EXPERIMENTAL COMPARISON OF LOCALISED MAGNETOSTRICTION DIFFERENCE UNDER SINUSOIDAL AND PWM EXCITATIONS

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Abstract: The majority of power transformers are usually energized by sinusoidal excitation. However, there is a growing demand for using PWM excitation on power electronics devices for energy savings. As awareness of the environment also increases, the importance of noise and vibration issues becomes more significant. Increasing non-linear loads over time affect the ageing and lifetime of transformers. Such cases also cause to change the nominal values of transformers. It is important that mechanical parameters such as vibration and noise can be accurately measured and examined so that all necessary functions can be entirely performed as other electromagnetic performances. For this reason, it is necessary to analyse the vibration movements of transformers and determine their characteristics, especially locally under changing operating conditions. Magnetostrictive is known as the main source of vibration and noiseof the transformer core. This paper presents localized magnetostriction of transformer core measured by strain gauges under sine and PWM voltage excitations. For validation of the study in this paper, a no-load strain measurement was performed experimentally on a real 20kVA three-phase three-limb T-joint transformer assembled in a laboratory.

Localized magnetostriction in the rolling and transverse directions of the lamination under sinusoidal and PWM voltage excitations was carried out. The results of the experiment were compared with each other in terms of the location of the sensors.

The Finite Element Analysis (FEA) was used to simulate the magnetic behavior of the transformer based on time-dependent analysis of magnetic field density, force, e.t. distributions under no-load conditions, respectively.

In conclusion, evaluating the localized magnetostriction characteristic, especially under PWM voltage excitation, is essential for interlamination electromagnetic and electromechanical behaviors.

Keywords: Magnetostriction, magnetization, PWM excitation, strain, magnetic field, power transformer.

1. INTRODUCTION

As it is well known, transformers are fundamental electrical machines that efficiently provide energy transmission and distribution without voltage drop. In recent years, substations of the power transformers have become closer to residential areas with the rapid urbanization and the increasing energy demands. Meanwhile, reducing noise and vibration in urban areas becomes more significant as awareness of the environment increases. Therefore, it is important that vibration and noise characterizations of power transformers are determined and considered during the manufacturing stage in industry. Increasing non-linear loads over time affect the aging and lifetime of transformers. Such cases also cause to change the nominal values of transformers. It is important that mechanical parameters such as vibration and noise can be accurately measured and examined so that all necessary functions can be entirely performed as other electromagnetic performances. For this reason, it is necessary to analyze the vibration movements of transformer cores and determine their characteristics, especially locally under changing operating conditions [1]. The noise and vibration causes of the transformer are varied and are mentioned in [2]. Although it is generally known that they are caused by magnetostriction and electromagnetic forces, it also depends on magnetostrictive properties of the magnetic core material, the design of corner joints, and the stacked type of core lamination [3]. When the magnetic flux transfers to cross-over materials, especially in the core joints, even localized small movement, the electromagnetic force causes noise and vibration. Moreover, according to [4], magnetostriction depends on clamping, flux density distribution, magnetic properties of electrical steel behavior, deformation of core laminations, etc. Thus it is known as a no-load noise of the core and is generally determined experimentally.

Magnetostriction changes the lamination dimension of the material in response to the magnetization of the core [5]. The critical problem in the overall design of the transformer is that the core material has higher magnetostriction and noise based on stacking and joint types, especially in the inter-layers of the core. In addition, the applied voltage type is another affecting factor in this situation. Therefore, many techniques have been applied to determine the magnetic characterization of the core and its dependent variables. Studies have incorporated various measurement methods, sensör techniques, analyses, and experimental research related to the computation and evaluation of magnetostriction. Also, realistic solutions can be obtained by using the Finite Element Method (FEA) to determine magnetic flux density and losses due to the non-linear characteristic of the core. 3D electrical and electromagnetic analyzes can be done on time dependency by using FEA.

