ABOUT AXIAL CLAMPING FORCE MONITORING AT POWER TRANSFORMER WINDINGS DURING THEIR ACTIVE LIFETIME

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Abstract **– The variation of the axial clamping forces of the windings cannot be monitored over the active lifetime of the transformers. The insurance of a preset level of the forces has a determinant role in maintaining the safety in operation at short-circuit stresses. The paper describes the generation modes of the axial forces in transformers as well as the evaluation of the mechanical condition of the power transformers. Axial force calculation and the theoretical aspects referring to the mechanical structure for the fastening of the core-winding assembly shows the importance of these constructive part design in maintaining the mechanical stability under the action of the short-circuit forces. There are presented critical situations related to the behaviour of the multi-layer windings from the Continuously Transposed Cables (CTC).**

Keywords**:** *Power transformer, axial clamping force, Continuously Transposed Cable, active lifetime.*

1. INTRODUCTION

The power transformer is one of the most expensive components of the electric power transport and distribution network.

The modern transformer monitoring systems control the thermal duty as well as main insulation and bushings condition and send the information in the control room of the transformer station. The evaluation of the received information warns on the need for a remediation of the failures found in the cooling system or for the disconnection with a view to technical checks. A very important problem in the proper operation of the transformers is the mechanical stability of the winding axial clamping system.

The clamping system used in transformer manufacturing should provide a proper clamping level during the active transformer lifetime irrespective of the mechanical, electric or thermal factors influence or of the possible changes in insulation general condition. In most cases, the power transformers have a rigid clamping system that compresses the windings on each column at a value depending on the electrodynamic stresses taking also into account the insulating material characteristics as well as the existing manufacturing technology. There are cases when the working and operation conditions impose the use if some special transformers having, as specific constructive element, special systems for winding axial clamping [1]. To maintain the mechanical stability of transformer windings over a time period is a difficult matter taking into account that the transformer as static equipment can be considered a “live” component, “in action”, of the power grid. The constructive parts of the power transformer that are considered in a continuous “action” are: magnetic core, windings, electric connections, OLTC, bushings as well as solid and liquid internal insulation. All of them are subjected to some magnetic, dielectric, mechanic, thermal stresses and also to a change of the dielectric properties of the solid insulation and electroinsulating oil over time and under the action of moisture. The cumulated effect of these factors leads to insulation ageing and to dielectric properties decrease generating the occurrence of some irreversible phenomena liable to diminish the active lifetime of the transformers.

Though the power transformers proved their reliability, a series of failures during operation are generated by the loss of the mechanical stability that is impossible to control without taking them out of operation and untanking them.

Since this is a problem of a great importance both for the power grid and for power transformer manufacturers this paper aims at presenting a series of considerations on the axial clamping forces form the transformers.

After a review of the clamping systems for winding pressing and stabilization on core columns, made usually by transformer manufacturer, there are presented the evaluation methods for the mechanical condition of a transformer. Hereinafter, there are presented elements used for the calculation of the axial forces in the insulating structure and there are defined some critical situations appeared in transformer practice, generated by conductor displacement and winding deformation.

The aspects presented in the paper could be a beginning for a thorough study of the mechanical stability of the power transformers by monitoring it during operation.

2. EVALUATION OF THE METHODS FOR AXIAL CLAMPING FORCES GENERATION IN POWER TRANSFORMERS

2.1. Rigid axial clamping system

At present, to generate the axial clamping forces in transformer manufacturing it is used the classical method consisting of a rigid pressing system placed both at the upper and at the lower parts of transformer windings [2,6]. The pressing system consists of the following elements for the entire range of power transformers starting from the ones with small powers and low and medium voltages, ranged 10-40MVA/15-110kV, to transformers with high and very high powers and voltages ranged 50-400MVA/110-400kV:
- metallic structure consisting of: upper and lower frameworks, pressing plates and tie rod plates mounted on core columns and made of ordinary/ non-magnetic steel;
- bolts, clamp nuts and metallic pressing plates made of ordinary/ non-magnetic steel, placed at the upper part of the windings;
- common clamping rings made of transformerboard, placed at the upper and lower parts;
- insulating supports made of transformerboard, both at the upper and at the lower parts.

