

Calculations for Short Circuit Withstand Capability of a Distribution Transformer

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Abstract

During normal lifetime, transformers are submitted to a variety of electrical, mechanical and thermal stresses. One of the most critical situations is that caused by external short circuits, which produces high currents in the transformer windings and hence high internal forces in the windings. These forces are potential sources for damaging transformers. In this paper the different parameters for short circuit withstand capability of a transformer is calculated considering a 1500KVA, 22KV/415V, Dyn11 Distribution Transformer .The short circuit withstand test of a Transformer cannot be performed in the Test Laboratory of any manufacturer. There is a need for a high test field power, especially for large units with ratings of 100MVA and above. The tests can only be performed at a few powerful test stations, such as those operated in KEMA (Netherlands), EDF (France), CESI (Italy) or IREQ (Canada) [1]. Short circuit tests are expensive. The cost of the test itself is high. The cost also increases due to activities such as, transporting the transformer under test from the factory, local installation at the test laboratory and again at the factory, untanking and inspection, repetition of dielectric tests etc. For this reason the IEC standards also permits demonstration of the short circuit ability using calculation and design considerations.

Keywords: IEC, KEMA, EDF, CESI, IREQ

1. Introduction

The short circuit test is carried out to verify the integrity for stresses, primarily mechanical, developed when short circuit current flows through the transformer. The tests must be carried out on a new transformer ready for service, protection accessories such as Buchholz relay and pressure relief device must be mounted. Routine tests must be conducted on the transformer prior to the short circuit test. If windings have tappings, the reactance and resistance must be measured for the tapping positions at which the short circuit test will be carried out [2]. There are many agreed, different ways of calculating the short circuit withstand capability of power transformers. But for distribution transformers, for the combinations of the type of windings we are using (i.e., Foil/Enamelled wire, Foil/Rectangular copper, Rectangular copper/rectangular copper), there are no agreed standard methods. The most important aspect is the strength imparted by the resin dotted paper, which is used as an inter layer insulation in these winding types. This insulation imparts additional strength to the windings during

processing, bonding the individual windings as a single unit and presenting a composite structure to the short circuit forces, rendering the windings very capable against such forces. In the following calculations, weight age has not been given to this aspect. Hence, the actual figures, if any, will be much better and safer compared to the derived values. Even though the high voltage winding is symmetrically placed with respect to the low voltage winding, for calculations certain asymmetry is assumed, which in reality is not true. By the very nature of this assumed asymmetry, the calculated figures are purely hypothetical and since the stresses are lower even at this assumed asymmetry, they will be much lower under practical conditions.

2. Rating of the Transformer

All electrical systems are susceptible to short circuits and the abnormal current levels they create. These currents can produce considerable thermal and mechanical stresses in electrical distribution equipment. Therefore, it's important to protect personnel and equipment by calculating short-circuits currents during system upgrade and design. The rating of the transformer for which the short circuit withstand capability is calculated are

1500KVA 22KV/415V 39.37/2086.81A Short Circuit Impedance is 6% Vector group Dyn11

Table1: Design Parameters

Parameters	Specifications	Measured (HV Side)	Measured (LV Side)
Short Circuit Impedance	6% (Normal Tap)	6.222%	----
Reactance	---	0.6%	----
Per unit Impedance	---	0.063	----
Resistance per Phase at 75°	---	2.49271 Ω/Phase	0.000214 Ω/Phase
Winding height	---	52.8 cm	59 cm
No of Turns Per Limb	---	1221	14
Current Density of winding	---	1.59 A/mm ²	1.6077 A/mm ²
Mean Diameter of winding	---	----	29.55cm
Copper Thickness	---	----	0.22 cm

3. Calculations of the Short Circuit Parameters

3.1. Asymmetrical Short Circuit Current

Short circuit current normally takes on an asymmetrical Characteristic during the first few cycles of duration [4]. The asymmetrical short circuit current for the High Voltage (HV) and the Low Voltage (LV) windings are calculated

$$I_{sc} = \sqrt{2} \times (1 + e^{(-\pi \times R/X)}) \times (I_{ph}/E_z) \quad \dots\dots\dots (1)$$

Where,

I_{ph} = Rated Phase Current

R = % Resistance

X = % Reactance

E_z = Per unit impedance

$R/X = 0.6/6.222 = 0.0965$

For HV Winding

$$I_{sc} = \sqrt{2} \times (1 + e^{(-\pi \times 0.0965)}) \times (22.73/0.0625)$$

$$I_{sc} = 894.2 \text{ A}$$

For LV Winding

$$I_{sc} = \sqrt{2} \times (1 + e^{(-\pi \times 0.0965)}) \times (2086.81/0.0625), \text{ where } \pi = 3.141$$

$$I_{sc} = 82089.5 \text{ A}$$

3.2. Hoop Stress

The radial forces produced by the axial leakage field act outwards on the outer winding tending to stretch the winding conductor, producing a tensile stress (also called as hoop stress) [5]. The Hoop stress for the HV and the LV windings are calculated.

