Characterisation of the core and winding vibrations of power transformers with regulator windings

by:

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Summary

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This dissertation presents research and experimental work done to characterize the core and winding vibrations of power transformers with regulator windings by measuring the tank vibrations. The experimental tests were performed in the manufacturing plant whilst the transformers under investigation were subjected to the standard factory acceptance tests, specifically the no load loss test (open circuit test) and the full load loss test (short circuit test). The vibration measuring sensors that were used included a laser Doppler vibrometer and a tri-axial accelerometer and the vibrations were recorded with a CoCo-80 data logger. The test results show that the characteristics of the core and winding vibrations of transformers with and without regulator windings are very similar, but in the case of transformers with regulator windings, the winding vibrations have a few more dependencies. Thus this research and experimental work provide key insights into how the core and winding vibrations of power transformers with regulator windings are influenced by the regulator windings, how the tank vibrations of transformers with regulator windings should be measured and the difference between the vibrations of transformers with and without regulator windings. The importance of this is that most of the research that has been done on transformer vibrations, have been done on transformers without regulator windings, but most practical transformers do have regulator windings. Thus there is a shortage of practical transformer vibration information, which this study aims to address.

Acknowledgements

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1. Introduction

1.1. Background

Power transformers act as links between the generation, transmission, distribution and customer electrical energy networks as can be seen in Figure 1-1. As with any link, if it is removed from the system, the system is left incomplete and unable to fulfil its objectives. From Figure 1-1 it can be seen that power transformers are used to adjust the voltage, and thus current level, between the different electrical energy networks. Two of the main goals of this voltage and current adjustment is to ensure that the energy transferral process is as reliable and as efficient as possible.

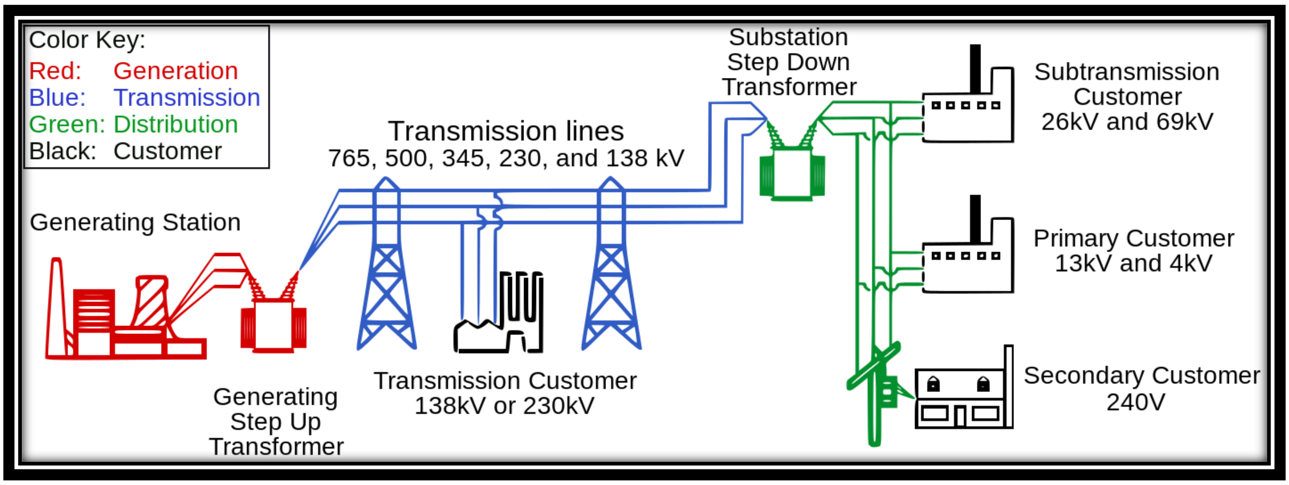

Figure 1-1: Generation, transmission, and distribution electrical energy network (Anon., 2004)

From the above discussion it is quite clear that power transformers are one of the most critical equipment categories in the national electrical energy network. Critical in the sense that they are present all over the national electrical energy network and when they are offline, electrical energy cannot be transferred from the electrical energy utility to the customers. Besides the fact that power transformers are very critical, they are also very costly, meaning that their initial investment cost is very high, and when they are offline, it may have severe impacts on human endeavour and economic activity in a specific region. For these reasons it is of the utmost importance that power transformers are highly reliable.

