

## Transformer Short Circuit Design

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### Introduction:

Power transformers are projected to work for a period of twenty to twenty-five years and during service life, external or internal faults might occur which generates short circuits. Moreover, the constant rise in requirement of power supply resulted in addition of more generating ability and interconnections in power systems, which have contributed to amplify short circuit ability of grid system creating short circuit capability of transformer more rigorous. External short circuits generate asymmetrical short circuit currents which are much higher in magnitude than the service currents and lead to destructive short circuit forces. The amount of the short circuit current is a function of numerous parameters which are short circuit impedance and system impedance.

### What is short circuit?

A short circuit is an electrical short between the phases or to ground and the faults that are affecting the transformer design are single line to ground fault and three phase symmetrical fault. Usually three phase faults generate higher fault currents in transformer but for Yd transformers, single line to ground fault are severe. Faults results in an excessive current flowing through the circuit. The consequences of short circuit can be everything from just a minor malfunction to a disaster. The consequences are dependent of the system's capacity for driving current in short circuit situation and how long time the current is allowed to flow without damaging the equipment connected.

### Short Circuit Forces:

When an external fault occurs in the transmission line (short circuit event), the symmetrical currents are 6-7 times the normal operation currents, and peak asymmetric currents are 15-18 times normal operation currents. The basic equation to calculate electromagnetic force acting on current carrying conductor at any instant is given by

$$|B| = \frac{\mu_0}{2\pi r} I$$

$$F = B \times IL \quad \&$$

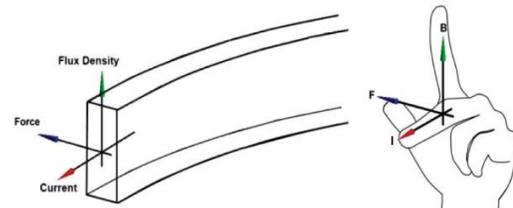
B = Flux Density (Vector quantity)

I = Current (Vector Quantity)

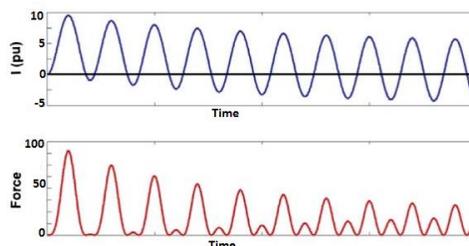
L = Length of conductors

$\mu_0$  = Magnetic Constant

r = distance from magnetic field



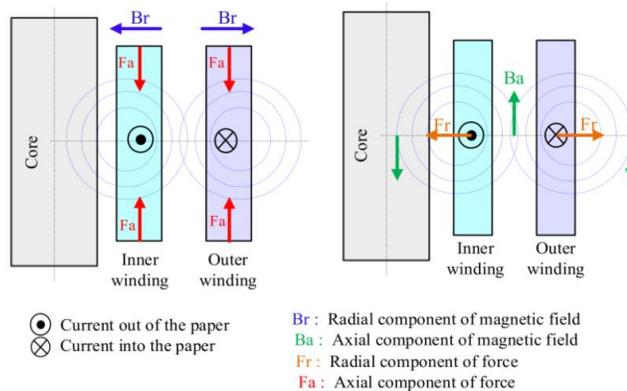
The direction of forces is readily apparent from the Fleming's left-hand rule, when the middle finger is in the direction of current and first finger in the direction of field, the thumb points in the direction of force. The forces experienced by winding are proportional to the square of current and are unidirectional and pulsating in nature. The relationship between current and force are show in figure below.



### Types of forces:

If the analysis of forces is done in two directions with the current density in Z direction, the leakage flux density at any point can be resolved in two components; one is the radial direction and other in axial direction. The radial forces are generated by the interaction of short-circuit current and axial components of the leakage flux density. These massive electromagnetic forces can displace or deform the windings. The overall effects of these forces are detailed below:

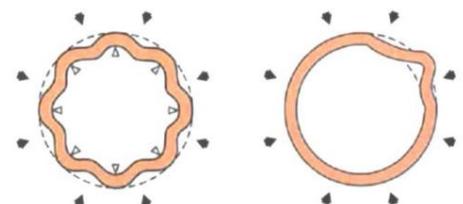
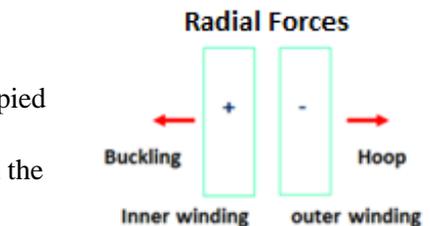
- Radial Force: They act inward on the inner winding producing compression failure, and they act outwards on the outer winding producing hoop tension failure.
- Axial Force: They are generated parallel to the height of the winding, and they act in the opposite direction due to the pattern of the magnetic field. These opposing forces can be of two types, i.e., axial compression forces and axial expansion forces. Axial compression forces directed axially towards the winding centers and can collapse the winding. Axial expansion forces directed axially toward the top and bottom clamping plates and can bend or break them, permitting axial instability



### Failure due to radial forces:

- Hoop stress in outer winding: If a winding is firmly wound, the conductors in the radial can be assumed to have a consistent tensile stress. As the majority of the winding in the radial direction is occupied with copper (ignoring paper insulation on conductors), the ratio of stiffness to mass is high. The natural frequency is much higher than the exciting frequencies, and consequently chances of resonance are secluded. Under tension, if the stress exceeds the yield strength of the conductor, a failure occurs. The conductor insulation may get damaged or there could be local bulging of the winding.
- Buckling stress in inner winding: Conductors of inner windings, which are subjected to the radial compressive load, may fail due to bending between supports or buckling. If the spacers are supported by the core structure, the conductors can bend between the supports all along the circumference if the stress exceeds the elastic limit of the conductor material. This form of buckling is termed as forced buckling.

The forced buckling failure could also occur when thick cylinders of a stiff material are used. An unsupported buckling, in which the span of the conductor buckle carries no relation to the span of axial supporting spacers, is called free buckling. The free buckling failure mostly occurs with thin winding cylinders, where conductor has higher stiffness and the axial spacers are not firmly supported on thin cylinder.



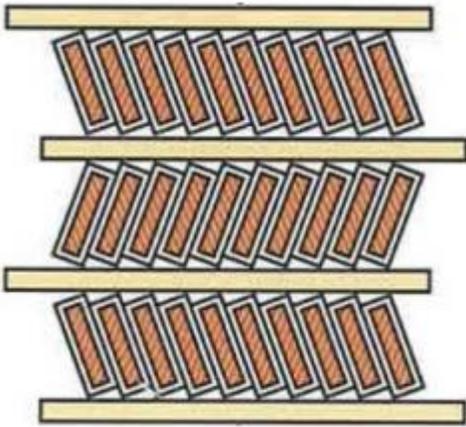
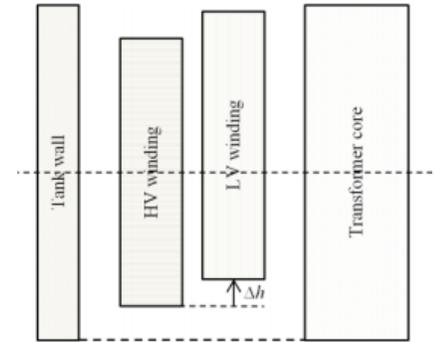
(a) Forced buckling.

(b) Free buckling.

## Failure due to axial forces

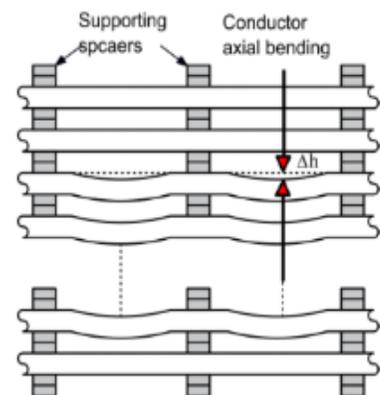
There are three failure modes due to axial forces which are explained in detail below.

- Axial Displacement of winding:** Due to different current direction in outer and inner windings, each winding experiences different direction of axial forces at the same time. Therefore, it is essential to have a perfect alignment between both windings with respect to the center line. A small displacement in one of the windings could cause asymmetry on the forces distribution thus further increasing the axial forces in both windings. When the forces are large enough to overcome the clamping force, a transformer winding can be vertically displaced from its original position. High axial forces could lead to deformations of the clamping structures such as pressure rings, core clamps and windings.



