

Voltage and vibration fluctuations in power transformers

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ABSTRACT

A power transformer is designed to work within a range of steady-state voltages and to be capable of withstanding emergency voltages according to its design requirements. However, both voltage variations and changes in the transformer's structural properties are responsible for changes in transformer vibration. A separation of the sources of the changes in transformer vibration is necessary for extracting possible changes in the transformer's structure for condition monitoring purposes. Common sources of voltage variation, *e.g.*, power source fluctuations and secondary loading operations, are investigated with a focus on their effects on transformer vibration. The effects of changes in the winding and core clamping pressures on transformer vibration are also investigated. Experimental results show a high correlation between voltage fluctuation and vibration changes without transformer structure anomalies. When the system's clamping force changed, the vibration difference becomes much larger than that induced by background voltage variations.

1. INTRODUCTION

Transformer vibrations are mainly generated in the transformer core and windings by electromagnetic and magnetostrictive forces, and there is an enormous body of research in this area (Boczar, et al, 2008). Magnetisation in the transformer core area is well known as a source of magnetostriction and core vibration. With respect to the magnetic force between individual sheets of the laminated core, the attractive or repulsive forces are also deemed to be a possible source of core vibration. It should be noted that both magnetostriction and magnetic forces in the transformer core are closely related to the primary voltage, which determines the magnetic field in the core. On the transformer winding, the only force applied to it is the electromagnetic force. It is very straightforward to show that electromagnetic forces are proportional to the square of the load current (García, Burgos, and Alonso, 2006). Since the consumption of electricity in local power grids usually occurs randomly, the transformer load varies over time, which induces voltage fluctuation. The corresponding change in the magnitude of the secondary voltage, expressed as a percentage of the rating voltage, is defined as voltage fluctuation (Lackey and Palmer, 1977).

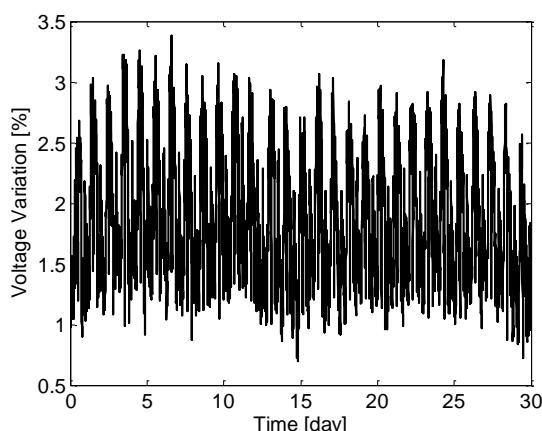


Figure 1. Time-history of voltage variation around the rating voltage of a 500 kV/250 MVA power transformer.

Figure 1 shows the voltage fluctuation (r.m.s) time-history of a 500 kV/250 MVA power transformer over the period of a month. A voltage variation of between 1 and 3% was found from the measurement.

The voltage fluctuation of a power transformer is permitted within a certain range, and is determined by fluctuations in the source voltage and loading current. It has a direct influence on the transformer's dynamic responses, by causing a change in core vibration. Because voltage fluctuation in an electrical network will also cause current changes in the winding, winding vibration can also be a cause of such changes in the transformer's dynamic properties as well.

In view of the previous research, the mechanical integrity of both windings and core stacks is vitally important to a transformer's normal operation. Mechanical looseness and winding deformation have been studied as typical causes of the loss of a transformer's mechanical integrity for decades (Berler, et al, 2000).

As a transformer ages, the mechanical endurance of the paper insulation is considerably decreased. Therefore, for a given clamping clearance, the clamping pressure will vary according to the expansion or shrinkage tendency of the cellulose (Prevost, Krause, and Woodcock, 2000). Under extremely harsh conditions, electromagnetic forces can cause deformation damages to the windings. The structural changes caused by thermal, chemical and mechanical deformations would all accumulate over time, and eventually result in failure if not regularly maintained. Therefore, research into failure detection methods has become increasingly popular and has precipitated the development of fault prognosis (García, Burgos, and Alonso, 2006).

The vibration features associated with the changes in the mechanical parameters of a transformer's winding and core can be employed as a useful fault detection tool (García, Burgos, and Alonso, 2006). Currently, variations in transformer vibration are mainly explained by changes in the transformer's structure. However, when the voltage varies in a transformer circuit, the excitation forces, which generate transformer vibration, also change accordingly. This paper will focus on the relationship between vibration variation and voltage fluctuation in power transformers based on a 10 kVA single-phase transformer.

