Transformer Tank Vibration Modeling as a Method of Detecting Winding Deformations—Part I: Theoretical Foundation

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***Abstract*—In this paper, a model developed for a transformer monitoring system to estimate transformer tank vibration is presented. The model calculates vibration on the transformer tank starting from some input variables that can be easily measured on the transformer. Tank vibration is also measured, showing a good concordance between estimated and measured values if the transformer is healthy. In case of a winding deformation winding vibration and, consequently, that of the tank, changes and a big difference between estimated and measured vibration appear. To estimate tank vibration, the model takes into account the main physical phenomena generating vibrations in the different transformer elements and how these vibrations are superposed and transmitted to the tank. The model has been tested experimentally on a test transformer fitted with internal and external accelerometers. A deformation has been provoked in the test transformer winding with the aim of testing the model's ability to detect it. The model has been also tested on several in-service grid transformers. The results of the experimental validation are shown in Part II of the paper.**

***Index Terms*—Condition monitoring, failure early detection, power transformer, tank vibration, winding deformation.**

I. Introduction

TWELVE to 15% of transformer failures are caused by winding deformations provoked by the high electrodynamic forces appearing during short circuits [2]. These geometric variations lead to an increase of the winding vibration and, consequently, to an increase of the solid insulation mechanical fatigue. In this way, the isolation can be degraded and short circuits between turns will appear [3]. On the other hand, a change in the distances among conductors implies a change in series and shunt capacitances and, thus, the voltage distribution in case of lightning or switching overvoltage being different from that which the transformer was designed to withstand, increasing the risk of failure. From these considerations, the relevance of an early detection of winding deformations is clear.

Some techniques, such as frequency-response analysis (FRA) [2], [4] or leakage reactance measurement [5], are widely used to detect changes in transformer geometry, especially winding deformations. Although, in recent years, some publications have appeared reporting some online application of these techniques [6], [7], at the moment they are used only in offline tests. Transformer tank vibration monitoring is proposed in this paper as a complementary technique to FRA or leakage reactance measurement (LRM) having the advantage that it can be used for online monitoring and, thus, catastrophic failures can be avoided between successive maintenance outages.

Vibration analysis is a key test in rotating machines' predictive maintenance programs and is widely used to detect onload tap changer failures by means of the noise signature analysis during tap regulation [8], [9]. Use of the main tank vibration as a diagnosis tool is not very common, nonetheless some references have been found as to the monitoring of this variable.

Booth in collaboration with MIT [10] proposes vibration monitoring using a back-propagation neural network that calculates the amplitude of 100-, 200-, and 300-Hz vibration components, taking as input variables the three main harmonics of the core vibrations, current, and temperature in several transformer points. Aschwanden [11] monitors vibration and analyzes 19th main harmonics by means of a self-organizing Kohonen map. Mechefske [12] reports an experience about tank vibration monitoring over two twin units, one of them with a loose winding clamping, reporting significant differences between the amplitude of harmonic vibrations, the time to reach the steady-state after a load change and the harmonic content in the high-frequency range in both transformers. Bartoletti [8] uses four parameters (total harmonic distortion in the low- and high-frequency range, the sum of harmonic amplitudes, and ratio of main harmonics) to classify transformers into new, used, and anomalous. Finally, the Cutler–Hammer company commercializes a system to detect winding deformations or loosened clampings in the core [13]; the system measures vibrations at 12 points placed at the top of the tank with the transformer working on no load and with high loads. From these measurements, winding and core clamping coefficients are calculated.

In this paper, the use of a model to monitor tank vibrations is proposed. The strategy of model-based transformer monitoring systems was proposed by MIT researchers [14] with the aim of allowing the early detection of failures in a transformer. For this purpose, some transformer key variables are calculated by models from some input variables. A great difference between calculated and measured values is an indication as to a structural change in the transformer, and an alarm is then emitted.