The first issue that this study will focus on is the measurement technique used during the experimental study. There are various methods to measure magnetostriction, such as optical methods, laser vibrations, strain gauges. Although strain gauges are the oldest and most common, their sensitivity is limited [6]. However, laser and optical methods have higher sensitivity than strain gauges. Despite this, It is preferred in the measurements to be made in the localized and inter-laminations in terms of ease of use and not being affected by temperature. [4,7–9].

Another issue is the excitation voltage applied during the operation. Studies carried out so far have generally been conducted using sinusoidal voltage [4,9–14]. These studies are only cover works where measurements are made using strain gauges. In the analyzes made with different voltage types, harmonic components were used in addition to the sine and their comparisons were made.

In [13,15,16], researchers examined the harmonic components effect and compared the overall magnetostriction measurement using single sheet samples with different methods. Then [5,17] used PWM excitation and studied harmonic and switching frequency effects to show caused higher magnetostriction. Even if they use PWM excitation, it is just for overall measurement or localized magnetostriction measured on the surface of the core.

Our motivation is that localised strain values were measured and compared for different core locations with the help of strain gauges all fixed on top and bottom of test laminations under PWM and sinusoidal excitation voltages. As mentioned [3,18–20], the air gap and joint types affect the magnetostriction considerably. Since the magnetic flux density and strength are higher in the core joints, these regions were considered for localized strain measurements. The results of the experiment were evaluated by considering the studies in the literature. Thus, we contribute to a better understanding of the effect of measured localised strain values on PWM excitation voltage compared to sine excitation voltage.

In this study, to validate the accuracy of the experimental method in this article, a no-load strain measurement was performed on a real three-phase dry-type transformer in the laboratory. Localized magnetostriction in the rolling and transverse directions of the upper and lower sides of the lamination under sinusoidal and PWM excitation was measured, analyzed, and compared with each other in terms of the location of the sensors. It does not include frequency dependence, especially under PWM stimulation; only 800 Hz switching frequency was used. The fundamental frequency was 50 Hz, similar to the sinusoidal excitation frequency. ANSYS/Maxwell was used to show the magnetic flux density and force distribution, especially in the middle limb and at joints. It is modeled and analyzed under no-load conditions. The instantaneous values and images obtained from these time dependant analyses help us to better interpret the magnetostriction values according to the regions.

It is possible to summarise the main purpose of this study as follows:

- To measure the strain value between localized inter-laminations by strain gauge method under sinusoidal and PWM simulations.

- Comparing results for accuracy and performance using characteristic measurements at different positions on the top and bottom of the same lamination.

- Analysis of transformer core to show magnetic flux density and force via FEA at different excitation values.

The rest of the paper is organized as follows. Section 2 describes the materials and methods. Experimental setup and measurements have been explained in section 3. Results and discussions are shown in section 4. The conclusions are summarised in section 5.

2. MATERIALS AND METHODS

2.1 Strain Gauge Method

There are several methods to measure magnetostriction in electric machines. Optical methods are trendy; however, the strain gauge method has been used mainly for localized measurement. This method has some disadvantages; careful measures should be taken in fitting strain gauges since the lamination coating has to be removed completely. The strain gauges also have a limited fatigue time.

Pro wire foil strain gauge is shown in Fig. 1. It consists of a thin film attached to the probe wires. The electrical resistance of the wire varies in proportion to the amount of strain it experiences.

Figure 1. Pro wire foil strain gauge.

2.2 Magnetic Flux Density and Magnetostriction Under Sinusoidal and Rectangular Waveforms

Magnetostriction is defined as changing in dimension when the material is subjected to the magnetic field. The measured strain result is called magnetostriction [20].

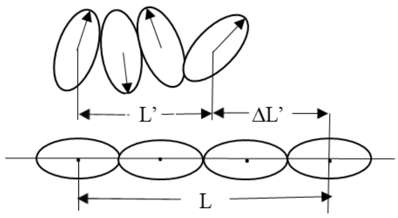


Figure 2. Magnetostriction schematic diagram [20].

