Frequency of supply, Hz; A_i = Net cross sectional area of the core, cm^2; φ_m= Maximum value of main flux, Weber;

Net cross sectional area of the core,

$$A_i = \sqrt{s} / 5.58 \quad \text{(or)} \quad A_i = \varphi_m / B_m \qquad (3)$$

We have, $A_i = k_i d^2$

But, since it is not stepped core, there is no need to consider the factor ki.

Thus, $A_i = d^2$ (4)

$$d = \sqrt{A_i}$$

The form of magnetic frame of VT is core type (square shape). So, the circumference condition (the length, the width, the height of core and yoke, and the width take place by the winding) will be calculated.

Width of the window, $b_w = D - d$ (5)

We have, $L / D - d = 2.5$

Then, we choose the value of L within the ratio, $L / D - d = 2.5$.

If L=16.6 cm, (D- d) = 6.64 cm

Width of the window,

$b_w = D - d = 6.64$ cm

Center to center distance between cores,

$D = b_w + d$ (6)

Overall length of the yoke,

$W = 2D + 0.9d$ (7)

Gross cross section area of iron core,

$A_{gi} = A_i / k_s$ (8)

Where, Stacking factor (k_s) = 0.9

Gross yoke section area, $A_{gy} = 1.15 \times A_{gi}$ (9)

Width of the yoke, $b_y = 0.9d$ (10)

Height of the yoke, $h_y = A_{gy} / b_y$ (11)

Main dimension of window consists of the height and the width of the window. Main dimension of the yoke consist of overall length (W), width of the yoke and the height of the yoke.

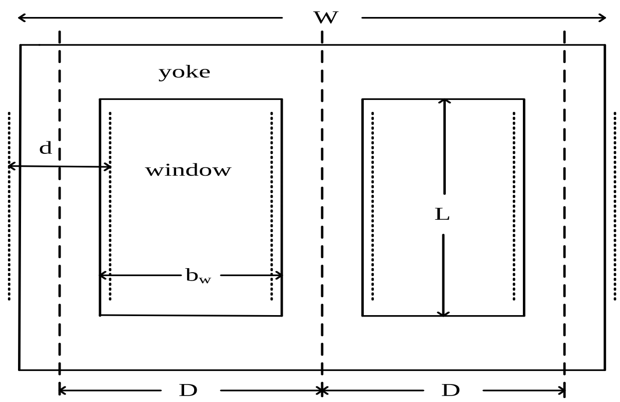

Figure3. Main Dimensions of Magnetic Frame.

The winding design of VT is similar to the winding design of the power transformer. The power transformer is considered with turns per volts and so is the voltage transformer.

The primary winding = turns per volts × primary voltage (12)

The secondary winding = turns per volts × secondary voltage (13)

sectional area of primary winding, $a_1 = I_1 / \partial_1$ (14)

Where, I_1, current per phase in primary, A; ∂_1, current density, A/ mm^2 ;

Axial space for primary winding = length of core – (0.2+0.2) (15)

$$\text{Axial space for one turn} = \frac{\text{Axial space for primary winding}}{\text{Axially arranged}} \quad (16)$$

Axial space for one strand = Axial space for one turn/1 (17)

Therefore, size of rectangular strand = 1.0 mm ×1.0 mm

Modified sectional area of rectangular strand = 0.86 mm^2 (from table)

Size of strand with double cotton covering (fine) = 1.1mm× 1.1 mm

Cross sectional area of secondary winding,$a_2 = I_2 / \partial_2$ (18)

Where, I_2, current per phase in secondary, A; ∂_2, current density, A/ mm^2 ;

Axial space for primary winding = length of core – (0.2+0.2) (19)

$$\text{Axial space for one turn} = \frac{\text{Axial space for secondary winding}}{\text{Axially arranged}} \quad (20)$$

Axial space for one strand = Axial space for one turn/1(21)

Therefore, size of rectangular strand = 22 mm ×1.4 mm

Modified sectional area of rectangular strand = 30.6 mm^2 (from table)

Size of strand with double cotton covering = 22.5 mm ×1.9 mm

The length of the tank, $L_t = b_y + L + b_y + \Delta l$ (22)

The width of the tank, $B_t = W + \Delta b$ (23)

The height of the tank , $H_t = h_y + \Delta h$ (24)

Where, Δl = Total clearance length, cm; Δb = Total clearance width, cm; Δh = Total clearance height, cm;

Volume of the cores = 2 × A_{gi}× L (25)

Weight of the cores = volume of the cores × density of the transformer steel (26)

Flux density in cores = 1.5 Tesla

Thus, specific losses in the cores = 1.5 W/kg (from figure)

Iron losses in the cores = specific losses × weight of the cores (27)

Volume of the yokes = 2 × A_{gy} × W (28)

Weight of the yokes = Volume of the yokes × density of transformer steel (28)

Flux density in the yokes = 1.5 Tesla

Thus, specific loss = 1.5 W /kg

Iron losses in the yokes = specific loss × weight of the yokes (29)

Total iron losses= Iron losses in the cores × Iron losses in the yokes (30)