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The advantage of model-based monitoring in contrast to a traditional threshold-based one is that transformer global working conditions are taken into account when emitting an alarm. Many commercial monitoring systems use this technique to monitor some variables, mainly temperature [11], [15].

The proposed vibration model calculates a vibration main component on the tank wall under given working conditions. The model takes into account how vibrations are generated in different transformer components and how these vibrations are superposed and transmitted until reaching the tank. Comparing the calculated vibration with the measured one, the model is able to detect winding deformations that lead to a change in the transformer vibration. Differences between measured and computed vibration can also be due to looseness of windings or core. To make the model applicable both to new and to in-service transformers, all of the input and output variables must be measured using external sensors only.

To test the model experimentally, a test transformer was used with accelerometers placed on several internal and external points. In order to load the transformer with varying loads and power factors over a wide range, the opposition method described in IEC 60 076-2 Standard was used. Vibration measurements were performed on the test transformer under different loads, power factors, and temperatures. To test the model's ability to detect winding deformations, a deformation has been provoked in the test transformer winding. Finally, the model validation over an inservice grid transformer owned by the Spanish utility Unión Fenosa is analyzed in the companion paper [1].

II. Vibration Model

Vibrations in a transformer are generated by the different forces appearing in the core and in the windings during the operation. Next, the phenomena causing vibrations in the transformer are briefly reviewed.

A. Forces in the Transformer

The main sources of vibration are forces appearing in the winding and the core. As the model calculates fundamental vibration (100 Hz), vibration generated by partial discharges is not taken into account.

Winding vibrations are due to electrodynamic forces caused by the interaction of the current in a winding with leakage flux (B_d). These forces are proportional to the current squared and they have components in axial and radial directions. Axial forces tend to compress the winding vertically. In a simple case of a two-winding transformer, radial forces tend to compress the internal winding and to expand the external one, since currents in both windings flow in opposite directions. Fig. 1 shows the directions of radial and axial forces and their relative magnitude depending on the height ($F'_{\rm rad}F'_{\rm ax}$) and the radius ($F''_{\rm rad}$) of the transformer winding.

Since vibration depends on current squared and taking into account that current is practically sinusoidal (50 Hz in Europe), the winding vibration main harmonic component is that of 100 Hz. Some contribution to 100-Hz vibration can come due to magnetizing current harmonics or to some residual harmonic currents

$$F_w \propto i^2. \tag{1}$$

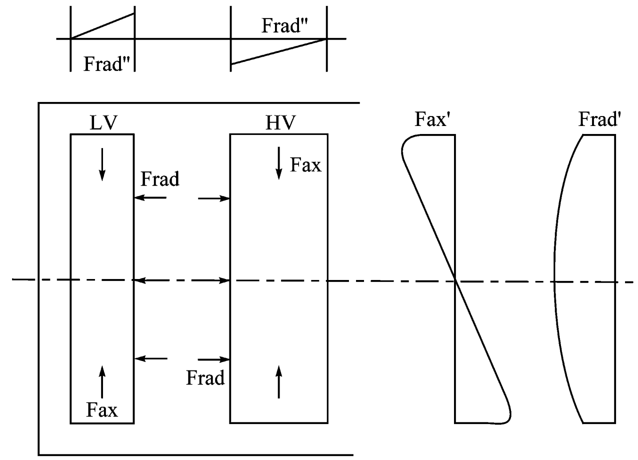

Fig. 1. Forces distribution within the windings. Taken from [16] and modified.