$$\sigma_{mean} = K_{copper} \times (I_{ph}^2 \times R_{dc}) / (H_w \times E_z^2) \text{ kg/cm}^2 \quad \dots\dots\dots (2)$$

Where,

I_{ph} = Rated Phase Current

R_{dc} = Resistance per phase at 75°C

H_w = Winding Height

E_z = Per unit impedance

$$K_{copper} = 0.031 \times \{(1 + e^{(-\pi \times R/X)})/1.8\}^2 \quad \dots\dots\dots (3)$$

$$= 0.031 \times \{ (1 + e^{(-\pi \times 0.0965)}) / 1.8 \}^2 = 0.029$$

For HV Winding

$$\begin{aligned} \sigma_{mean} &= (0.029 \times 22.73^2 \times 2.49271) / (52.8 \times 0.0625^2) \\ &= 181.1 \text{ kg/cm}^2 \text{ (Maximum Allowed 700kg/cm}^2\text{)} \end{aligned}$$

For LV Winding

$$\begin{aligned} \sigma_{mean} &= (0.029 \times 2086.81^2 \times 0.000214024) / (59 \times 0.0625^2) \\ &= 117.3 \text{ kg/cm}^2 \text{ (Maximum Allowed 700kg/cm}^2\text{)} \end{aligned}$$

3.3. Radial Bursting Force

In a transformer with concentric windings, the axial component of leakage flux density interacts with the current in the windings, producing a radial force (F_r). This is a well known phenomenon responsible for the mutual axial repulsion between the inner and outer windings. The radial flux component interacts with the windings currents, producing an axial force which acts in such a way to produce an axial compression or expansion of the winding coils [2]. With the transformer operating under normal conditions, the forces are small. However, during external fault situations, the currents and fluxes reach high values, producing extreme radial forces. In general, transformers are designed to withstand the maximum current peak of three-phase short circuits calculated as if the transformers were connected to an infinite busbar

$$F_r = (2\sigma_{mean} \pi I_{ph} N) / (S \times 100000) \text{ MT} \quad \dots\dots\dots (4)$$

Where,

N = No of Turns per Limb

S = Current Density of winding

For HV Winding

$$F_r = (2 \times 3.14 \times 181.1 \times 22.73 \times 1221) / (1.59 \times 100000)$$

$$F_r = 199 \text{ MT}$$

For LV Winding

$$F_r = (2 \times 3.14 \times 117.3 \times 2086.81 \times 14) / (1.6077 \times 100000)$$

$$F_r = 134 \text{ MT}$$

3.4. Supports to be provided in and for LV winding

The spacers are inserted to provide the necessary strength to the winding against the radial forces. Every conductor has radial oil flow due to the use of radial spacers for conductor support [6]. Spacer thickness can be changed to allow improved cooling and decreased winding rise or directed oil flow within the winding can be applied to improve the effectiveness of the winding conductor cooling

$$N_1 = (D_m / (T \times N)) \times \sqrt{(12 \sigma_{mean} / E)} \text{Nos.} \dots\dots\dots (5)$$

Where,

σ_{mean} = Hoops Stress in kg/cm²

D_m = Mean Diameter of winding in cm

T = Copper Thickness in cm

E = Young's Modules for copper, which is 1.13×10^6 Pascal

$$N_1 = (29.55 / (0.22 \times 14)) \times \sqrt{(12 \times 117.3 / 1130000)}$$

$$= 0.4 \text{ Nos}$$

Here no supports are necessary. Actual support provided in the form of Partinax cylinder which is continuous. LV cooling duct are spaced at 19 mm (14 mm between the supports). There are 29 such supports. Hence support for LV winding is more than adequate.

3.5. Internal compressive Forces on winding

The inner winding experiences radial forces acting inwards tending to collapse or crush it, producing a compressive stress. Due to the fringing of the leakage field at the ends of the windings, the axial component of the field reduces resulting into smaller radial forces in these regions [7]

$$F_c = 0.034 \times S_n \times (E_z \times H_w) \text{ MT} \dots\dots\dots (6)$$

Where,

S_n = Rated kVA

E_z = Per unit impedance in Ohms
 H_w = Winding Height in cm

The internal compressive forces on the winding was found to be

$$F_c = 14.60 \text{ MT}$$

Force in LV winding, $F_c = 9.74 \text{ MT}$ around (2/3) of the compressive forces on the winding

Force in HV winding, $F_c = 4.87 \text{ MT}$ around (1/3) of the compressive forces on the winding

3.6. External axial Imbalance Force due to axial asymmetry

$$F_a = 6.4 \times (I_{sc} \times W)^2 \times (X/H_g) \times L_g \times 10^{(-8/L_{rg})} \dots\dots\dots (7)$$

Where,

‘ I_{sc} ’ is 894.2 and ‘ W ’ is 1221

X/H_g = Assumed asymmetry is 0.015 (1.5%)