The reliability of power transformers can be improved by testing the transformers before they leave the manufacturing plant to ensure that they are up to standard, and by continuously monitoring the transformers in the field. In South Africa, all transformer manufacturers must subject their transformers to a series of standard factory acceptance tests to ensure that their transformers are up to standard. The standards for these standard factory acceptance tests are included in the IEC 60076 series for power transformers. Also, in the past few years, energy utilities have started using very sophisticated on- and offline transformer condition monitoring techniques, which may include infrared thermography (IT), partial discharge mapping (PD), frequency response analysis (FRA), recovery voltage measurement (RVM) and vibration monitoring, to monitor the health of their transformers in the field.

Most of the condition monitoring techniques as mentioned above, directly or indirectly monitor the condition of the transformer solid insulation system. This is due to the fact that most failures in power transformers involve and eventually result from a breakdown of the transformer solid insulation system (Bartley, n.d.). Although the main goal of the solid insulation system is to isolate the windings, it also plays a role in the clamping pressure of the windings and thus the vibration characteristics of the windings. This means that if the solid insulation deteriorates, the winding clamping pressure reduces which decreases the resistance of the windings to the radial and axial electrodynamic forces imposed on it, which in turn causes the characteristics of the winding vibrations to change.

For these reasons winding vibration monitoring can be used to determine the state of the solid insulation system and thus the state of the transformer. Although this seems quite simple, it is rather complicated because the windings are not the only part of the transformer that vibrate. Thus it is not the only part that influences the vibration characteristics. In fact, there are five main sources of vibration in transformers. They are the core, windings, tap changer if it has one, fans and oil pumps depending on the cooling method (also known as the refrigeration system), and lastly external vibrations such as mechanical resonance as a result of the fluctuations in the line frequency and its harmonics, etc.

Unlike the winding vibrations, the on load tap changer vibrations are not periodic or sinusoidal and (Foata, et al., 1999) also report that the main frequency components of on load tap changers are in the range of kilohertz, whereas the main frequency component of the winding vibrations is equal to two times the line frequency (100 Hz in South Africa). Due to the significant difference in the characteristics and main frequency components of these two vibration sources, it would be safe to assume that their contributions can be separated quite easily. The vibrations caused by the fans and oil pumps have specific frequencies, depending on the rotational speed of the fans and pumps, and can also be separated from the winding vibrations. The line frequency noise (50 Hz in South Africa) can also be filtered out quite easily. Seeing that these three vibration sources can be separated from the winding vibrations, they will not be investigated.

The core vibrations on the other hand, just like the winding vibrations are periodic and sinusoidal in nature and they have the same main frequency component which is equal to two times the line frequency (100 Hz in South Africa). This means that the vibrations caused by these two sources superimpose onto one another which makes it difficult to separate the contributions of each vibration source and determine the state of the solid insulation system. Thus to be able to determine the state of the solid insulation system, both of these vibration sources will have to be investigated. Furthermore, by investigating the core vibrations, the state of the core clamping system can also be determined.

1.2. Scope of research

This study focusses on characterizing the core and winding vibrations of power transformers with regulator windings in order to fully understand how the regulator windings influences the core and winding vibrations. This information can then be used to devise an online vibration monitoring procedure for power transformers with regulator windings which will lead to better condition monitoring of these transformers and would improve the maintenance and reliability of these transformers and thus, the electrical energy grid. To date, most of the research that has been done on transformer vibrations have been done on transformers without regulator windings (Shengchang, et al., 2006), (Garcia, et al., 2005), (Garcia, et al., 2006), (Garcia, et al., 2006), (Bartoletti, et al., 2004), but most practical transformers do have regulator windings. There is therefore a shortage of practical transformer vibration information, which this study aims to address. This study was limited to two aspects and they are as follows:

- Investigation range
- Instrumentation

Only the vibrations of power transformers with regulator windings are measured in this study, but these vibrations are compared to the vibrations of transformers without regulator windings, which means that the vibrations of transformers without regulator windings are also investigated in this study. The experimental tests were performed in the manufacturing plant whilst the transformers under investigation were subjected to the standard factory acceptance tests, specifically the no load loss test (open circuit test) and the full load loss test (short circuit test). In terms of the short circuit test, it may be important to note that the maximum short circuit current is the rated current of the transformer. Thus in this dissertation, the short circuit test refers to the full load loss test and not the short circuit withstand test. The tap changers that are included in the investigation are plus (linear) and plus minus (buck boost) tap changers. Furthermore, only three phase, core type, multi-layer transformers with double wound low voltage (LV) and high voltage (HV) windings, and separate regulator windings that are connected to the HV windings, are considered in this study. The winding and conductor types of the LV, HV and regulator windings are also taken into account. Of the transformers that are included in this study, four different winding types are used and they are helical, disk, layer(x) and loop layer and the three different conductor types are strip, continuously transposed conductor with epoxy (CTCE) and twin paper.

The vibration measuring sensors that were used included a laser Doppler vibrometer and a tri-axial accelerometer and the vibrations were recorded with a CoCo-80 data logger. The main motivation for the equipment that was used is their non-invasiveness. All of this equipment can be set up and taken down quite easily and very fast, and it does not require that much space.

1.3. Overview of dissertation

This dissertation is divided into six chapters and has two appendices that summarize the most important characteristics of the equipment used and also the complete specifications of all the transformers that are included in this study.

The first chapter provides an introductory overview of the project and the reasoning behind undertaking the research. Chapter two consist of a literature review where the operating principles of transformers, the vibration characteristics of transformers without regulator windings as discovered in previous transformer vibration monitoring studies, and the theories for the vibrations of transformers with regulator windings are summarized.

In chapter three the specifications that determined which measuring equipment would be used in this study are summarized and the setup for the practical measurements is presented. The practical measurements for the transformers under investigation are summarized, discussed and compared to the vibration theories of transformers with regulator windings as summarized in the literature review in chapters four and five.

Chapter six summarizes the main conclusions that were drawn from the research and makes recommendations for future work.

2. Literature review

The most important and relevant information of all the literature that had been reviewed for this study is summarized in this section. The literature review is subdivided into the following subsections:

- Operating principles of transformers.
- Transformer vibration excluding the effects of regulator windings.
- Past transformer vibration monitoring studies.
- Expected transformer vibrations including the effect of regulator windings.

2.1. Operating principles of transformers

A transformer is a device that makes use of electromagnetic induction to couple electrical energy from one circuit to another, while maintaining electrical isolation between the two circuits (Guru & Hiziroglu, 2001). In other words, it transfers power from one circuit to another without any electrical contact between the two circuits or changing the frequency, but it may be at a different voltage, thus also a different current level. Consider the transformer as shown in Figure 2-1 below with copper windings and a ferromagnetic core.