From the magnetostriction definition, there is a relation between excitation voltage, flux density, and magnetostriction. It is seen in the following equations for sinusoidal excitation [21,22]:

$$U_0 \sin \omega t = -N_1 A \frac{dB}{dt} \tag{1}$$

$$B = \frac{-U_0}{N_1 A} \int \sin wt = \frac{U_0}{N_1 A} \cos wt = B_m coswt \tag{2}$$

B, N_1, A, μ, B_m are called magnetic flux density, the number of turns, cross-sectional area, the magnetic permeability of the core, and the peak magnetic flux density, respectively.

The relation between magnetic flux density and voltage for rectangular waveform excitation is as follow [23]:

$$u(t) = -N_1 A \frac{dB(t)}{dt} \tag{3}$$

$$\int_0^T \left|\frac{dB(t)}{dt}\right|^k dt = \frac{1}{(N_1 A)^k} \int_0^T |u(t)|^k \tag{4}$$

k is constant in derivation. The solution function of the rectangular waveform in one cycle is:

$$u(t) = U_m \begin{cases} 0 & 0 < t < T(1-D)/2 \\ 1 & T(1-D)/2 < t < T/2 \\ 0 & T/2 < t < T(2-D)/2 \\ -1 & T(2-D)/2 < t < T \end{cases} \tag{5}$$

$$U_{rms} = K f B_m A \tag{6}$$

K, the transformer excitation voltage form factor is selected as 1 for rectangular wave excitation and 1.11 for sinusoidal excitation [24].

Because of the voltage excitation waveform, magnetic flux density behavior also has a linear behavior [23]:

$$B(t) = B_m \begin{cases} -1 & 0 < t < T(1-D)/2 \\ -1 + \frac{4}{TD}\left[t - \frac{T(1-D)}{2}\right] & T(1-D)/2 < t < T/2 \\ 1 & T/2 < t < T(2-D)/2 \\ -1 + \frac{4}{TD}\left[t - \frac{T(2-D)}{2}\right] & T(2-D)/2 < t < T \end{cases} \tag{7}$$

$$B_m = \frac{U_m D}{4 N_1 A f} \tag{8}$$

Using magnetic flux density and flux density derivations, from Eqn (1) to Eqn (8), magnetostriction coefficient (λ) can be derived in Eqn (9) [21,22].

$$\lambda = \frac{\Delta l}{l} = \frac{\varepsilon_s U_0^2}{(N_1 \omega A B_s)^2} cos^2 \omega t \tag{9}$$

ε_s is the coefficient of magnetostriction saturation.

According to Eqn. (9), there is a direct relation between strain value, excitation voltage level, and magnetic flux density. Significantly for localized measurement, this relation is beneficial to estimate the strain value by finding the magnetic flux density.

In addition, according to Eqn. (9), the magnetostriction coefficient varies according to the amplitude of excitation voltage. Therefore, magnetostriction occurs with a fundamental frequency of 100 Hz for an excitation voltage of a fundamental frequency of 50 Hz.

3. Experimental Set-up and FEA Analysis of 3-Phase Dry-Type Transformer

A three limb three-phase transformer core was built from 264 layers, a single-step lap, three laminations per step layer of 0.3mm grain-oriented silicon electrical steel. For sinusoidal excitation, the transformer core was energized through three-phase variacs for voltage regulations. An inverter (Parker AC10 IP20 5.5kW 400V 3ph AC Inverter Drive) was used to supply PWM excitation power to the three primary windings of the core and allowed the core to be magnetized at peak flux density from 0.5T to 1T. The primary and secondary windings, both connected in star configurations, had 50 turns each. For each setting, the fundamental frequency is 50 Hz. Switching frequency and modulation index are two essential parameters in PWM applications, therefore switching frequency was chosen as 800 Hz. The output voltage was adjusted by changing the modulation index under the PWM excitation.