2. EXPERIMENTAL SETUP

The test transformer was a 10 kVA single-phase transformer with rating voltages of 415/240 V. Its nominal current was 20

A in the primary winding (240 turns) and 35 A in the secondary winding (140 turns). Winding clamping pressure was uniformly supplied by four bolts through two resin pressboards. The transformer core was stacked by 0.27-mm-thick grain-oriented silicon-iron (SiFe) sheets. At each joint region, overlapping was created using the conventional single-step-lap method. The core stack was fixed in place by sets of metal brackets clamped with eight bolts.

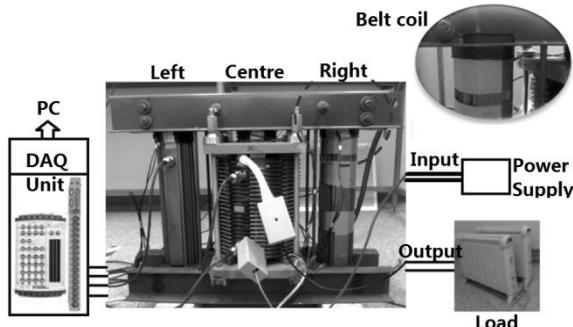


Figure 2. The experimental rig and test procedure schematic.

The transformer assembly is shown in Figure 2. A variable transformer was employed to supply desirable input voltages (0 to 460 V) to the model transformer. At the low-voltage (LV) end, a group of heaters were connected in parallel to act as resistive loads. During the tests, the model transformer was fed with variable voltages and operated with a series of loading combinations. Two kinds of mechanical failure were introduced to the model transformer in terms of winding and core clamping looseness. For all of the above cases, both the high and low voltages and the transformer's vibrations were recorded for further analysis. The measurement of these voltages was realised by using two step-down transformers to adjust the high voltage (HV) into an acceptable range for the DAQ card.

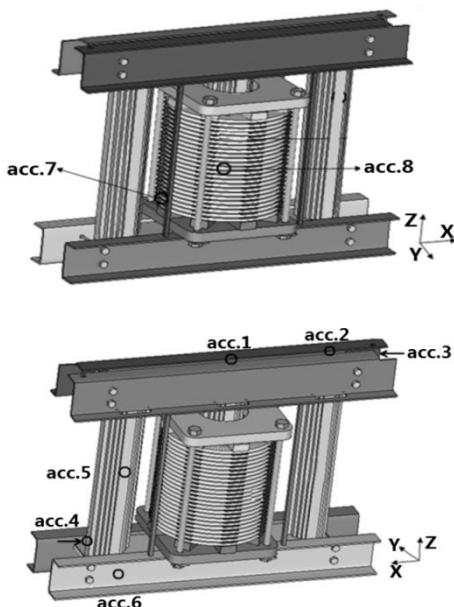


Figure 3. Measurement locations.

The vibration of the transformer was measured by eight high-sensitivity accelerometers (IMI, model 601A12), attached to eight locations on the transformer. Their locations are shown in Figure 3. The acceleration signals were amplified and digitalized by a DeltaTron Conditioning Amplifier (Brüel & Kjaer) and a USB 6259 DAQ card (NI). Each limb of the core was wound tightly by a belt coil (seven turns) to measure

the main magnetic flux in the core while excluding the influence of leakage flux. All of the tests were performed at room temperature.

3. RESULTS AND DISCUSSION

3.1 Voltage fluctuation and its relation to transformer vibration

Voltage fluctuation in the transformer circuit mainly comes from the power source variability and changes in transformer loading status. In this section, voltage fluctuations induced by those factors will be studied together with transformer vibration. As depicted in Figure 1, a voltage variation time-history of an in-service power transformer (500 kV/250 MVA) was recorded in September 2010. In the absence of automatic voltage regulating equipment, the transformer voltages varied with the loading variations. This normal voltage fluctuation commonly appears in most power grids and usually does not affect industry applications. However, the issue of whether its effects on transformer vibration can be neglected has not yet been verified. The following discussion, based on the experimental study of a model transformer, could provide a useful and instructive understanding of this topic.