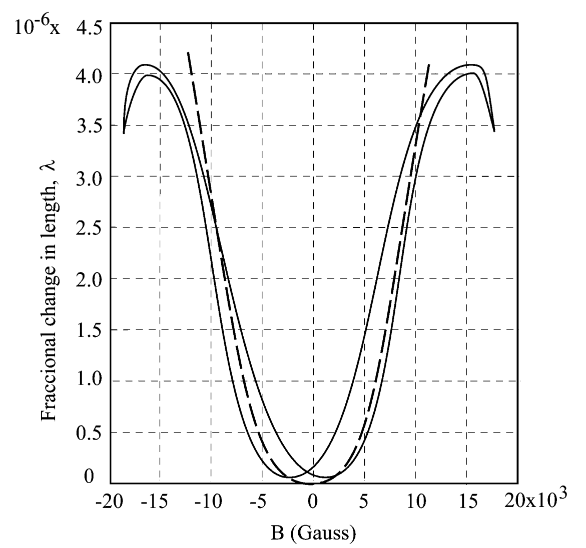

Fig. 2. Iron magnetostriction as a function of induction. Taken from [17] and modified.

Core vibration is caused by magnetostriction and magnetic forces.

Magnetic materials suffer minute changes in their dimensions of a few parts per million, when they are submitted to a magnetic field (magnetostriction) [17]. Fig. 2 shows the relationship between length variation (in %) and iron magnetic flux density. As can be seen, the curve represents hysteresis. Neglecting the hysteresis effect, this curve (plotted in the continuous line in Fig. 2) can be replaced by the idealized curve plotted in the dashed line in Fig. 2. The mathematical expression of the idealized curve can be approximated to a quadratic law, establishing a linear relation between the elongation and the flux density squared.

Taking into account the relation between applied voltage and flux density (2) and admitting the elongation is proportional to the force, the result is magnetostriction forces being proportional to voltage squared

$$U = \frac{2\pi}{\sqrt{2}} f N B_s \quad (2)$$

$$F_c \propto U^2. \quad (3)$$

Magnetostriction forces fundamental frequency is 100 Hz (in Europe), with harmonics being an even multiple of 50 Hz. Higher frequency harmonics are due to the nonlinear character of this phenomenon. Magnetostriction causes vibrations only in the core plane in an iron homogeneous mass [18], but the core is made of laminations and the joints between legs and yokes are overlapped. Under these conditions, flux density distribution is irregular because of small variations of the gap between legs and yokes laminations and by the interlaminar flux in the joints. This irregularity causes other magnetostriction forces to act in a plane perpendicular to the core [19]. Moreover, laminations have microscopic irregularities and friction among sheets excites other core vibration modes in a direction perpendicular to that of the lamination plane.

Other kinds of forces appearing tend to minimize the air-gap length between legs and yokes and, thus, the energy in the magnetic circuit. The forces are sinusoidal of 100-Hz frequency [18].

B. Transformer Vibrations

The forces analyzed in the previous section give rise to vibrations in the core and in the winding in various directions. Core and winding vibrations interact and transmit through the oil and the transformer supporting elements to the tank. To establish the model equation, it is assumed that the tank vibration in a given direction results from the addition of the winding and core vibrations in that direction multiplied by corresponding transmission coefficients

$$v_{\text{tank}} = t_1 v_{\text{winding}} + t_2 v_{\text{core}}. \quad (4)$$

Taking into account that winding and core vibration are proportional to current and voltage squared, respectively, and that both variables present their main components at 50-Hz frequency, the result is

$$v_{\text{tank},100} = t_1 i_{50}^2 + t_2 u_{50}^2. \quad (5)$$

A theoretical justification of this equation is provided in Appendix A.

To compute tank vibration from the superposition of core and winding vibration, the relative phase angle between both vibrations must be taken into account. As winding and core vibration depend on current and voltage, respectively, the phase angle between them depends on the power factor of the electrical load being transmitted through the transformer. To consider the phase angle between vibrations, the model will be formulated in complex variables.

C. Temperature Influence

To model vibrations properly, transformer temperature influence must be properly addressed.