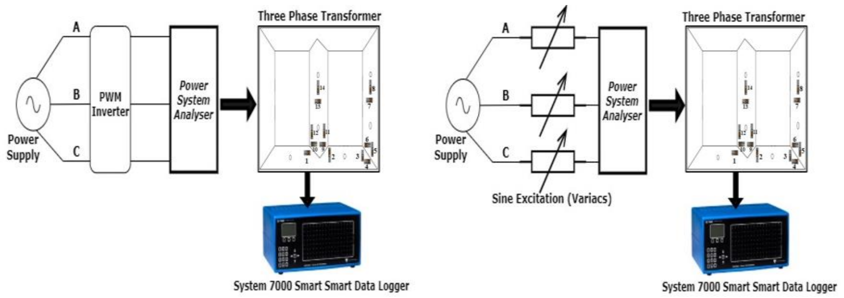
The diagrams represent the experimental setup of the three-phase transformer under sinusoidal and PWM excitations under no-load operation are shown in Fig. 3 (a) and (b), where the strain gauge positions in the core are illustrated. In order to measure the strain value, strain gauge sensors were used.

Table 1 shows the specification of the strain gauge data logger used to collect the strain values at different transformer core locations simultaneously.

Table I. Specification of StrainSmart® Data Acquisition System/ Vishay System 7000 Strain Smart Data system [25].

Measurement accuracy	±0.05%
Measurement resolution	0.5 µstrain
Gauge factor	2
Scan rate per second	2048
Chanel number	Up to 128
Bridge resistor	120

Strain gauge specifications are shown in Table II. The lamination coating where the strain gauges adhered to was removed entirely to directly make good contact with the steel. Then strain gauge arrays were connected to the data acquisition card via twisted wires to avoid detecting any harmonic noise from the surroundings. The laminations were stacked and clamped with the torque wrench at 5 Nm.



a b

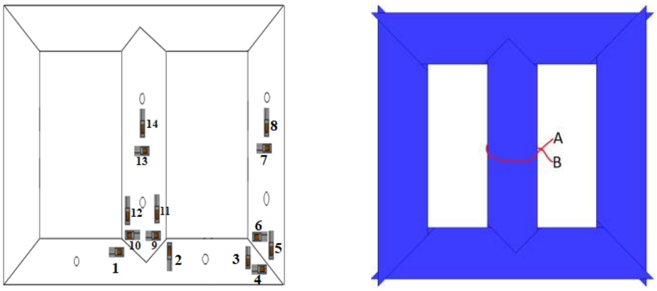
Figure 3. Experimental setup for **a)** PWM excitation **b)** sinusoidal excitation.

Table II. Strain gauge specifications.

Features	**Value**
Gauge Length	8mm
Gauge Factor	2
Gauge Resistance	120Ω
Length	13mm
Width	4mm
Minimum Operating Temperature	-30°C
Maximum Operating Temperature	+180°C
Dimensions	13 x 4 mm

The strain data of the core lamination were acquired and saved through the data logger software. For all different magnetic flux density situations, measurements were repeated three times and averaged to minimize undesirable changes in sensor detection sensitivity. The saved numerical data were analyzed using LabVIEW and MATLAB software.

On both sides of the transformer test lamination, twenty-eight strain gauges have been attached at predefined locations (see Fig. 4). Measurements were repeated for three different magnetic flux density conditions: 0.5T, 0.8T, and 1T. Therefore, a reference single-turn search coil was used in the middle limb of the transformer to calculate flux density between A and B points, as shown in Fig. 4.b.



a b

Figure 4. a) The location of the strain gauges in the lamination **b)** Reference search coil position.

Each strain value on the top and bottom sides of the lamination was measured to compare each other for the sinusoidal and PWM excitations. The measured strain values on the top and bottom sides of the laminations are different. After repeating the measurements three times, the final value is calculated as the mean value of those three measurements. Lamination thickness is an effective parameter for magnetostriction, so these findings are expected since the thickness of the laminations used is 0.3 mm.

