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Parameters Affecting the Performance of Transformers Under Short Circuit - A CPRI Experience

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Transformers are basic electrical machines and they form a very vital link in any electrical power transmission networks. During its service life, a transformer may experience number of short circuits in the system in addition to the abnormal overloading and switching impulses. Such abnormal conditions can cause the movement of the windings and failure of the supporting structures due to electro – mechanical forces and may result in total failure due to inadequacy in design and defective manufacturing process. Further, the rapid growth of fault level in the system network is major a concern for short circuit withstand capability of a transformer in service for a long period of time. With advanced modern technology and available short circuit test facilities, transformer manufacturing industry is now enabling to produce the reliable and safe transformers. Performance evaluation during ability to withstand short circuit test in a fully equipped testing laboratory is still final measure of checking the overall quality of the transformer from the point of design, material used, production process and quality control. Central Power Research Institute (CPRI), is having an experience of more than fifty years in the field of short-circuit testing. The roles of various factors which affect the performance of transformers under short-circuit conditions are discussed along with the analysis of the failure cases during the short circuit testing.

1.0 EFFECT OF SHORT CIRCUIT FORCES

Static forces can be calculated by any one of the following established methods i.e. Roth method, Rabin method, method of images and finite element method. Different methods of calculation of forces are well documented in 1979 by CIGRE working group.

2.1 Radial Forces

During the flow of short circuit current through a transformer with concentric windings, the radial electromagnetic forces generated by the axial component of the leakage magnetic field produce a radial pressure, which tends to collapse the inner coil. This pressure is almost uniformly distributed in the middle height-section of the inner winding.

2.1.1 Exterior Winding

The stresses must not cause inadmissible extension of the conductors, because of the risk of short circuit with the tap winding usually placed outside the main winding. The winding operation must be carried out so as to ensure maximum tightness and thus avoid the risk of short circuit between turns due to radial vibrations.

2.1.2 Inner Winding

The compressive stress may lead to buckling of the conductors. Solid radial supports are required to prevent the buckling of conductors.

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2.2 Axial Forces

These forces are caused by the interaction of the current flowing in the turns of the winding and radial component of the magnetic flux lines. For windings of equal height and uniformly distributed amp-turns, each winding is subjected to moderate compression.

2.2.1 Internal Compressive Forces

The values of these forces can exceed the initial clamping pressure. The spacers and spacing segments must therefore be radicalized to avoid deterioration of the layers of paper covering the conductor. The oil impregnating the spacers has the effect of acting as a damper and limits the amplitude of the vibrations.

2.2.2 Forces on the Supports

The layout of the winding must be such that, whatever the position of the tapping, the forces on the supports do not exceed the allowable limit. Stabilization of the windings must be carried out in the factory before final wedging in such a way that displacement of centers between the winding is restricted to very fine limits in order to minimize the forces on the supports.

The design of a power transformer with respect to the short circuit withstand capability is directed towards the limitation of the short circuit current values, as well as towards the control of the forces and stresses executed by the same short circuit current inside the transformer.

The following parameters, stresses/forces to be calculated and checked at the time of design for making of short circuit proof transformer:

- First peak value of short circuit current.
- Asymmetrical short circuit Amp-turn.
- Hoop Stress.
- Radial bursting forces.
- Number of supports to be provided in windings.
- Internal axial compression.
- Axial imbalance force due to axial asymmetry.
- Maximum compressive pressure in the radial spacers.
- Tensile stress in the tie rods.
- Tilting of conductors (Resistance to collapse).
- Calculation of most highly stressed coil.
- Bending stress on clamping ring.