There are several physical processes by which temperature influences vibration. First of all, magnetostriction is a nonlinear phenomenon which is dependent on temperature [17]. Moreover, temperature changes give rise to a change in oil viscosity that influences vibration transmission to the tank. Finally, temperature variations cause dilatation or compression of structural elements changing their natural vibration frequencies as well as the amplitude of forced oscillations. It is clear that temperature must not be included in the model as a system excitation, but must be introduced by a variation on the equation parameters instead. A simplified form to take into account temperature effects is given by

$$v_{\text{tank},100} = (\alpha + \beta\theta_{to}) i_{50}^2 + (\gamma + \delta\theta_{to}) u_{50}^2. \quad (6)$$

The vibration model algorithm is given by (6), where $v_{\text{tank},h}, i_h$, and u_h are complex variables that correspond to the real and imaginary parts of the tank vibration, current, and voltage main frequency components, and α, β, γ, and δ are complex parameters whose value depends on transformer geometry and which must be computed from data measured on the transformer. Parameters in (6) change slowly in time, because as the transformer ages, clamping pressure decreases, so vibration becomes greater [20]. Because of that, parameters must be recalculated after some years using the model.

D. Other Vibration Sources

Although the model only includes the calculation of vibrations produced by the core and by the windings, other elements vibrate during the transformer operation. These additional vibration sources are analyzed next explaining their influence in the model.

Every operation of the tap changer (LTC) produces a characteristic acoustic wave which propagates through the transformer oil and structures [21]. The model described in this paper is based in the analysis of the periodic vibrations and does not consider the LTC vibrations as they appear only after an LTC operation, producing transient vibrations that are added to the periodic ones caused by the core and the windings. In addition, some authors reported that the main components of LTC vibrations lie within the range of kilohertz [21], [20]. The great difference of the frequency range of both phenomena is another reason that justifies analyzing them separately.

The elements of the refrigeration system (i.e., oil pumps and fans) also generate vibrations that are added to the main vibrations. These elements do not operate in a continuous way, as they used to be switched on or off depending on the transformer working temperature, but when they work, a periodic vibration signal appears. As will be explained in the next section, the effect of this vibration is considered by the model by a different set of model parameters.

III. Vibration Experimental Analysis

A set of measurements was performed on the test transformer to adequately choose the point of the tank where vibrations should be measured, so that it reflects the transformer internal behavior as well as possible. The influence of the transformer refrigeration mode has been also analyzed.

As described in the companion paper, the test transformer was fitted with internal and external accelerometers and was installed into a test facility allowing the load and power factor

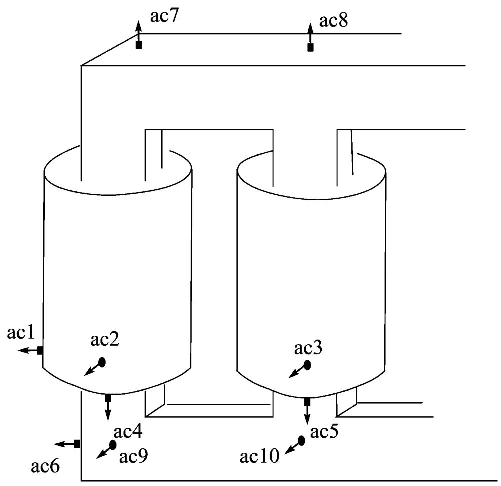

Fig. 3. Internal accelerometer installed on the test transformer.

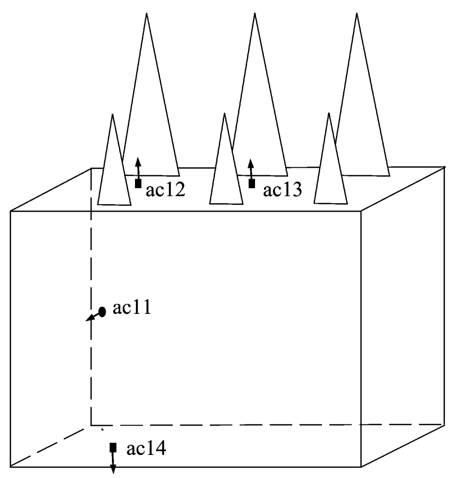

Fig. 4. Accelerometer installed on the test transformer tank.