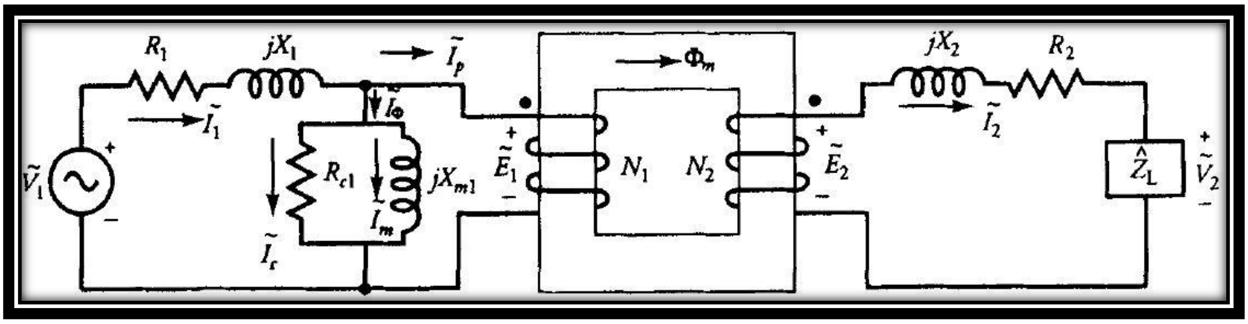

Figure 2-1: Equivalent circuit of a transformer (Guru & Hiziroglu, 2001)

In Figure 2-1, $\tilde{V}_1$ and $\tilde{V}_2$ represent the alternating source and load voltages respectively. R_1 and R_2 represent the primary and secondary winding resistances respectively and jX_1 and jX_2 represent the primary and secondary winding leakage reactances respectively. The currents that flow through the primary and secondary winding resistances and leakage reactances are known as the source and load currents and they are represented by $\tilde{I}_1$ and $\tilde{I}_2$ respectively. The core loss resistance and magnetizing reactance are represented by R_{c1} and jX_{m1} respectively and the currents that flow through them are known as the core loss and magnetizing currents which are represented by the symbols $\tilde{I}_c$ and $\tilde{I}_m$ respectively. $\tilde{I}_\Phi$, which is the sum of the core loss and magnetizing currents, is known as the excitation current and $\tilde{I}_p$ is known as the primary winding current.

Furthermore, $\tilde{E}_1$ and $\tilde{E}_2$ represent the induced electromotive force (emf) over the primary and secondary windings and N_1 and N_2 represent the number of turns in the primary and secondary windings respectively. Φ_m represents the mutual flux in the core and last but not least, $\tilde{Z}_L$ represents the load.

Now first consider the case where an alternating voltage source is placed across the primary winding and the secondary winding is left open as shown in Figure 2-2 below. A small alternating current (AC), known as the no load current, is drawn from the alternating voltage source. This no load current is very small compared to the transformer full load current and is a combination of the currents caused by the magnetic and copper losses, to be more specific:

- Magnetic losses:
  - Core loss current which consists of the hysteresis and eddy current losses.
  - Magnetizing current which sets up the mutual flux.
- Copper losses:
  - Winding loss current caused by the resistance, however small it may be, of the copper winding. It is important to note that the copper losses are directly related to the square of the current flowing through the winding, thus when a load is connected to the secondary side, the copper losses will be much higher than when the transformer is in the unloaded or open circuit condition.

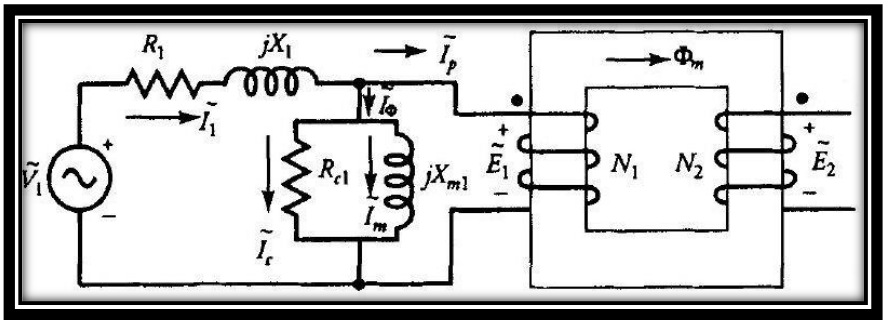

Figure 2-2: Equivalent circuit of an open circuited transformer (Guru & Hiziroglu, 2001)

The core and winding loss currents only contribute towards the losses of the transformer, but the magnetizing current plays a very important role. When an alternating current, in this case the magnetizing current, flows through a coil, in this case the primary winding, it sets up an alternating magnetic field in and around the coil which in turn induces an alternating magnetic flux in and around the coil. Seeing that the primary winding is wound over a ferromagnetic core, most of the alternating magnetic flux will flow through the core seeing as it always follows the path of least resistance. The direction of this alternating magnetic flux can be determined by making use of the circular right hand rule for current flow in a solenoid, and from this rule it can be determined that the mutual flux flows up the core inside the primary winding, and thus it flows clockwise through the core.