In this study, the 3-D FEA model of the three-phase dry-type transformer was modeled using ANSYS/Maxwell software, as shown in the 2D front core shape in Fig. 4.b. Magnetic flux density distribution has been performed with transient analysis to show different magnetic flux density behavior at the same condition and compare practical and simulation results. In addition, the power, loss, and energy distributions in the transformer are seen instantaneously. In this way, the distributions, especially in the joint areas, can be easily seen. Moreover, the line has drawn in the center of the middle limb of the transformer core to obtain the transient magnitude of magnetic flux density, as seen in Fig.5.

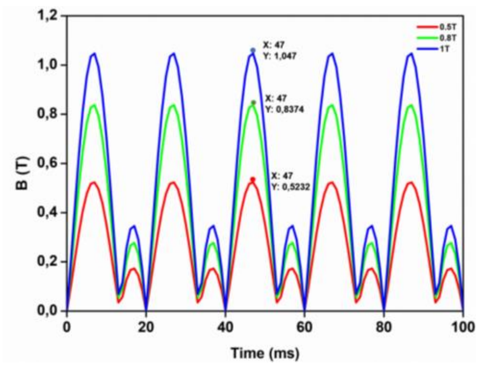


Figure 5. The amplitude of magnetic flux density in the middle limb under sine waveform

4. RESULTS AND DISCUSSIONS

Fig. 4 shows strain gauges localization in the inter-lamination area. Strain gauges were placed intensively in the rolling and transverse directions, especially in the joint areas. There are 14 sensors on both sides of the test lamination. The experiment was carried out using the sine and PWM excitations with a magnetic flux density of 0.5T, 0.8T, and 1T to study the strain across the transformer core under no-load conditions. In this experiment, the clamping factor (5 Nm constant applied torque), lamination thickness, the weight of the stacked lamination on the sensors were fundamental variables for magnetostriction and were kept constant as mechanical stress during the experiment. After experiments were performed, the results were analyzed and compared, as shown in Fig. 6. The results conclude that strain values in PWM simulation are higher than those values under sinusoidal excitation. Moreover, peak to peak strain value increases as expected with higher flux density.

The core laminations were overlapped in one step, so there are overlaps at the corners. Thus, leakages occur between laminations with the effect of air gaps and non-linear flux movements. Therefore, the Maxwell force generates the collision between the laminations to generate magnetostriction. Since it is known that the strain frequency is twice (100 Hz), the fundamental frequency of the excitation voltage a sharper increase in strain and vibration values is expected, especially when PWM excitation is applied.

The instantaneous magnetic flux density distributions obtained from time-dependent FEA analyses for 0.5T, 0.8T, and 1T values are shown in Figure 6. All figures were drawn under the same conditions. The maximum value of the localized flux density was 0.5T, approximately as depicted in red color. As can be seen from the figures, when the desired flux density is obtained with the search coil, the flux density in the joint and middle limb is higher than the other parts. These high levels of flux densities have an impact on the distribution of magnetostriction values.

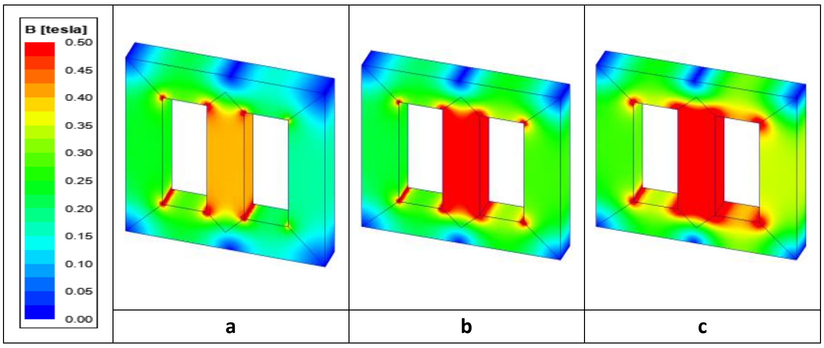


Figure 6. Magnetic flux density distribution for **a)** 0.5 T **b)** 0.8T **c)**1T.