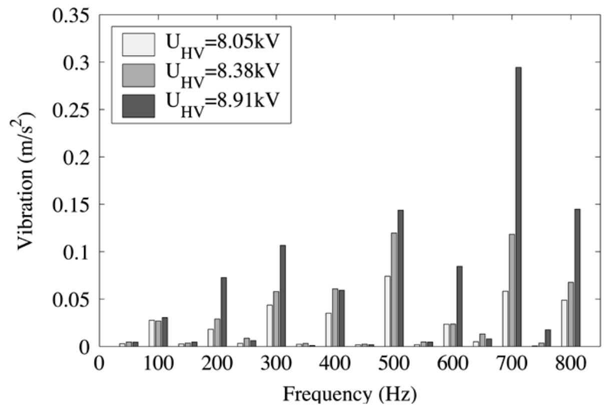

Fig. 5. Central phase winding vibration in an axial direction (accelerometer ac5) for different applied voltages with the transformer on no load.

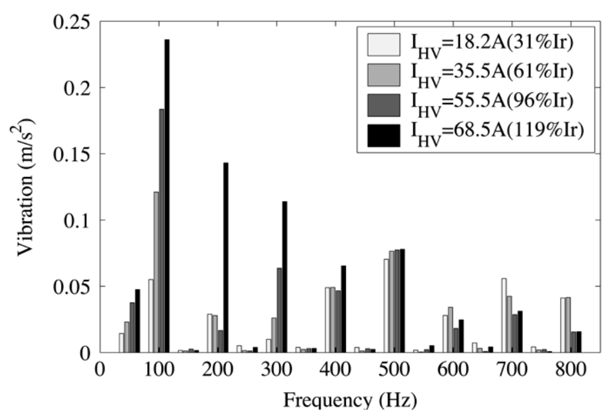

Fig. 6. Winding axial vibrations (accelerometer ac5) for different loads.

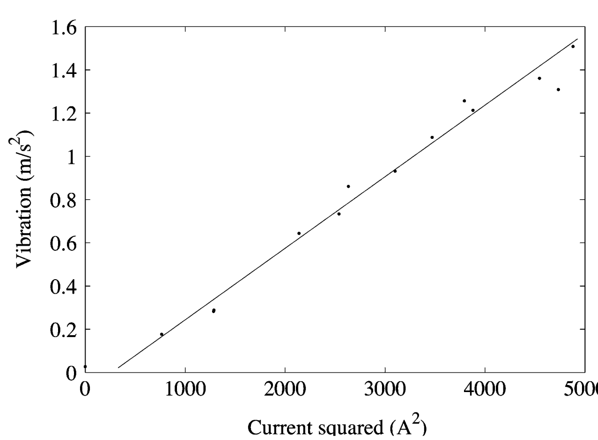

Fig. 7. Winding axial vibration versus current squared.

to be varied over a wide range. In this section, its main conclusions are resumed. Figs. 3 and 4 show the location of the accelerometers.

To analyze core-generated vibrations, some no-load tests with different supplying voltages were carried out. Several tests were made also with different loads to analyze winding-generated vibrations.

Fig. 5 shows winding vibration in axial direction on no load. Fig. 6 shows winding vibration under four different loads (between 30% and 119% rated current). As can be seen, the main vibration frequency appears at 100 Hz; these 100-Hz vibrations are generated by the windings as it did not appear when the transformer was not loaded (Fig. 5). The 100-Hz vibration presents a linear relation with current squared, as shown in Fig. 7. A correlation 0.80 was obtained between both variables. This is coherent with the theoretical analysis of the winding vibration. Higher vibration harmonics have an amplitude that is much lower than that of the main component (100 Hz).