3.0 FACTORS CONSIDERED FOR ENHANCING THE SHORT-CIRCUIT PERFORMANCE

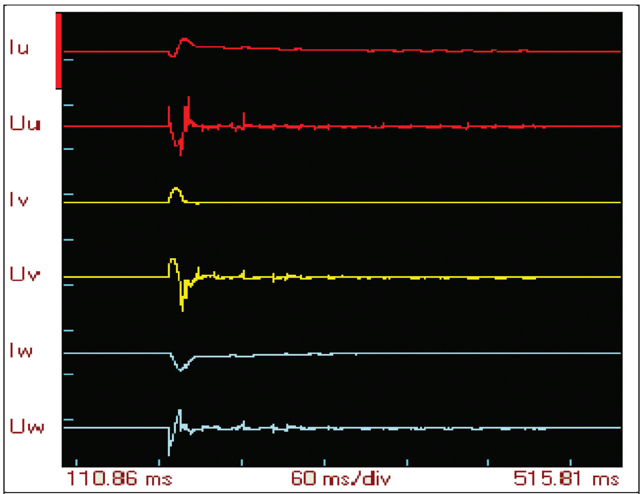
- Use of epoxy–bonded continuously transposed conductors instead of individually insulated flat conductor.
- High-density pressboard in windings and end insulation components.
- Elastic stabilization of windings and tolerances concerning winding lengths under specified clamping force and relative positioning of the windings.
- Core and coil clamping structure consisting of robust and stiff parts duly fastened.
- Large sizing of all pressure rings, pressure and support blocks and their securing by means of pin holders and fastening devices.
- Securing of all winding exit leads and connections to bushings and tap– changers.
- Final clamping of the winding blocks after impregnation with oil carried out to secure adequate evenly distributed and long lasting axial force on them.

4.0 TYPICAL FAILURE CASE STUDIES OF SHORT-CIRCUIT TESTS PERFORMED ON VARIOUS RATING OF TRANSFORMERS

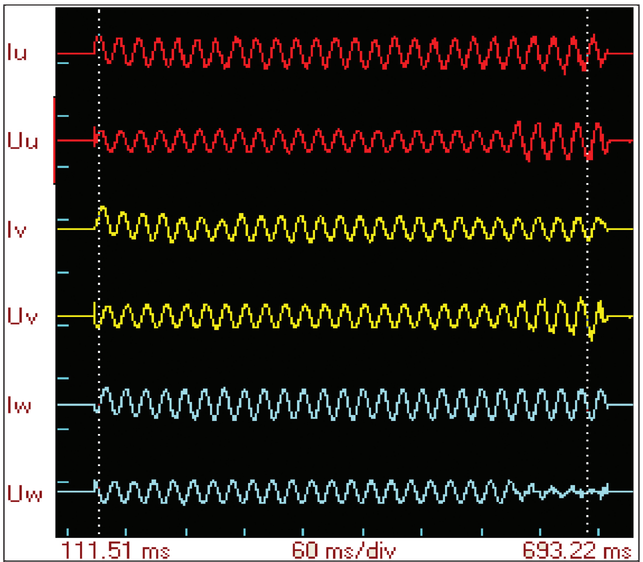
Different Case studies are tabulated below:

Sl. No.	Rating	% Variation in reactance	Waveforms condition	Observations
1	5 MVA, 33/11.55 kV	Large variation in % reactance after 6th short circuit test on lowest tap	Current and Voltage waveform collapsed. (Refer Osc. No. 1)	- Heavy sound noticed. - V ph HV winding found twisted. V ph LV bushing broken. End blocks and spacers of V ph found displaced. - Oil carbonized. (Refer photograph P-1)
2	1600 kVA, 6.6/0.433 kV	2.739 % after 5th short circuit test on normal tap	Current and Voltage waveform distorted. (Refer Osc. No. 2)	- No-load current abnormally high. - Insulation resistance found zero. - Carbonized oil came out from pressure relief valve. - End blocks at bottom side found loose. - Arcing marks noticed on LV busbar. Paper insulation of winding burnt. (Refer photograph P-2)
3	1.5 MVA, 33/0.69 kV	Large variation in reactance after 2nd short circuit test on highest tap	Current and Voltage waveform distorted after 427 ms. (Refer Osc. No. 3)	- Abnormal sound noticed. - W phase of HV winding damaged and conductor burnt. - Some end blocks and spacers displaced and loose. - Oil carbonized. (Refer photograph P-3)
4	630 kVA, 22/0.433 kV	48.018 % after 7th Short circuit test.	Voltage waveform distorted. (Refer Osc. No. 4)	- No-load current abnormally high. - V phase HV winding deformed. - Some end blocks and spacers found displaced and loose. Some fallen in the tank. (Refer photograph P-4)
5	8 MVA, 33/11 kV	12.35 % after 3rd Short circuit test on highest tap.	Current and Voltage waveform distorted. (Refer Osc. No. 5)	U phase LV bushing found broken and Oil Came out violently from LV bushing.
6	5 MVA, 33/11 kV	7.264 % after 2nd Short circuit test on highest tap	R&Y phase Current waveform distorted. (Refer Osc. No. 6)	- LV to Earth insulation resistance found zero. - No-load current abnormally high.
7	800 kVA, 33/0.433 kV	53.054 % after 8th Short circuit test on lowest tap	No abnormality in waveforms.	- Variation found in HV winding resistance - Delta lead found opened. - The brazing and mechanical supports are not proper. (Refer photograph P-5)
8	1.5 MVA, 33/0.69 kV	39.496 % after 2nd Short circuit test on highest tap	No abnormality in waveforms.	- Variation found in winding resistance. - U and V phase winding of one coil damaged and conductor broken. - Some end blocks and spacers displaced and loose. - Oil carbonized. (Refer photograph P-6)
9	50 MVA, 132/33 kV	3.32 % after 4th Short circuit test on lowest tap	Current and Voltage waveforms distorted.	- Insulation resistance value becomes very low. - Oil came out from vent. No abnormality noticed on HV winding, however Slight buckling of LV winding noticed, due to radial forces on the inner winding.
10	4 MVA, 11/3.45 kV	3.462 % after 4th Short circuit test on normal tap	Voltage and current waveform distorted.	- Abnormal sound noticed. - No-load current abnormally high.

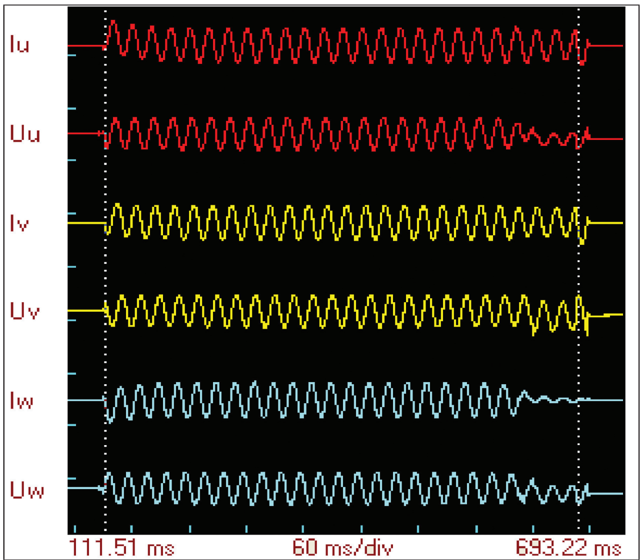
Typical Oscillograms of failure of transformer during short circuit testing:



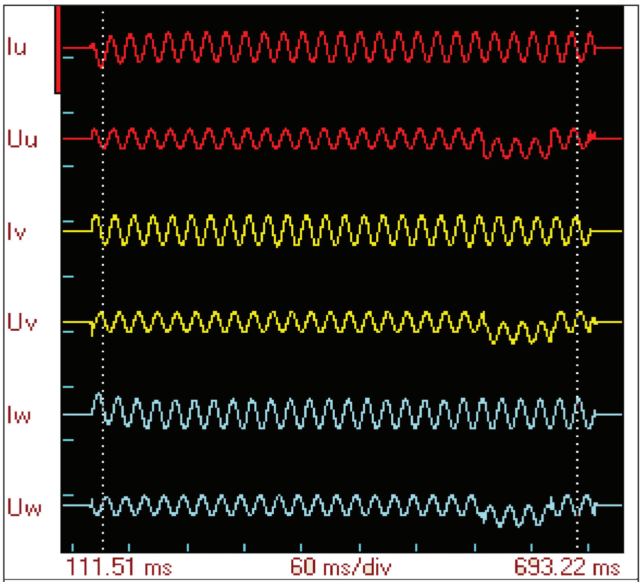
OSC. NO. 1. 5 MVA, 33/11.55 kV TRANSFORMER