3.1.1 Flux measurement and its engineering implementation

Voltage fluctuation in a transformer electrical network can directly affect the magnetizing process in the transformer core, which can be reflected by differences in flux density and distribution. Consequently, the magnetic and magnetostrictive forces are greatly affected. Therefore, core vibrations induced by magnetic forces and magnetostrictive effects will be changed at the same time. Since the transformer's HV and LV windings both enclose a certain volume of a non-ferromagnetic zone, the leakage flux within these areas contributes to the induced voltages. Direct measurement of the high or low voltages would include certain values of leakage electromotive force (EMF). In order to discover the relationship between vibration changes and voltage fluctuation, which is induced only by main flux variation in the transformer core, three belt coils were utilized to exclude the effects of leakage flux.

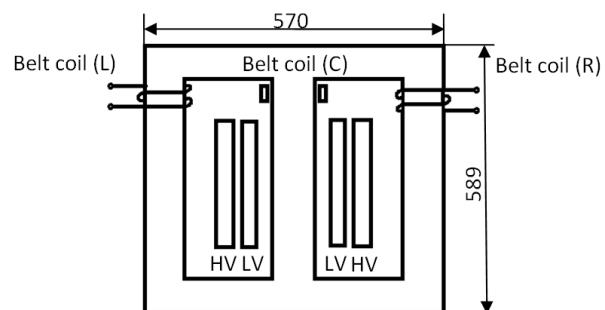


Figure 4. Schematic for main flux variation measurement through belt coil-induced EMF.

Three belt coils were installed at the left, central and right limbs. Each coil was wound clockwise with seven turns at the same location close to the top yoke (see the image in Figure 2). The overall dimensions of the core and belt coil locations are shown in Figure 4.

Belt coil-induced EMFs were recorded simultaneously with high and low voltages, currents and accelerations. Although the EMF induced by the belt coils excluded the influence of leakage flux, additional installations of those belt coils would cause unavoidable modifications to the power transformer. In

practice, voltage measurement in the transformer HV/LV ends is more convenient. To avoid those modifications, a test was designed to verify whether the load voltages can be substitute parameters for measurement of flux variation.

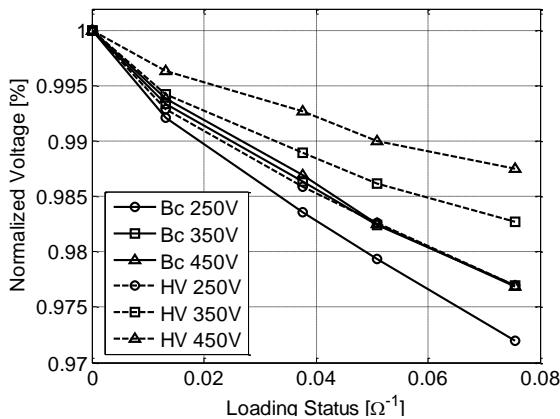


Figure 5. Centre belt coil inductive voltage and HV winding voltage under different load statuses.

In this test, induced voltages in the centre belt coil and the HV winding were measured under five load cases controlled by switching on different heater groups. The five loading statuses from the open circuit to a $13.24\ \Omega$ resistive load are defined as L1 to L5 load case. Figure 5 shows the normalized voltages for the five load cases at three operating voltages. Each voltage recorded from both belt coils and transformer winding were normalized with the voltage of the open-circuit load case. The dashed lines show inductive voltages in the centre belt coil at 250 V, 350 V and 450 V input voltages. In general, those inductive voltages all decrease with the load case from L1 to L5. The solid lines show voltage variation in the HV winding at the three input voltages. Like the voltage induced from the centre belt coil, HV winding induced voltage decreases with the load case as well. Since leakage flux is usually larger when the ferromagnetic core becomes saturated, the voltage tendencies at the 250 V and 350 V operating voltages show smaller discrepancies than that of the 450 V operating voltage.

The above discussion suggests that the primary voltage (*i.e.*, HV) variations can also be used as an estimator of the magnetic flux fluctuation when direct measurements in an in-service transformer are inconvenient.