Force, energy, and total loss distributions are instantly shown in Figure 7 under constant magnetic flux density conditions. As can be seen from the FEA analyses, the densities are again in the joint regions, and all of these values are the factors that affect the magnetostriction separately. All these analysis results support each other, thus considering the non-linear behavior of the transformer, the importance of local consideration of experimental measurements and evaluations becomes apparent. This situation is also important to carry out and evaluate the experiments locally, especially highlighting the issues that magnetostriction should be considered at the design stage.

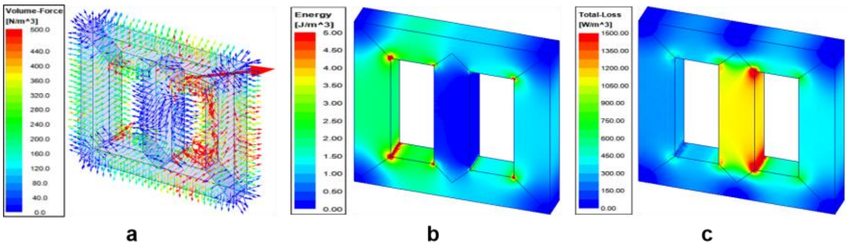


Figure 7. a) Force distribution **b)** Energy distribution **c)** Total loss distribution for same magnetic flux density condition.

Six positions have been chosen for discussion, 2 of them in transverse directions the others in rolling directions; these are numbered as 3, 9 and 1, 5, 8, 14 strain gauges, respectively. It is expected that the strain value in the transverse direction is lower than in rolling directions. However, strain values of those locations in the corner are also expected to be higher. Due to the higher magnetic flux density at the joint region, the strain values in the transverse direction are as high as the rolling ones.

Fig. 8 shows the measured peak to peak strain values of the sensors mentioned above. The graphs show four different values for each magnetic flux density of 0.5T, 0.8T, and 1T. The four different values represent outputs of sensors attached to the top and bottom of the test lamination at the same locations under sinusoidal and PWM excitations.

It can be seen from Figure 8 that there is a consistency in the variations of strain values at the top and bottom of the test lamination. This is illustrated as reducing stress values under the test laminations on the lower yoke (Sensors 1 and 3). Similar behavior has been noticed for the two sensors located at the middle of the central and outer limbs (Sensors 8 and 14) near the clamping locations. The opposite behavior on the central and outer limbs near the joints (Sensors 5 and 9) is also depicted in this figure. These trends are applicable to the three excitations at 0.5T, 0.8T, and 1T, all under sinusoidal and PWM energizations.

The variations of the strain values on the top and bottom of the test lamination are attributed to the lamination bending effect at different locations across the transformer core. The bending might be originated from the roughness of the lamination surfaces and the locations of the bolts that secure the laminations together. This study provides the best locations for the bolts to achieve the lowest value of generated noise due to the magnetostriction.

Sensors 3 and 9 are in the transverse direction. Therefore, it is expected to have a lower strain than the other four sensors; however, they are close to the joint areas. Therefore, the values measured with these two sensors are almost equal to the values of other sensors.

Although sensor 5 in rotational position does not seem close to the joint region, the strain value is larger than the others in the PWM excitation condition due to overlaps vibrations.

These findings show that each strain gauge has its magnetostriction value. Moreover, magnetostriction is affected by the local variables due to the area where the sensor is attached.

Each of these values is at a fundamental frequency. As we mentioned in the reference work above [8,9,22], it is seen that the strain values in the PWM excitation state are much higher than in the sinusoidal excitation state. The most important point to be considered is that to accommodate sensors above and below same points on the test lamination, air gaps are created in the transformer core in the inter-lamination regions. The weights of all laminations on the sensor are also effective. The transformer is tested laid in a horizontal position. In addition, since strain gauges are very sensitive to external sounds, 25-44 ppm peak values are acceptable, especially in PWM excitations.