Vibrations measured at different points of the tank when the transformer is on load were also analyzed to find the zone in which vibrations are closest to the internal ones. As can be seen in Fig. 8, the vibration at the bottom of the tank is very similar to that obtained in the winding axial direction (Fig. 6). The 100-Hz component of the bottom tank vibration presents a quadratic dependence with current as shown in Fig. 9. A correlation coefficient of 0.96 is obtained between both variables. When the transformer is on no load, 100-Hz vibration also appears in the tank (Fig. 10) whose amplitude increases with the supplying voltage (Fig. 11), which means that the 100-Hz component at the tank is also caused to some extent by the core vibration.

From these tests, it has been concluded that the most adequate points to measure the vibrations on the tank are at the bottom of the tank under the core legs.

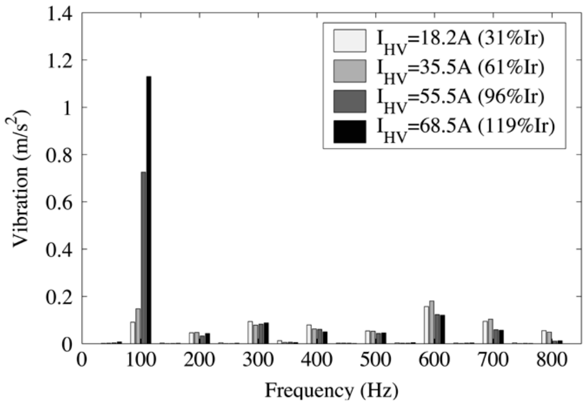

Fig. 8. Vibrations of the bottom part of the tank (accelerometer ac14) for different loads.

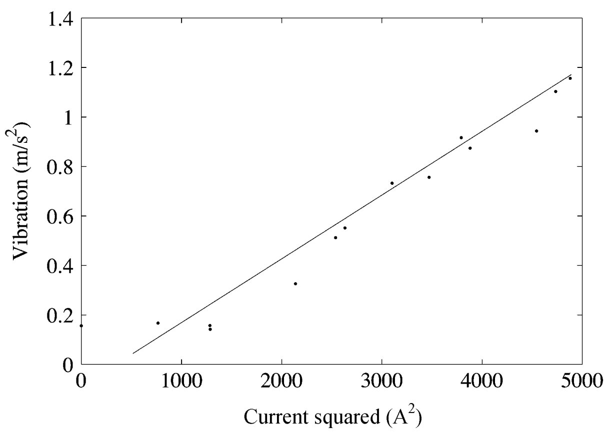

Fig. 9. Vibration of the bottom of the tank (accelerometer ac14) versus current squared.

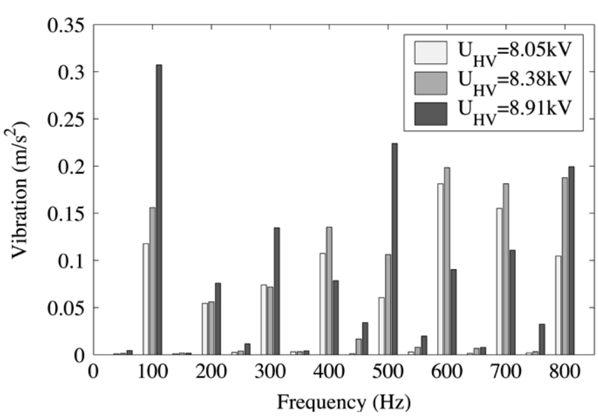

Fig. 10. No-load vibrations at the bottom of the tank (accelerometer ac14).

As can be seen in Fig. 8, an amplitude of higher vibration harmonics measured at this point of the tank (as those measured directly on the winding) is much lower than that of the 100-Hz component, and has no dependence with the model input variables. Based on these results, the model does not take into consideration high-order vibrations.