3.1.2 Power source variability and its relation to transformer vibration

For an in-service transformer, there is a voltage variation of around 3%, as found in Figure 1. To simulate the power source variation in the model transformer, a variable transformer was installed to provide certain voltage fluctuations and flux variation. Since flux density and its distribution within a transformer core determine the core vibration, voltage fluctuation might be related to the transformer's vibration status. In this paper, the sum of all of the testing points' squared accelerations in terms of A_{tot} is employed to describe transformer vibration.

$$A_{tot} = \sum_{i=1}^8 A_i^2 \quad (1)$$

Figure 6 shows the voltage and vibration variations at three operating voltages. The voltage variations are normalized by the minimum voltages of each operating voltage.

Power source variability in terms of voltage variation causes 5.8%, 3.59% and 2.58% maximum differences at 250 V, 350 V and 450 V operating voltages, respectively. With regard to those voltage fluctuations, the changes in transformer vibration are found to be 0.89 dB, 0.64 dB and 0.84 dB. For all three operating voltages, the vibration fluctuates in the same way as voltage variation.

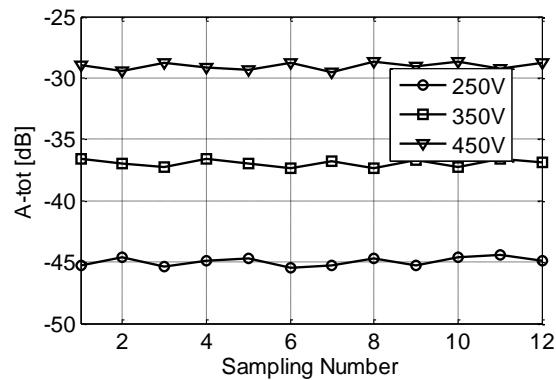
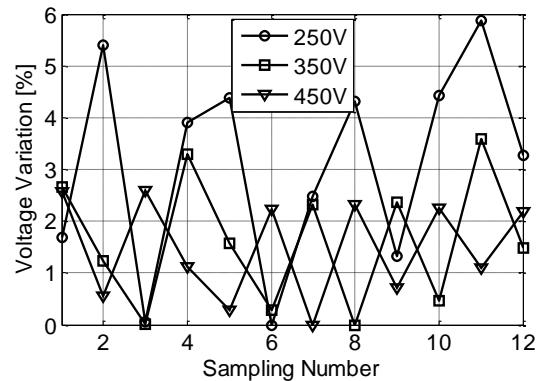


Figure 6. Power source variability and corresponding effects on transformer vibration.

For further investigation of the relationship between transformer voltages and vibration, correlation coefficients between them were calculated at three operating voltages. The correlation coefficient is calculated by:

$$\rho_{VA} = \frac{\text{cov}(V, A)}{\sigma_V \sigma_A} = \frac{E(dV - \mu_V)(dA - \mu_A)}{\sigma_V \sigma_A} \quad (2)$$

Where ρ_{VA} is correlation coefficient, σ_V (σ_A) is standard deviation of voltage variation (A_{tot}), dV (dA) is voltage (A_{tot}) variation, μ_V (μ_A) is mathematical expectation of voltage variation (A_{tot}).

Table 1 shows the correlation coefficients between transformer vibration and voltage fluctuation tendency.

Table 1. Correlation coefficients between voltage and vibration fluctuations.

Operating voltage	250 V	350 V	450 V
Correlation coefficient	0.974	0.9605	0.9148

Table 1 shows high correlation coefficients between vibration fluctuation and voltage variation due to power variability. Since the only parameter changed in each test is voltage, the vibration variation can be readily related to the changes in the

transformer voltage.

3.1.3 Loading status and its relation to transformer vibration

In this test, the secondary loading was shifted among 5 statuses. A comparison between the trend in voltage variation and the resulting vibration differences can be seen in Figure 7. Voltage variations at three operating voltages were normalized with voltages in the L5 load cases (full loading) by:

$$\Delta V_i = \frac{V_{Li} - V_{L5}}{V_{L5}} \times 100\%, (i = 1, 2, 3, 4), \quad (3)$$

where the reference voltages V_{L5} for the three operating voltages are 463.9 V, 371.7 V and 260.5 V. Voltage variations will be larger when switching between large loading spans, which are defined as secondary resistance variations. Figure 7 shows a clear decrease in primary voltages, while the maximum voltage differences are 2.96%, 2.29% and 2.1% as the resistive load decreases at the fundamental frequency. The overall trend in the transformer vibration is one of decline with the increase in resistive load. The maximum difference of measured acceleration between the open circuit and the full loading case is about 1 dB. As described in Section 3.1.1, a similar tendency can be found between voltage variation and changes in transformer vibration in Figure 5.