2.1.1. Pressing system description

In principle, for each column of the magnetic core, the pressing system of the winding assembly is placed in the upper part in symmetrically disposed pressing points established depending on the internal construction of the transformer. The axial clamping forces of the winding assembly at the upper part are generated as shown in Fig.1.

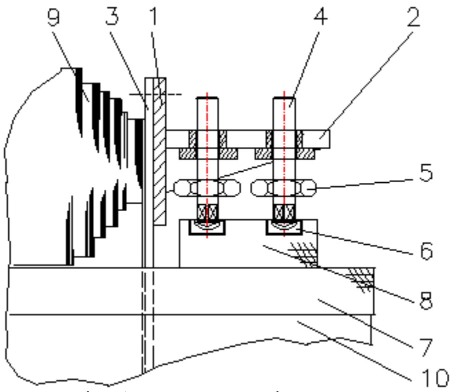

Fig. 1: Upper pressing system:
1- Upper framework; 2- pressing plate; 3- tie rod plate; 4- clamping bolt; 5- clamp nut; 6-metallic plate; 7- common upper clamping ring; 8- insulating support; 9- magnetic core-upper yoke; 10- winding assembly on one column.

On each column of the magnetic core, the winding assembly pressing at the upper part in the points located on the common clamping ring provides a winding axial clamping force uniformly distributed on the surface of the said ring.

At the lower part of the windings, on the lower frameworks, there are welded support plates on which there are fixed insulating supports made of transformerboard, similar to the ones from the upper part. Their location corresponds to the pressing points from the upper part. The winding assemblies lean upon the above insulating supports by common clamping rings as shown in Fig.2.

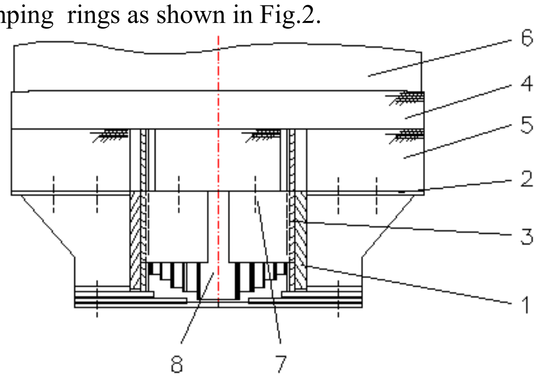

Fig. 2: Lower pressing system.
1- lower framework; 2- support plate; 3- tie rod plate; 4-lower common clamping ring; 5- insulating support; 6- one column winding assembly; 7- fastening screw; 8- magnetic core-lower yoke.

2.1.2. Mechanical stabilization of active transformer part

The mechanical stabilization of transformer windings is achieved in three distinct stages, namely:
1. Separate winding pressing;
2. Preliminary pressing of winding assemblies;
3. Mechanical fastening of transformer active part.

1. After the windings are made, they are pressed so that to frame within the overall dimensions specified by design documentation. So, the windings are compressed and dried separately in special ovens using a technology specific to each voltage class and winding type.

2. The separate windings formed in this way are mounted one in another and form the winding assemblies that are preliminary pressed at temperatures ranged within 95 - 105 ^{o}C in the same special ovens preparing them for the mounting on the magnetic core columns.

3. After mounting the winding assemblies on magnetic core columns and performing the electric connections between them, it is achieved the dimensional stability of the windings by applying two consecutive drying cycles in Kerosen vapour autoclaves at a temperature of 130^{o}C. The pursuing of these stages provides the proper drying of the paper and transformerboard solid insulation. At the same time, the winding pressing system is progressively and definitively clamped at the value prescribed by the technical documentation. The

extent to which these axial clamping forces are maintained during transformer lifetime represents a problem for all transformer manufacturers.

2.2. Special axial clamping systems

The transformers used in high power test laboratories or in electric ovens, operating in heavy duties and subjected to frequent short-circuits, have special pressing systems [1]. It is due to the fact that the internal structure for winding consolidation and pressing under the action of the axial forces frequently loses its time stability having as consequence transformer outage.

In practice, there are used two types of clamping systems, namely: elastic system and hydraulic one. As for the elastic system [1,3], it is about a hybrid system where the axial clamping is performed with pre-compressed calibrated springs. Within the hydraulic system [3], the axial clamping results from using a hydraulic cylinder system where the pressing system is maintained constant in time irrespective of transformer operation duty and at short-circuit transformers the pressing force is increased before each short-circuit.