The influence of the cooling mode in vibrations was also analyzed to determine if the status of the oil pump should be taken into account by the model. A set of measurements was taken with the transformer operating at constant load (106.5%) and

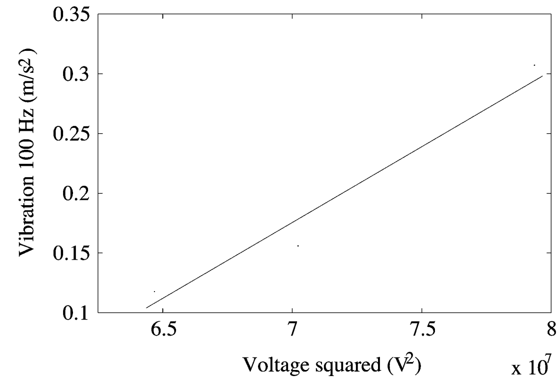

Fig. 11. No-load vibrations at the bottom of the tank (accelerometer ac14).

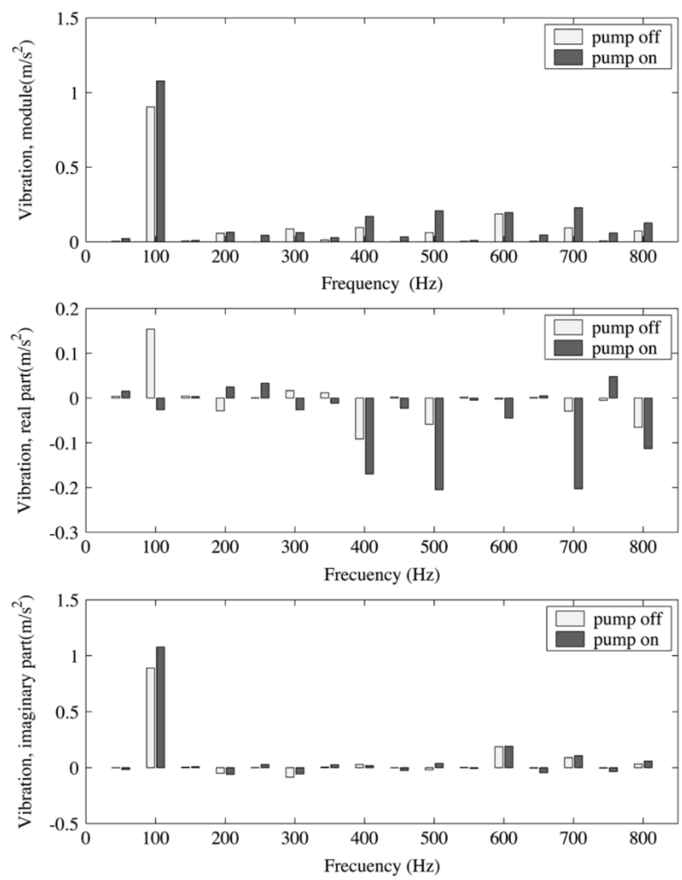

Fig. 12. Vibration in the bottom of the tank (accelerometer ac14) for natural oil circulation and forced oil circulation.

power factor (0.7) and the oil pump was switched on or switched off. Fig. 12 shows the measurements on the bottom of the tank in both cases. As can be seen, there are clear differences between both vibration spectra. So the model must consider separately the cases in which the transformer operates with the pump on from those in which the pump is off. The way to do this is by using a different set of model parameters ($\alpha_i, \beta_i, \gamma_i$, and δ_i) for each different cooling mode.

IV. Conclusion

In this paper, tank vibration monitoring has been proposed as a method to detect winding deformations in power trans-

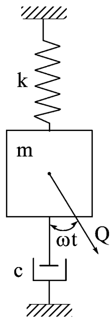

Fig. 13. Vibration of a mass suspended by a spring subjected to a sinusoidal force. Taken from [22].

formers. A model has been developed to calculate tank vibrations, taking into account transformer operating conditions. The vibration calculated value is compared with the measured one being a great discordance between both values a sign of a possible change in the transformer geometry.