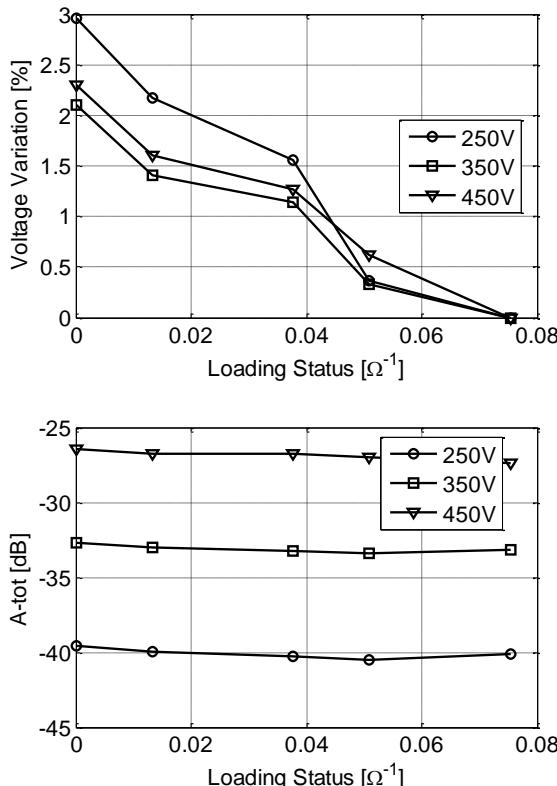


Figure 7. Voltage variation and the corresponding vibration changes at 5 loading statuses.

As the stability of the primary voltage supply can barely be identified simultaneously from the measurement of transformer input voltage, the measurement of voltage and vibration at different loading cases were conducted within a short time period and repeated more than three times to verify the real variations. In a short time period, the author assumes

that there is a constant voltage supply to the transformer.

A general understanding of voltage variation with load case can be gained by analysing the input impedance of the transformer circuit of an ideal transformer. To the power source, the transformer acts like an effective loading with input impedance Z_i . A voltage drop across Z_i can be described as an equivalent EMF, E_0 , with respect to the downstream loading. The transformer input impedance can be calculated from the transformer equivalent circuit (Yuan, 2006). Only inductive and resistive loadings are considered in the following equation for calculating transformer input impedance, as they are representative load types in commercial applications:

$$Z_i = R_1 + j\omega L_1 + \frac{\omega^2 L_1 L_2}{R_L + j\omega L_L + R_2 + j\omega L_2}, \quad (4)$$

where:

R_1, R_2 : Primary and secondary resistances,

L_1, L_2 : Primary and secondary inductances, and

L_L, R_L : Loading inductance and resistance.

As discussed above, a constant voltage supply, E_s , can be assumed in a short time period. Therefore, the equivalent EMF, E_0 , determined by Z_i can be affected by loading status.

For this test, since R_1 and R_2 are negligible compared with the winding inductive impedance, only resistive loads are connected in the LV end ($L_L = 0$). The input impedance can be decomposed and simplified as:

$$Z_i \approx \frac{\omega^2 L_1 L_2}{R_L^2 + \omega^2 L_2^2} R_L + j\omega \frac{R_L^2 L_1}{R_L^2 + \omega^2 L_2^2}. \quad (5)$$

The maximum measured resistive load, R_L , is 75.7 Ω and is much smaller than the secondary inductive impedance, ωL_2 , 1068 Ω. Thus, Eq. (5) can be rewritten as:

$$Z_i \approx \frac{N_1^2}{N_2^2} R_L + j \frac{R_L^2 L_1}{\omega L_2^2}. \quad (6)$$

It is clear that the input impedance is dependent on the resistive load. During the experiment, parallel connected resistive loads were gradually removed so that R_L increased. Therefore, the input impedance and correlated equivalent EMF would increase accordingly.

3.1.4 Loading shift-induced variation in transformer voltage and vibration

The above analyses are based on the measurement in steady states. However, the voltage fluctuation in transformer circuit will probably cause transient vibration. In this section, the transient vibration will be discussed for comparison with steady state analysis. The transient process was realised by switching on/off the heater from 0 to 100% loading. The test was repeated 10 times in order to guarantee different initial phases at the switching instant. Different from transformer energise and de-energise, evident spark and decay of current in primary winding cannot be found in loading shift-induced transient. As shown in Figure 8, there is only 2.23% decay in

primary current within 2.5s time period. The transformer voltage drops instantaneously at the switching point and then fluctuates around 0.1% variations.