There are some special transformer constructions as the ones used in the High Power Laboratory of ICMET [4,5] where it is used a classical rigid axial clamping system but due to a special construction of the tank, the pressing bolts may be tightened again after a number of short-circuits.

3. METHODS USED TO EVALUATE THE MECHANICAL CONDITION OF THE TRANSFORMER

The evaluation of the mechanical condition at a transformer is necessary to establish the result of a sudden short-circuit test in laboratory as well as to detect the decrease of the winding axial clamping force following the mechanical stresses in service due to short-circuit and in-rush currents, mechanical stresses appearing during transportation to the mounting place or following the thermal-oxidative ageing of the solid winding. The models used at present to evaluate the mechanical condition of the transformers are [5]:

■ Off-line methods:

- measurement of AC current leakage reactance of the transformer and its comparison with a reference value (fingerprint) [4];
- distortion measurement at a low voltage impulse (LVI) applied to the transformer related to a reference situation [5];
- Frequency response Analysis (FRA) of the transformer considered as a linear quadripole, also related to a reference situation [8].

■ On-line methods:

- Vibro-Acoustic Analysis (VAA) of the transformer which tries to detect, from the global vibration spectrum, the part that is affected by winding vibration [9] influenced by winding clamping weakening;
- transient oil pressure (TOP) in transformer tank [10], based on insulating oil pressure variation, where the significantly increased values of oil pressure are an indication of a critical loss of a winding system clamping force with no localization, related also to the previous measurements;
- direct axial force measurement in static and dynamic duty with force sensors [4,8]. This method was drawn up by ICMET and successfully used for the first time at the short-circuit transformers from the High power laboratory of ICMET. At present, the direct axial force measurement system implemented by ICMET replaces the common clamping bolts with special bolts with integrated force sensors having the same dimensions as the original ones, as shown in Fig.3.

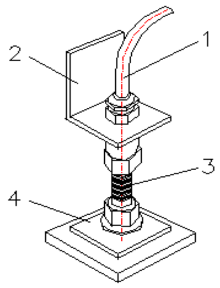

Fig.3: Clamping bolt with integrated force sensor.
1-force sensor; 2- metallic structure; 3- clamping bolt; 4- insulating pieces

The special sensor bolts offer to the system the capability to measure both static and time variable pressing forces within a frequency range between 50Hz and hundreds of Hz determined by the electrodynamic forces and by the eigenfrequencies specific to the construction. The software conceived for this system allows the acquisition; comparison and model based processing of the measured data taking into account the temperature and moisture of paper oil insulation. As regarding the costs, the new system with integrated force sensors is very cost-effective. So:

• the system enables the long term monitoring for one day, one week, one month, one year, of the events occurred during transformer operation;

• it can be used during transportation to transformer mounting place;

• it confers reliability due to the possibility to compare the real clamping forces with the initially prescribed ones and finally, the signalling of some abnormal situations during the entire transformer lifetime.

• the method can be used both as support for development tests and for the validation of some off-line testing methods, for example Frequency Response Analysis (FRA);

• on the basis of the information offered by this monitoring system, a data base type "Transformer Information System" may be set up as part of the project "Transformer Lifetime Data Management" developed at world level by CIGRE SC A2.

The presented methods can be applied to evaluate the mechanical condition of the power transformers starting from the detection of incipient failures to more serious ones that generally develop in progressive insulation deterioration followed by mechanical collapse.

4. CALCULATION ELEMENTS OF AXIAL CLAMPING FORCES. CRITICAL SITUATIONS

Transformer behaviour under the action of the axial forces generated in operation is associated with a combination of factors including: design of the windings and of the entire insulating system as well as the mechanical winding pressing that assumes a proper axial clamping. The pressing systems used at present in transformer manufacturing are scarce with respect to the uniform pressing of the windings mounted on the same column of the magnetic core. This is due to the following aspects:

• The clamping systems are common for an assembly of two or three windings (fig. 4).