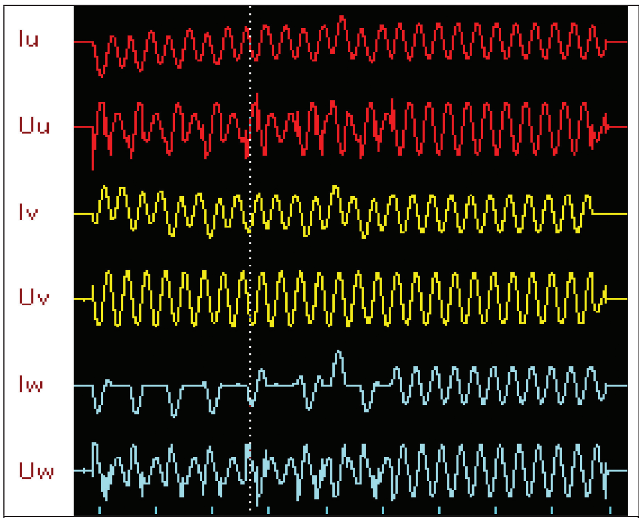
OSC. NO. 2. 1.6 MVA, 6.6/ 0.433 kV TRANSFORMER



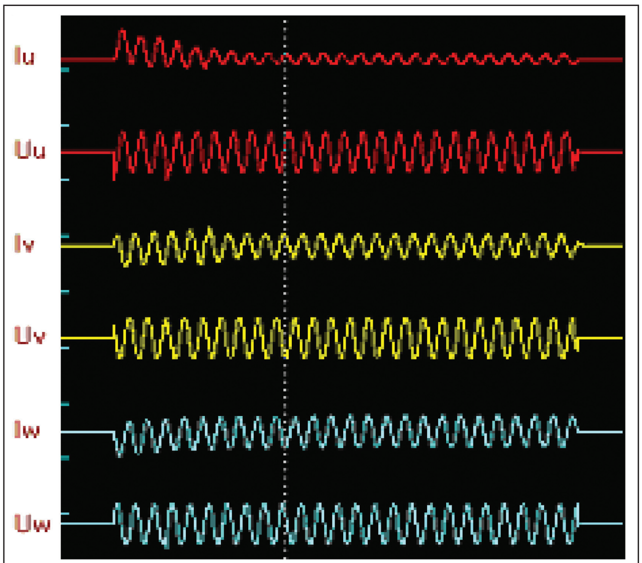
OSC. NO. 3. 1.5 MVA, 33/ 0.69 kV TRANSFORMER