Inner paper insulating paper thickness = 0.26 mm

Wire thickness for first layer = 1.1 mm

Final layer insulation thickness = 0.4 mm

Inner paper insulating paper thickness for 15 layers =14 × Inner paper insulating paper thickness (31)

Wire thickness for 15 layers = 15 × Wire thickness for first layer (32)

Length of wire = Wire thickness for 15 layers + Inner paper insulating paper thickness for 15 layers + Final layer insulation thickness (33)

The mean length per turn, $L_{m1} = 2d + 2h_y + 4c + \pi d_1$ (34)

Where, d = Width of the core, cm; h_y = Stack of the core, cm; c = Core corner thickness, mm; d_1 = Wire length, cm;
Total length for axially turns = L_{m1} × axially turns (35)

Resistance per phase of secondary winding,
$R_1 = \rho L_{m1} / a_1$ (36)

Where, ρ = specific resistance, ρ =0.0216 Ω-mm^2 /m at (+75°C)
Total copper losses in primary winding = $3 \times I_1^2 \times R_1$ (37)

d_2 = Wire thickness for one layer + Final layer insulation thickness (38)

where, d_2 = Wire length for secondary winding, cm;
The mean length per turn, $L_{m2} = 2d + 2h_y + 4c + \pi d_2$
Total length for 4 turns = $4 \times L_{m2}$ (39)

Resistance per phase of secondary winding,
$R_2 = \rho L_{m2} / a_2$ (40)

Total copper losses in secondary winding = $3 \times I_2^2 \times R_2$ (41)

Total losses = total iron losses + Total copper losses in primary winding + Total copper losses in secondary winding (42)

Output power = VT Rating × power factor (43)

Input power = Output power + total losses (44)

Efficiency = (Output power / Input power) ×100% (45)

VI. RESULT DATA OF VOLTAGE TRANSFORMER

The design summary of voltage transformer and performance results is briefly described in this journal. To calculate the voltage transformer design, first step is based on the main data and the properly assumed values. Important specifications needed to initiate in design are given in Table I. Besides, for the best voltage transformer design, it must be considering the requirement of the voltage transformer applications and many other functions. So, the design is worked out by various approximation methods based on accumulated experience realized in different formulae, equations, tables, charts, etc. Table II, III, IV, V, VI and VII are detail calculation result data.

TABLE I: DESIGN SPECIFICATIONS OF VOLTAGE TRANSFORMER

specifications	Symbol	Unit	Design Value
Rated Output			
VT Rating	S	VA	50
Rated Secondary	-	-	66000/√3 :110/√3
Voltage	V	V	110/√3
Frequency	F	Hz	50

TABLE II: DESIGN SUMMARY OF VOLTAGE TRANSFORMER FOR MAGNETIC FRAME

Specifications	Symbol	Unit	Design Values
Width of the window	b_w	cm	6.64
Length of the core	L	cm	16.6
Center to center distance between cores			
Overall length of the yoke	D	cm	9.5
Width of the yoke	W	cm	21.574
Height of the yoke	b_y	cm	2.574
	h_y	cm	4.057

TABLE III: DESIGN SUMMARY OF VOLTAGE TRANSFORMER WINDING DESIGN

Specifications	Symbol	Unit	Design Values primary side	Design Values secondary side
Turn per phase	N_p, N_s	turns	2286	4
Current per phase	I_1, I_2	A	0.0013	0.79
Sectional area of conductor	a_1, a_2	mm^2	0.00066	0.4
Size of rectangular strand	-	mm, mm	1.0 × 1.0	22×1.4
Modified sectional area of rectangular strand	-	mm^2	0.86	30.6
Size of strand with double cotton covering	-	mm, mm	1.1 ×1.1	22.5 ×1.9

TABLE IV: DESIGN SUMMARY OF VOLTAGE TRANSFORMER FOR TANK

Specifications	Symbol	Unit	Design Values
Diameter of the tank	L_t	cm	26.288
Width of the tank	B_t	cm	24.194
Height of the tank	H_t	cm	5.057

TABLE VI: PERFORMANCE DESIGN OF THREE PHASE THREE WINDING TRANSFORMER

Specifications	Symbol	Unit	Design Values	
Volume of the cores	-	cm	301.456	
Weight of the cores	-	kg	2.261	
Iron losses in the cores				
Volume of the yokes	P_i	W	3.39	
Weight of the yokes	-	cm^3	252.153	
Iron losses in the yokes	-	kg	1.89	
Total length of the winding	P_{iy}	W	2.835	
Resistance per phase	-	m	31.533	0.595
Copper losses	R_1, R_2	Ω	1031.99	0.032
Efficiency	P_1, P_2	W	0.0043	0.062
	η	%	87.7	

VII. CONCLUSION

In this paper, voltage transformer is designed to transform the voltage from high values to low values. For designing the voltage transformer, it is important to know the information of the substation. To design the VT's voltage ratio, it must be known the line voltage on the substation. Then, the 50VA,

$66000/\sqrt{3}:110/\sqrt{3}$ rating voltage transformer is designed. And the design calculation of voltage transformer is calculated in order to obtain the various results of efficiency, losses and output from various current density of voltage transformer.

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