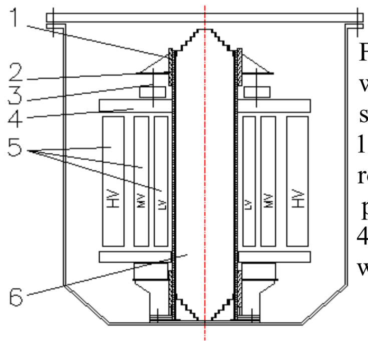

Fig.4: Common winding clamping system
1-frameworks; 2- tie rod plates;3-common pressing system; 4-clamping rings; 5-windings; 6-core

• The low, medium and high voltage windings composing the assembly from one column are completely different from the constructive viewpoint though they have the same geometric height.

• The compressibility degree is different due to the different quantities of active materials (copper - insulation) depending on the type and technical characteristics of the windings (voltages, currents, coil type, etc. That is why, the action of the axial clamping force, applied by means of the common clamping system, will be different at the level of each winding of the whole assembly.

In order to remove this deficiency, it could be used an independent clamping system for each winding placed on the same column, where transformer construction and existing technology allow it. This assumes the existence of some separate clamping rings and pressing system for each concentric winding from the column. Up to then, at global level, taking into account the influence of these aspects on the proper operation of the transformers on their entire lifetime, it shows to be just to make efficient the axial clamping monitoring by using the new axial force measurement system as the one proposed by ICMET [4,5].

4.1. Mechanical stressing of the winding clamping rings

The common clamping rings are the main elements that can be destroyed by the electrodynamic forces appeared during the short-circuits. Under the action of the electrodynamic forces generated in the windings, the ring sections placed between two bolts tend to deform themselves. Consequently, it is very important to know the value of the forces acting on these transformerboard rings so that to be able to determine the critical value in case of failure. The stress on a circular clamping ring can be calculated, in a first hypothesis, assuming that the ring bears the force in the points where the clamping bolts are located [7]. The bending moment (M_1) and the resistance module (W) of the clamping ring are given by:

$$M_1 = \frac{F_{at}\pi D_m}{8n^2} \quad \text{[kgf.cm]}, \qquad (1)$$

$$W = \frac{1}{6}ch^2 \qquad (2)$$

resulting the maximum bending stress given by:

$$\sigma_{1\max} = \frac{M_1}{W} = \frac{3\pi F_{at} D_m}{4ch^2 n^2} \text{[kgf/cm}^2\text{]} \qquad (3)$$

where:
F_{at} – total axial force
D_m – medium ring diameter
c – radial ring width
h – ring thickness
n – number of clamping (pressing) points

If the clamping ring is considered fixed beam (second calculation hypothesis) the bending moment becomes M_2 :

$$M_2 = \frac{F_{at}\pi D_m}{12n^2} \quad \text{[kgf/cm}^2\text{]} \qquad (4)$$

The resistance module remaining the same, calculated with relation (4.2). In this case, the maximum bending stress is given by relation:

$$\sigma_{2\max} = \frac{M_2}{W} = \frac{6\pi F_{at} D_m}{12ch^2 n^2} = \frac{\pi F_{at} D_m}{2ch^2 n^2} \text{[kgf/cm}^2\text{]} \qquad (5)$$

Comparing relations (4.3) and (4.5) it results:

$$\sigma_{1\max} > \sigma_{2\max}$$

When designing, the stress can be calculated taking the mean value of the two moments above namely:

$$M_3 = \frac{\pi F_{at} D_m}{10n^2} \text{[kgf/cm}^2\text{]} \qquad (6)$$

It results the bending stress:

$$\sigma_{3\max} = \frac{6\pi F_{at} D_m}{10ch^2 n^2} = \frac{3\pi F_{at} D_m}{5ch^2 n^2} \text{ [kgf/cm}^2\text{]} \qquad (7)$$

The value of which must be within the permissible limits established on the basis of the material properties and safety coefficient.

4.2. Mechanical stress in the metallic structure of the pressing system

The frameworks shall bear the the static load of the transformer (core and winding weight) during the transport, mounting and handling activities as well as the clamping, fastening and stabilization stresses of the windings during manufacturing. During a short-circuit appeared in the transformer, the axial forces and the mechanical shocks act on the frameworks and tie rod plates, submitting them to high shearing and tensile forces that tend to destabilize mechanically this rigid structure.