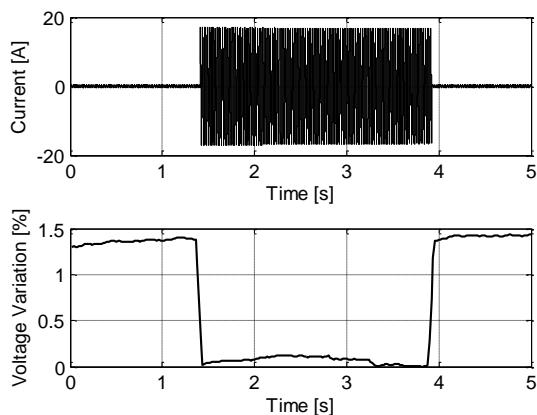


Figure 8. The transient current and voltage variation.

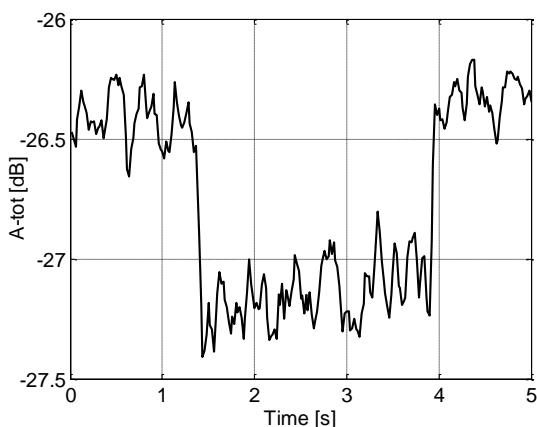


Figure 9. The transient vibration induced by loading shift.

With respect to transformer vibration, sudden decrease or increase can be found in Figure 9. Although load current reaches maximum 16.6A in the primary winding after switching on heaters, the transformer vibration remain follows the variation trend of operating voltage. The maximum decrease of transformer vibration is 1.06dB in the transient process. Compared with the vibration fluctuation in steady states, loading shift-induced transient process does not introduce obvious extra fluctuations in transformer vibration.

In the above cases, the vibration variation has nothing to do with structural changes. It is caused by voltage fluctuations due to power variability or loading shift. This fluctuation alters the magnetization in the core and the current in the winding, and then affects transformer vibration as well. However, vibration induced by core magnetostriction and magnetic forces will first be considered since current-induced transformer vibration is usually small.

3.2 Effects of structural changes on transformer vibration

Power transformers are often exposed to multiple short circuit shocks, insulation aging, and repeated thermal processes. As a result, the mechanical strength of transformer insulation becomes weak. Furthermore, mechanical defects and insulation weaknesses affect each other. One of the consequences is a decrease in clamping pressures in both the winding and core assembly. As part of the aim to study the

variations in transformer vibration due to structural changes, winding and core clamping pressure reduction will be studied as transformer structural changes in this section.

A vibration method based on vibration energy distribution and harmonics analysis was described in (Berler, et al, 2000) for diagnosis of decreases in clamping force. Coefficients of the winding and core clamping pressures were calculated using thirty parameters, and specific criteria were selected to evaluate the degree of transformer fixation in (Berler, et al, 2000). However, voltage fluctuation and its relation to vibration characteristics were not been studied in detail.

In this test, the transformer vibration and voltage fluctuation were recorded simultaneously with or without structure modification. This modification is realized by reducing the winding clamping force from 0% to 90% looseness which is defined as rotation angle from fully clamped status (0% looseness). Since the secondary loading was kept constant (open circuit), voltage fluctuations mainly came from the power supply. As described in Figure 10, the normalized voltage fluctuates randomly under different voltage ratings (normalized by the minimum voltages of each operating voltage). Based on the discussion in Section 3.1.2 about vibration changes due to power variability, transformer vibration should varies with the same trend of voltage fluctuation if there are no changes in other aspects, e.g., structure changes. When certain structural changes (winding clamping force) are introduced, the trend of vibration is apt to be altered. For example, the vibration increased when the input voltage at 450V rating decreases between 70% and 80% winding looseness in Figure 10. The controversy between voltage and vibration fluctuation is attribute to the structural changes as it is the only variation beside input voltage.