L_g = Mean length of winding ie., 130.6 cm

$L_{rg} = H_w/\pi + (\text{radial depth HV} + \text{radial depth LV} + \text{H-L gap})/2 + \text{Core to LV clearance}$
 = 23.72 cm (Length of radial stray path)

$$F_a = 6.30 \text{ MT}$$

3.7. Tensile Stress in Tie Rod

In the order to prevent deformation under short-circuit forces windings are compressed under top and bottom clamping members with the help of tie rods. The axial end thrust under fault conditions is minimized by the suitable balance of the ampere-turns over the length of windings. In case of bigger transformer, the HV tapping leads are taken out from two positions to balance the short-circuit forces in a much better way [6].

$$P_t = (F_a - 1/3F_c) \times 1000 / (N_t \times A_t) \text{ kg/cm}^2 \dots\dots\dots (8)$$

Where,

No of Tie Rods (N_t) = 4 nos

Diameter of Tie Rod (D_t) = 1.6 cm

$$\text{Area of Tie Rod } (A_t) = (\pi/4) \times D_t^2 \text{ cm}^2$$

$$A_t = 2.02 \text{ cm}^2$$

$$P_t = (6.3 - 4.87) \times 1000 / (4 \times 2.02)$$

$$P_t = 177.0 \text{ kg/cm}^2, \text{ Maximum Allowed } 1100 \text{ kg/cm}^2$$

3.8. Bending Stress on Wooden Beam

The wooden beam is subjected to stresses while lifting core-winding assembly, during clamping of windings, or due to short circuit end thrusts. Usually, the short circuit stresses decide their dimensions. The stresses in the wooden beam are determined from the calculated values of the short circuit forces acting on them.

$$\sigma_{max} = (F \times L_c) / (B \times D^2 / 6) / n / N_{cb} \quad \dots\dots\dots (9)$$

Where,

$$\text{Total Axial Force } (F) = (F_a - 1/3F_c) = 1430 \text{ Kg}$$

$$\text{Leg center or tie rod center } (L_c) = 49 \text{ cm}$$

$$\text{Beam thickness } (B) = 7 \text{ cm}$$

$$\text{Beam height } (D) = 23 \text{ cm}$$

$$\text{No. of Jacking Points } (n) = 4$$

$$\text{No. of sections on wooden Beam } (N_{cb}) = 4$$

$$\sigma_{max} = 7.1 \text{ kg/cm}^2, \text{ Maximum Allowed } 1100 \text{ kg/cm}^2$$

3.9. Capability of Withstanding Thermal Effects

The thermal affect of the short circuit currents on winding temperatures is critical during a short circuit event. Fault winding currents are significantly higher than for normal loads and extremely high winding temperatures are possible unless these conditions are also considered during the conductor selection of the transformer [2]. During the short circuit event, heat transfer through the cooling arrangement is not considered since the thermal time constants of windings are much longer (usually several minutes) than the fault duration. For this reason, the winding temperatures during the fault shall be calculated

$$\theta_1 = \theta_0 + 2(\theta_0 + 235)/A \quad \dots\dots\dots (10)$$

Where,

$$A = \{106000 / (J^2 \times t)\} - 1 \quad \dots\dots\dots (11)$$

Normal Current Density (J_n)

Short circuit Current density (J) = J_n / E_z A/mm²

Duration of short circuit (t) = 2 Sec

Initial winding temperature (Θ_0) = Winding Temperature + Ambient Temperature Initial winding temperature = 65°C + 40°C = 105°C

For HV Winding

$$\theta_1 = \theta_0 + \frac{2(\theta_0 + 235)}{A}$$

$$\theta_1 = 105 + 2(105 + 235) / 80.9$$

$$\theta_1 = 113.4^\circ\text{C}$$

Where

$$A = \{106000 / (25.44^2 \times 2)\} - 1$$

$$A = 80.9$$

This value is below the permissible 250°C as per the Standards, Hence the cross sectional area of winding is sufficient as regards the short circuit [8].

For LV Winding

$$\theta_1 = \theta_0 + \frac{2(\theta_0 + 235)}{A}$$

$$\theta_1 = 105 + 2(105 + 235) / 79.1$$

$$\theta_1 = 113.6^\circ\text{C}$$

Where

$$A = \{106000 / (25.7232^2 \times 2)\} - 1$$

$$A = 79.1$$

This value is below the permissible 250°C as per the Standards, Hence the cross sectional area of winding is sufficient as regards the short circuit.

4. Conclusions

This design was tested for a distribution transformer of rating 1500KVA, 22KV/415V, Dyn11 .A representative transformer was sent to KEMA (Netherland) for the short circuit withstand test, no wonder the transformer passed the test without any disturbances created internally and externally of the transformer. This paper did evolve with my practical and theoretical experiences gained during my days in Transformer manufacturing, MNC companies.

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