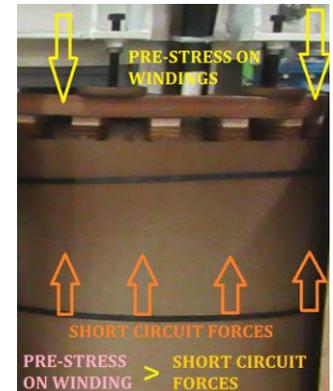
- Tilting of conductors:** When inner and outer windings are positioned in perfect alignment, the forces at the top and bottom ends of both windings are equal. In this condition, axial forces are compressing the winding from the top and bottom to the winding center line in which the highest compression is found. However, if the compressive forces exceed the permissible mechanical strength of the winding structure, it could cause conductors in the middle of the winding to be tilted. Since the forces acting on the winding are coming from two directions, top and bottom, the tilted conductors usually come in a pair and in adjacent discs.

- Axial bending between key spacers:** When two parallel adjacent conductors having current flowing in same direction, the magnetic force between the parallel conductors is attractive when the currents are in the same direction. The current flow direction in adjacent discs is same; hence they will get attracted to each other and try to bend conductors in unsupported span. The axial forces are not large enough to displace the entire winding. However, the forces which compress the winding still could cause conductors between the supporting spacers to bend. This will result in the oil filled gap between two conductors to change and damage to conductor insulation. The maximum stress in conductor due to bending occurs at the corners of the radial spacers.



### Effect of Pre-Stress:

The clamping pressure applied on the windings after the completion of core and coil assembly is called as pre-stress. It has a considerable impact on the reaction of windings during short circuits. The pre-stress reduces oscillating forces acting on the insulation. The winding displacements also reduce with the amplification in the pre-stress value. The value of pre-stress should be sensibly selected depending upon the characteristics of core and coil assembly. The pre-stress values shall be vigilantly premeditated and preserved during complete life of the transformer.



### Design to withstand Short Circuit:

With decades of experience and knowledge; and using universal design standards like IEEE and IEC, VTC/GTC has developed proven methods of calculations for short circuits withstand design. All transformers are vigilantly designed and all design considerations for short circuit design taken in consideration, named such as short circuit current calculation from the study of the system, the electromagnetic force calculations based on the short circuit currents, resultant mechanical forces calculation and calculation of strength of windings.

The Mechanical stresses induced in winding during short circuit event like radial forces buckling stress and hoop stress acting on inner and outer windings respectively; and axial forces generated due to axial displacement of winding or the design of winding structure to eliminate design failures like tilting and bending of conductors are taken care during winding design process. VTC/GTC has established design methodologies and proven technologies which consider all failure criteria and calculate optimum design of transformer.

### Winding Design

- Conductor selection – 0.2% yield strength is carefully chosen assuring that the tensile hoop stress will not be able to damage conductors during short circuit events. On various occasions, based on the design requirement, work hardened conductors are also used ensuring no difficulty during winding. The conductor dimensions are selected vigilantly assuring that the conductor can resist the compressive forces on its own, without depending on the key spacer and coil blocks. All CTCs used at VTC/GTC for winding construction are epoxy-bonded CTC conductor, which significantly improves the strength of the winding against buckling and tilting because of the bonding effect between strands due to the epoxy coating.
- Key Spacers: design of key spacers and radial number of key spacers in each disc is being selected vary carefully using Andersen FLD12 calculations defining optimum value for unsupported span for conductor between key spacers and winding cooling calculation. Coil Blocks: Coil blocks are provided to develop uniform magnetic centerline between transformer windings. As discussed in previous chapter during short circuit event, axial displacement of winding will create high axial forces and tend to deform the winding and clamping structure. Hence select on coil blocking material shall be done carefully. VTC user high strength laminated pressboard material for coil blocking assuring the material have enough strength to withstand short circuit forces. The type of insulation material used for coil blocks also depends on the dielectric stress in the end insulation region of windings. The placements of coil blocks are in line with key spacers creating a uniform vertical platform for axial load path direction.
- Pressure ring: The end clamping structures performance the most significant role in resisting axial forces during short circuits. They must preserve an effective pressure on the windings, applied typically on the clamping ring made of rigid insulating material (pre-compressed board or

densified wood). The type of insulation material used for the clamping ring depends on the dielectric stress in the end insulation region of windings. The design of pressure ring is subject to various factors like span to depth ratio of the material, maximum cutout for winding space, dielectric strength requirement for design. The flexural strength and modulus of elasticity for pressure ring material depends upon the short circuit force applied and span to depth ratio of the pressure ring. VTC design program considers all these factors and provide optimum material and dimensions for both top and bottom pressure ring to keep winding unharmed during short circuit events.