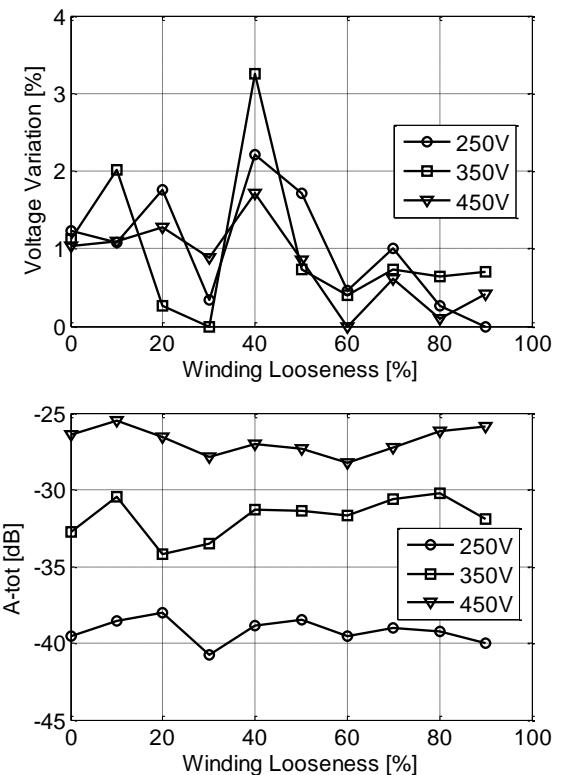


Figure 10. Voltage and vibration fluctuations at different winding clamping forces.

Figure 10 shows that the voltage discrepancy between 10% and 20% winding looseness is 1.88% at 350 V operating voltage while the reduction in transformer vibration is 3.78

dB. Referring to the voltage variation in Section 3.1.2, a 1.77% voltage difference causes 0.52 dB changes in vibration from sampling number 9 to sampling number 10 at a 350 V voltage input in Figure 6. Under the same voltage drop, the change in transformer vibration shows a 3.22 dB difference after introducing winding looseness. Compared to the vibration difference induced by structural changes, the power variability-induced changes in transformer vibration are relatively small. For the other winding clamping levels, extra vibration variation can always be found by comparing with power variability-induced changes in transformer vibration. It is evident that the measured vibration changes at different winding looseness levels mainly come from structural changes under small voltage fluctuations. The changes in the transformer's mechanical properties can be detected by vibration measurement. Therefore, monitoring the transformer's mechanical properties using vibration measurements becomes feasible. For a mechanical failure that will produce large vibration differences, a diagnosis based on the vibration method proposed in (Berler, et al, 2000) is capable of effective detection.

As can be seen from Figure 10, transformer vibration does not always increase as the winding clamping force is gradually reduced. A number of parameters are changed as the clamping loosens: e.g., friction between turns, damping and stiffness of winding stacks. The modelling of the vibration produced by electromagnetic force in windings has been discussed in (Wang, Pan and M. Jin, 2011). The further study of the underlying causes that govern this process is still ongoing.

A statistical study showed that fewer transformer failures occur in the transformer core than in the winding part (*An International Survey on Failures in Large Power Transformers in Service*, 1983). However, mechanical vibration is quite sensitive to changes in core lamination, e.g., a joint design difference (Weiser, Pfützner and Anger, 2000). Therefore, any faults in the core would cause a significant impact on magnetic circuit parameters. Since the flux density and its distribution greatly affect magnetostriction and magnetic forces between the laminations, those changes in the magnetic circuit are expected to produce certain variations in transformer vibration. In this part, the clamping pressure applied to the core assembly is defined as a variable parameter to simulate mechanical faults in the magnetic circuit. The voltage and vibration variations are investigated together for a summary of their relationship.

The voltage and vibration changes were measured for five levels of clamping looseness between 0 to 100%. Power variability-induced voltage variation shows a maximum 2% difference in Figure 11. The corresponding changes in transformer vibration are within a 0.5 dB range based on the above conclusion. From 50% to 100% clamping looseness, up to a 4.26 dB difference can be found in the transformer vibration. However, vibration variations are only less than 1 dB in the first three core clamping levels. In those cases, there are usually small contributions to the transformer vibration variation from those structural changes. Therefore, a determination of such mechanical failures becomes difficult.