The model takes into account how the vibrations are generated at different transformer components. Winding vibrations are provoked by the electrodynamic forces caused by the interaction of the current in windings with the leakage flux, and their value depending on the current squared. Core vibrations are caused by magnetostriction depending on the voltage squared. The model includes the effects of temperature on vibration generation, superposition, and transmission to the tank.

Only the main component of tank vibration is used in the model, as higher harmonics are much lower and do not show a strong dependence with current.

Tests have been carried out to localize the best point of the tank to place the accelerometers to measure vibrations. The conclusions of these tests are reported in the paper. The status of the oil pump affects vibrations, so the model parameters are different depending on the cooling mode.

APPENDIX

The forces appearing during transformer normal operation produce vibrations in the core and in the winding in several directions. To study the problem of the interaction of these vibrations, it can be simplified by analyzing the vibration of each element separately in a one-dimensional (1-D) way, taking into account only the forces acting on the considered direction.

In this way, the problem can be considered as being similar to the analysis of the vibration of a mass suspended by a spring when subjected to a sinusoidal force (Fig. 13). To take into account the oil friction for the windings vibration, a viscous damping term was included.

In [22], this problem is modeled through the differential equation

$$m\ddot{x} = -kx - c\dot{x} + Q\cos\omega t. \tag{7}$$

The solution of this equation is the adding of two terms: the first one represents the system natural response, and the second one is the system forced response

$$x = e^{-nt}(C_1\cos p_d t + C_2\sin p_d t) + M\cos\omega t + N\sin\omega t \tag{8}$$

where

$$p^2 = \frac{k}{m} \tag{9}$$

$$2n = \frac{c}{m} \tag{10}$$

$$q = \frac{Q}{m} \tag{11}$$

$$M = \frac{q(p^2-\omega^2)}{(p^2-\omega^2)^2+4n^2\omega^2} \tag{12}$$

$$N = \frac{q(2n\omega)}{(p^2-\omega^2)^2+4n^2\omega^2} \tag{13}$$

$$p_d = \sqrt{p^2+n^2} \tag{14}$$

where C_1 and C_2 are constants that can be computed from the initial conditions.

The system's natural response is oscillatory being $p_d/2\pi$ the natural frequency and vanishes with a time constant $1/n$ because of the viscous damping. The forced term is sinusoidal with the same frequency of the applied force. The forced response remains while the force is acting.

The output variable of our model is the acceleration of the mass that can be obtained by differentiating (8) twice

$$\begin{aligned}\ddot{x} = e^{-nt}&\left(\left(-C_1p_d^2 - 2np_dC_2 + n^2C_1\right)\cos p_d t\right.\\ &\left.+\left(-C_2p_d^2 + 2np_dC_1 + n^2C_2\right)\sin p_d t\right)\\ &- M\omega^2\cos\omega t - N\omega^2\sin\omega t.\end{aligned} \tag{15}$$

The forced vibration is oscillatory with the same frequency of the applied force and with an amplitude proportional to it

$$\ddot{x}_f = K_1Q\cos(\omega t) + QK_2\sin(\omega t). \tag{16}$$

Applying the previous analysis to winding vibrations and taking into account the expression of the force on the winding results

$$v_w \propto \left(\sum_h i_h\cos(2\pi ft + \varphi_{u_{1,50}i_f})\right)^2 \tag{17}$$

where i_h is the amplitude of the h-frequency harmonic of current and $\varphi_{u_{1,50}i_h}$ is the phase angle of this harmonic with respect to the phase origin, taking the 50-Hz component of high-voltage voltage as the phase origin.

In the same way, the expression for the core vibration is

$$v_c \propto \left(\sum_h u_h\cos\left(2\pi ft + \varphi_{u_{1,50}i_h}\right)\right)^2. \tag{18}$$

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