### Mechanical Design

- Pressure screw considerations: For the transformers designed for short circuit withstand capacity, pressure screw provides additional mechanical strength to the winding structure. The pressure screw clamping design, material and location is carefully selected considering short circuit forces acting on each winding. High strength structural bolts are used for pressure screw. Pressure screw pad area and no. of pressure pads are decided based on the short circuit force and effective support area requirement; and located at mean diameter of coil centering to axial key spacer and coil block load path.
- Tie plate: The design of tie-plate and material selection for the tie plate depends upon the calculated short circuit forces, weight of coil and coil assembly along with the weight of cables and cable support structure (un-tanking mass) and maximum current induced in windings. VTC/GTC design methodology considers all above mentioned parameters during design of tie-plate and provides optimum cross-sectional area with most suitable material for tie plate with minimum factors of safety of 1.50.
- Bracket / core clamp design: Bracket are selected based on the size of maximum and minimum core lamination width, type of core construction, short circuit forces, clamping force required on core and load loss requirements. Design of core clamps is made considering all above mentioned criteria. Tie plate locking arrangement to the top bracket is designed based on un-tanking mass and short circuit force considerations. Additional axial clamping is provided using structural rods placed between top and bottom brackets.
- Cable Rack Structure: As explained in axial bending between key spacer topic, when the direction of current is same in two parallel conductors, they create attraction. Same rule will be applied to the cables being connected to bushings and LTC and supported over cable rack. Cable rack supports and clut arrangement is designed considering weight of cables and forces generated in cable during short circuit event.

### Manufacturing

- Winding manufacturing: At VTC, winding manufacturing processes is strictly controlled. Winding are wound firmly on the dowel sticks placed on the thick cylinder which provides substantial support to the winding for withstanding the buckling forces developed on inner winding during short circuit event. Magnetic centers of the windings are maintained to be within the in-house quality standards.
- Dimension stability: VTC/GTC does strict control of dimensions during manufacturing process and closely monitors the dimensional stability till final stage of core and coil assembly process till tanking. After completion of winding process, they are wrapped with weatherproof cover and placed in area where temperature and moisture are controlled. The windings are placed in axial clamping structure to reduce rebound/ unspring effect of winding. Windings are tightened again and again before and after drying process.

- Drying process: VTC/GTC uses Vapor Phase Drying (VPD) system to for final core and coil assembly drying. Vapor-phase drying systems provides dehydration, degassing, impregnation to prevent aging, improve dielectric properties and reduce mechanical stresses. Vapor Phase Drying uses Hydrocarbon Vapor to transfer the heat to the transformer. Since Vapors can reach the most difficult areas of the transformer the drying results are optimum and even. Drying of transformers is done under vacuum to achieve the best results.
- Tight lowering of coils: Coils are lowered over the core legs. The core legs are designed and constructed in circular form to support total winding tube radially. On many occasions, circular dowel are inserted on core step gaps and tightened against core to provide at most circular form of the core to provide radial support to winding to counterattack bucking forces generated during short circuit event.
- Clamping before and after drying: All gaps / unsupported space between core clamps and bottom pressure ring is filled with mechanical support, made of same material as of coil blocks. Coils are compressed using pressure screws and tie plate tensioner to achieve required winding compression. Then the drying process is performed as mentioned above. Post drying, hydraulic machine pressing is performed on each winding during final coil clamping process. Once hydraulic jacks reach the clamping limit provided, pressure screws are tightened to achieve same clamping height as of hydraulic jacks, and then the pressure from hydraulic jacks removed which is being transferred to pressure screws. The pressure for hydraulic jacks is calculated based on the winding clamping force requirement calculated during winding design process. Manufacturing team carefully performs coil clamping process assuring hydraulic jacks are located on mean diameter of the coil and axially in line with key spacers.
- Total clamping of core and coil assembly: After VPD, before tanking process, final clamping process is performed. Manufacturing team check each hardware on core and coil construction (clamps, tie plates, pressure screws, core blocking arrangements), cable support construction, and tightening of cable clamps.

## Conclusion

Transformers are one of the key components in power generation and transmission lines and their service life is expected to be a minimum of 25 years. To ensure that the transformer reaches the required service life, properties of the insulation material and conductors, forces and over-voltages of electromagnetic origin need to be calculated accurately. This paper confirms that VTC/GTC designing and manufacturing considers all important aspects viz. Material selection, design, strength requirement, component assemblies, support structure and manufacturing process; for providing a “designed to withstand short circuit transformer”.

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