Core clamping looseness-induced changes in transformer vibration can be explained partly by domain theory and partly by changes in mechanical properties. The effects of stresses on the magnetic properties of SiFe laminations have been studied by several researchers (Daut and Moses, 1991). Linear stress, normal stress and a combination of these applied to SiFe sheets all lead to a magnetoelastic energy increase in

terms of magnetostriction. Domains formed within the SiFe sheets orient themselves in directions of easy magnetisation (Brailsford, 1970). An applied core clamping pressure destroys this balance, the angles of easy directions deviate and, hence, there is an increase in power loss and magnetostriction. However, in practice, the sensitivity to normal stress would be very low and only minor changes in the domain structure would be expected (Moses, 1974). A clamping force applied to the core assembly can only produce normal stresses.

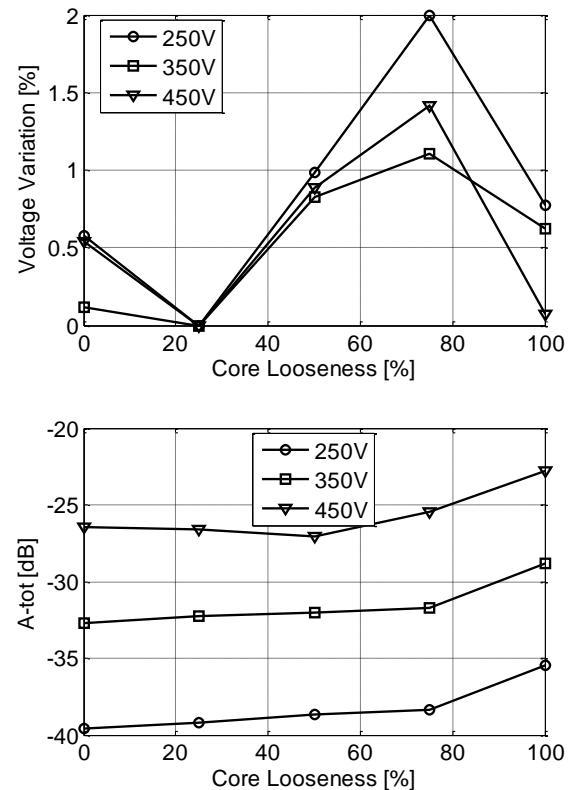


Figure 11. Voltage and vibration fluctuations at different core clamping forces.

There is no doubt that mechanical properties will change as the core clamping pressure decreases from a fully tight level. As one source of core vibration, the interlaminar magnetic force generates most of the out-of-plane vibration, which is strongly affected by the core's effective Young's modulus, which in turn will be reduced due to core looseness. In addition, the Young's modulus of a single SiFe sheet is also reduced with a small stress state.

As an indication of the magnetomechanical coupling efficiency, the magnetomechanical coupling factor, k , is defined as:

$$k^2 = 1 - Y^H / Y^B, \quad (7)$$

where Y^H represents Young's modulus under the magnetically free condition, and Y^B is that under the magnetically blocked condition. A corresponding experimental study records that k will be lowered due to extra stress (Bai, Ma and Jiang, 2008), which indicates a lower Young's modulus with respect to the smaller clamping pressure. In this way, the energy exchange between magnetic and mechanical energy will be more efficient and produce greater core vibrations.

4. CONCLUSIONS

The above results lead to the following conclusions:

- (1) As an indication of flux density, the induced voltage in the belt coil showed good agreement with the transformer's high and low voltages.
- (2) The relative fluctuation of source voltage was around 3% and a maximum 5.88% fluctuation was measured. Those voltage fluctuations induced a variation in the transformer vibration of less than 0.89 dB.
- (3) Loading switching generated a maximum voltage fluctuation of 2.96% and induced vibration changes of less than 0.96 dB.
- (4) As a representative transient vibration induced by voltage disturbance, loading shift between open circuit and full loading showed maximum 1.06dB vibration difference with 1.37% voltage variation.
- (5) A high correlation was found between voltage fluctuation and vibration changes when there was no change in the mechanical and electrical parameters of the transformer.
- (6) When the system's clamping force changed, the maximum change in voltage was 3.25% and the maximum change in vibration was 4.16 dB, which was much higher than the change induced by other fluctuations.

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