In sinusoidal wave excitation, the voltage varies from 0 to max or min value as a wave, but in PWM, it only progresses as min and max excitation voltage. In this case, the values in the graph explain the rise of the strain values in the PWM state up to approximately two times for the 0.8T and 1T excitations.

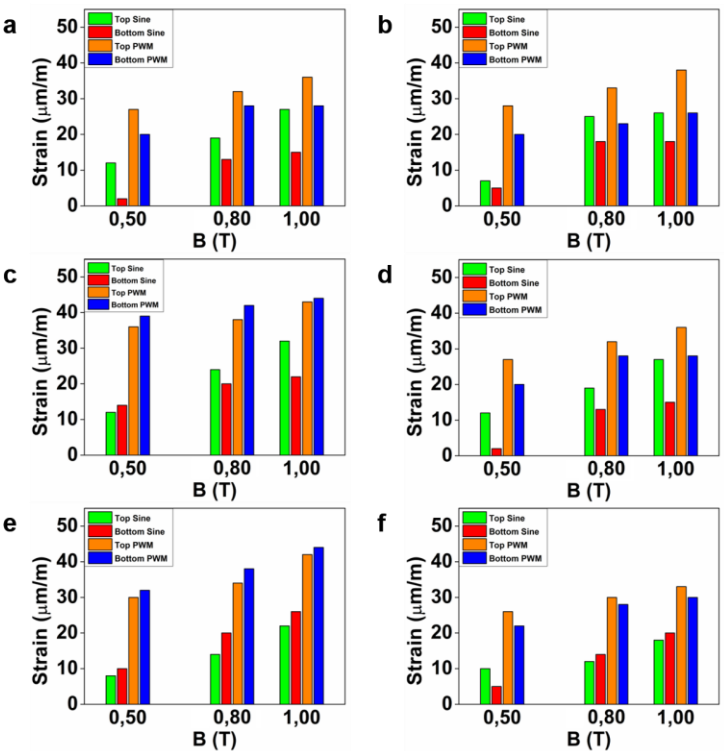


Figure 6. Localized peak to peak strain value at different flux densities on both sides of the lamination under sine and PWM excitations **a)** sensor 1 **b)** sensor 3 **c)** sensor 5 **d)** sensor 8 **e)** sensor 9 **f)** sensor 14.

In sinusoidal wave excitation, the voltage varies from 0 to max or min value as a wave, but in PWM, it only progresses as min and max excitation voltage. In this case, the values in the graph explain the rise of the strain values in the PWM state up to approximately 2 times for the 0.8T and 1T excitations.

5. CONCLUSIONS

This study intends to show the differences in strain values at localized interlaminar positions for the no-load condition under two different excitation voltages. All the measurements are subject to different magnetic flux densities, and transient finite element analysis of magnetic flux distribution in the core was conducted. The following results were obtained as follows:

- Since inter-lamination was studied, higher magnetostriction values were obtained than other studies, even under sinusoidal excitation.

- Since excitation occurs with peak values as max and min, strain values in PWM excitation are quite high compared to sinusoidal excitation.

- Since the magnetic flux density, loss distribution and forces are higher at the joint regions, high strain values are obtained from the sensors close to those regions, even if they are in the transverse direction.~~Since the magnetic~~

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~~flux density is higher at the joint regions, high strain values are obtained from the sensors close to those regions, even if they are in the transverse direction.~~

- PWM excitation is used at a fixed 800 Hz switching frequency. Therefore, the comparison was made only as sinusoidal and PWM excitations according to the lower and upper sensor values.

- Even if the measurement is taken from the same point, different values are read from the sensors located above and below the test lamination. This is due to the effect of the air gap, lamination thickness, and external sounds.

Future studies aim to examine and show the magnetostriction differences under PWM excitation at various switching frequencies.

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