For a good behaviour in such critical situations, the dimensioning of the entire metallic structure is made following some strength check calculations of the clamping forces and static load as well as of the dynamic short-circuit stresses.

4.3. Critical situations generated by the axial clamping force level

In practice, it is very often when critical situations of mechanical instability of transformer windings appear generated especially by the use of CTC in the low voltage winding. The physical and mechanical properties of CTC may influence unfavourably winding behaviour in case of a short-circuit stress [11]. In these cases, the axial clamping force level can cause the instability of the used CTC leading to its displacement, tilting or twisting inside the winding turns. Therefore, the uncontrolled level of the winding axial clamping forces namely, either too high level determining a clamping pressure over the permissible limit or too low level when the clamping pressure is insufficient, or even force absence (at the worn out transformers in operation), increases the probability of winding conductor displacement being a major cause of axial instability and failure. An important element that must be taken into consideration is CTC rigidity degree given by the number of elementary wires of its structure. In abnormal operation cases, the high rigidity degree of CTC can cause the irreversible deformation of the winding turns that is one of the main mechanical failure modes. Following some experimental studies, [11], it was drawn the conclusion that a CTC containing a small number of elementary wires is more mechanically stable than one with a greater number of elementary wires.

The failure modes generated by the axial forces mentioned in transformer practice that use CTC type conductor are the following ones [1,11]:

- Loss of winding axial stability due to coil wires tilting in the same direction transmitted to the whole cluster of adjacent wires inside the turn. This displacement has as a result the pushing of the next axially adjacent conductor cluster in opposite direction resulting a “zig-zag” displacement as can be seen in Fig.5.

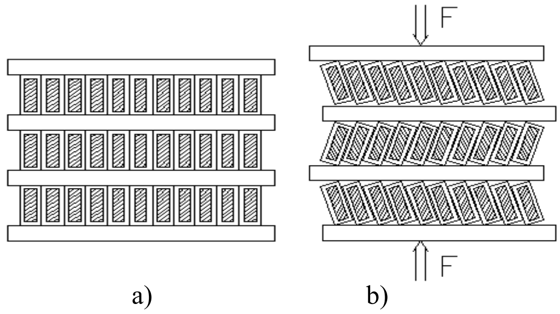

Fig. 5: Wires tilting under the action of axial force a) normal position; b) tilted position, result of exceeding a certain limit of axial effort

- Axial failure of the winding caused by elementary wires displacement inside CTC;
- Axial failure of multilayer type windings owed to telescoping, explained by the overlapping of some turns over other axially adjacent ones due to radial weakening of the turn because of conductor stretching;
- Conductor bending in the area where the spaces are placed as shown in Fig. 6.

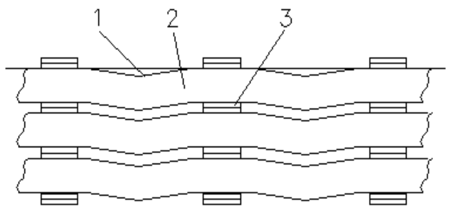

Fig. 6: Conductor axial bending between spacer rows .
1-conductor deflection; 2-winding conductor; 3-key spacer

- Deformation or even breakage of transformer clamping rings that may cause axial deformation of the winding
- Mechanical damaging of the insulation due to the friction between conductors and spacers and to hammering effect;

In all these critical situations, the immediate effects of the appeared failures are: damaging of conductor insulation and of the insulation between winding turns as well as short-circuit appearance between conductors or adjacent turns due to phenomenon amplification.

5. CONCLUSIONS

1. The present technology for the achievement of the axial clamping forces does not provide a long term mechanical stability of winding pressing in a power transformer during its active lifetime.

2. The issue of axial clamping proves to be a phenomenon difficult to control in time at the transformers with a rigid pressing system.

3. In the case of special transformers for heavy operation duties, whose construction uses special pressing systems, the winding mechanical stability is ensured for all their active lifetime but the constructive systems are much more expensive.

4. The multilayer type low voltage windings made of Continuously Transposed Cable (CTC) present a higher failure risk due to the high mechanical instability that is characteristic to this type of conductor.

5. At present, ICMET has developed a new system for the axial clamping forces monitoring by direct measurement with force sensors that replaces the common bolts both in permanent and in transient duty.

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