OSC. NO. 4. 630 kVA, 22/ 0.433 kV TRANSFORMER

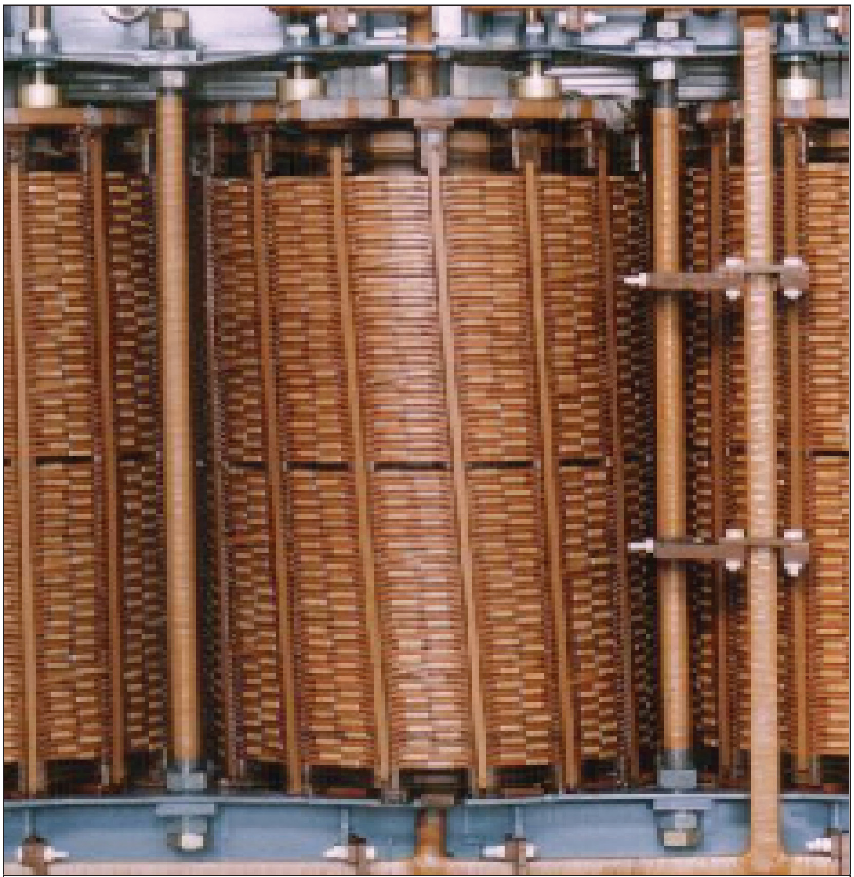


OSC. NO. 5. 8 MVA, 33/11 kV TRANSFORMER



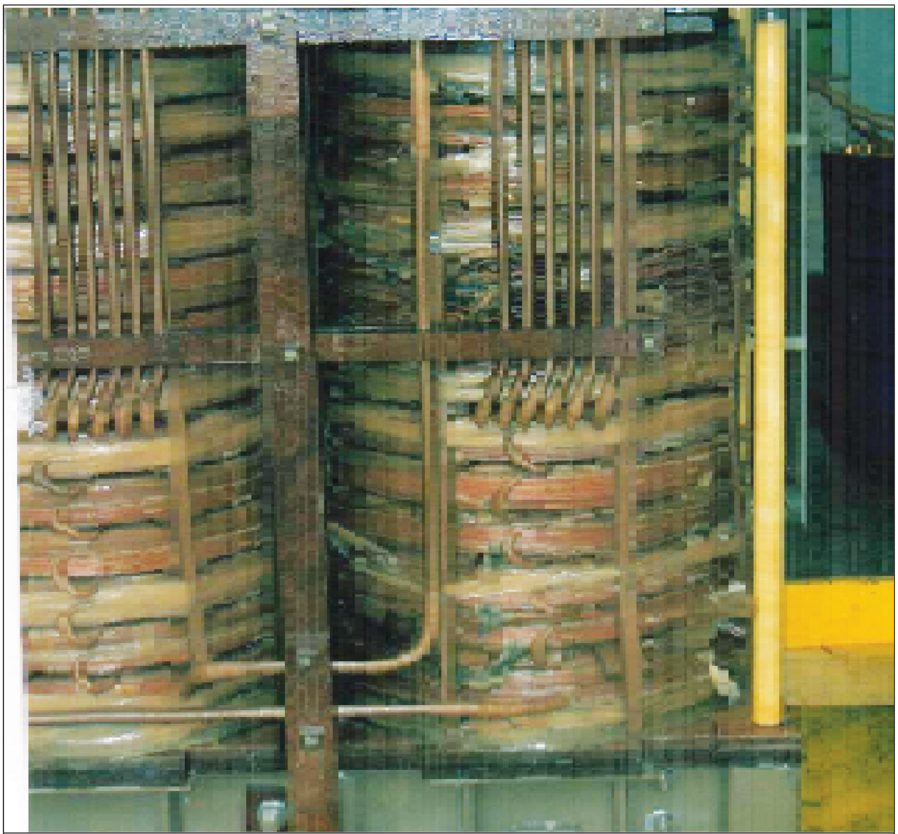
OSC. NO. 6. 5 MVA, 33/11 kV TRANSFORMER

Typical photographs of failure of transformer during short circuit testing:



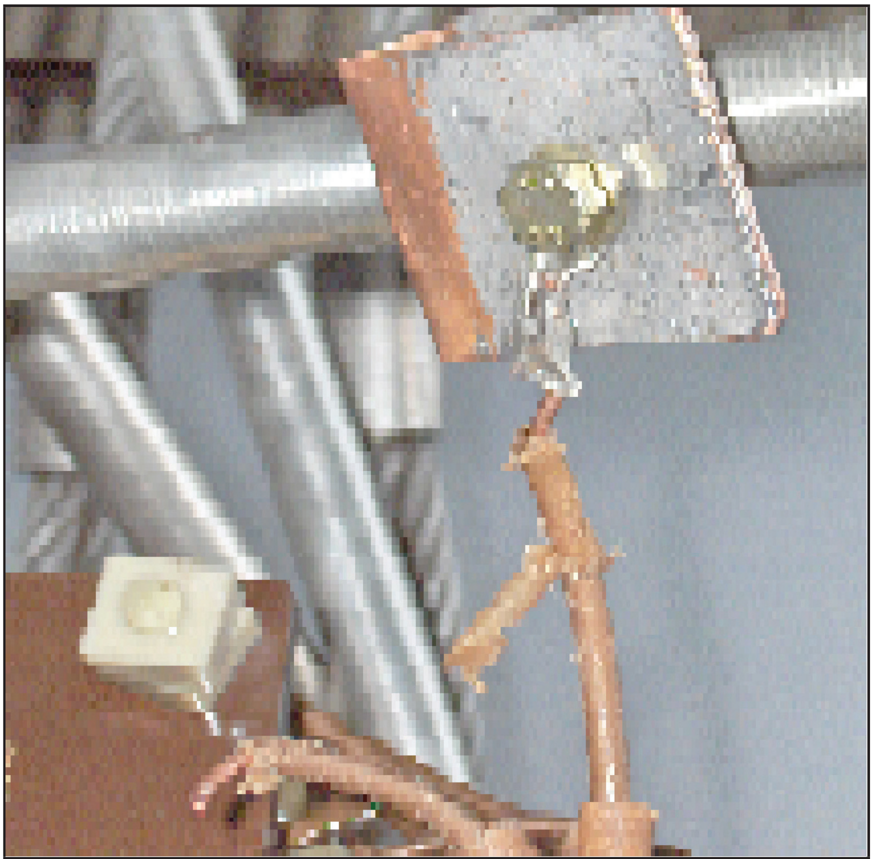
P-1. 5 MVA, 33/11.55 kV TRANSFORMER

P-2. 1.6 MVA, 6.6/ 0.433 kV TRANSFORMER



P-3. 1.5 MVA, 33/ 0.69 kV TRANSFORMER

P-4. 630 KVA, 22/ 0.433 kV TRANSFORMER



P-5. 800 kVA, 33/0.433 kV TRANSFORMER

P-6. 1.5 MVA, 33/0.69 kV TRANSFORMER

5.0 NATURE OF FAILURES

The natures of failures from the case studies are:

- LV winding terminals shorted to ground (tank).
- HV winding open circuited failure in the joints.
- Deformation of HV winding.
- Turn to turn short circuit, causing abnormally high no-load current.
- Delta leads opened.
- Arcing occurred at tap changer terminals.
- Insulation failure.
- Displacement and looseness of end blocks, spacers and pressure ring.
- Flashover across windings.
- Carbonization of oil, pressure relief vent operated.
- Broken or cracked LV bushing.
- Tank body buldged.

6.0 CONCLUSION

From the review of above case studies we can summarize various facts as below, which may help in preventing failure of transformers during short circuit:

- The success of short circuit test is highly dependent on many factors such as proper design tool, detailed material specifications, winding capability under axial and radial forces, core construction, overall manufacturing quality and adequate test set-up.
- Thorough analysis of the magnetic field and electromagnetic forces.
- Coil assembly should be made reasonably tight with proper supports for tapping and delta leads.
- Mechanical robustness of winding assembly and proper supports to joints and termination.
- The most important diagnostics to evaluate the test results are the reactance measurements, loss measurements and the visual inspection of active part after short circuit-test.

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