Now according to Faraday's law, the alternating magnetic flux in the core will induce an emf over the primary and secondary windings seeing that they are both wound over the ferromagnetic core. Faraday discovered that the magnitude of the induced emf is equal to the number of turns multiplied by the time rate of change of the magnetic flux flowing through the coil. The direction of the induced emfs can be determined by making use of Lenz's law which states that: "When an emf is generated by a change in magnetic flux according to Faraday's law, the polarity of the induced emf is such that it produces a current whose magnetic field opposes the change which produces it." The work of Faraday and Lenz can be used to set up a single equation that can be used to calculate and determine the magnitude and direction of the induced emfs respectively and it is shown in equation (2.1) below.

$$e = -N\frac{d\Phi}{dt} \tag{2.1}$$

where e is the induced emf, N is the number of turns and $\frac{d\Phi}{dt}$ is the time rate of change of the flux. The induced emf over the primary winding is slightly lower than the source voltage due to the voltage drops caused by the primary winding resistance and leakage reactance, and the induced emf over the secondary winding is determined by the primary and secondary winding turn's relationship. It is very important to note that although a voltage is induced over the secondary winding, no current flows through it seeing that it is open circuited.

Now consider the case were a load is connected over the secondary winding as shown in Figure 2-1 above. The load draws an alternating current from the emf induced over the secondary winding. This current, known as the load current induces an alternating magnetic field in the secondary winding which in turn induces an alternating magnetic flux in the secondary winding. Once again, seeing that the secondary winding is also wound over the core, most of this flux flows through the core. The alternating magnetic flux created by the load current opposes the alternating magnetic flux created by the magnetizing current, which means that there is now less flux in the core, thus the induced emfs over the two windings drop according to Faraday's equation.

Seeing that the induced emf over the primary winding can only be slightly smaller than the source voltage, more current will be drawn from the source which increases the flux created by the source current, which in turn ensures that the mutual flux reaches a value that ensures that the induced emf over the primary winding is only slightly smaller than the source voltage. This means that the mutual flux in the core must remain constant over all loads to ensure that the induced emf over the primary winding is only slightly smaller than the source voltage, and this is the case. In most well designed, practical transformers, the change in the mutual flux from no load to full load is only 3% (Guru & Hiziroglu, 2001).

It is however very important to note that when it is said that the magnetic flux remains constant, it means that the rms value of the flux stays constant. From Faraday's law it is known that an emf can only be induced over a coil if there is a change in the magnetic flux through the coil, thus if the magnetic flux is constant, no emf will be induced over the primary or secondary windings.

Most practical transformers are three phase, multi-layer transformers with double wound LV and HV windings. In other words, the LV windings are assembled over the core limbs and then the HV windings are assembled over the LV windings. Furthermore, for transformers with tap changers, separate regulator windings that are connected to the LV or HV windings – more often than not the HV windings – are assembled over the HV windings. In this study, this is the only configuration that is investigated and it is referred to as multi-layer transformers with double wound LV and HV windings, and separate regulator windings that are connected to the HV windings. The mutual flux for this configuration also remains more or less constant from no load to full load and is discussed in detail in the next few paragraphs.

Figure 2-3 below shows the cut through, front view, of a three phase, practical transformer with a tap changer where the regulator winding is placed over both the LV and HV windings. From this figure it is clear that the LV, HV and regulator windings of a single phase are placed over the same core limb. The individual windings are wound tightly for mechanical resilience against electrodynamic forces and the space between the windings is a composite oil-pressboard (cellulosic) duct and how wide it is and the ratio of oil to cellulose are determined by cooling requirements and required dielectric clearances. Thus the space between the windings is also known as a dielectric clearance or cooling duct.

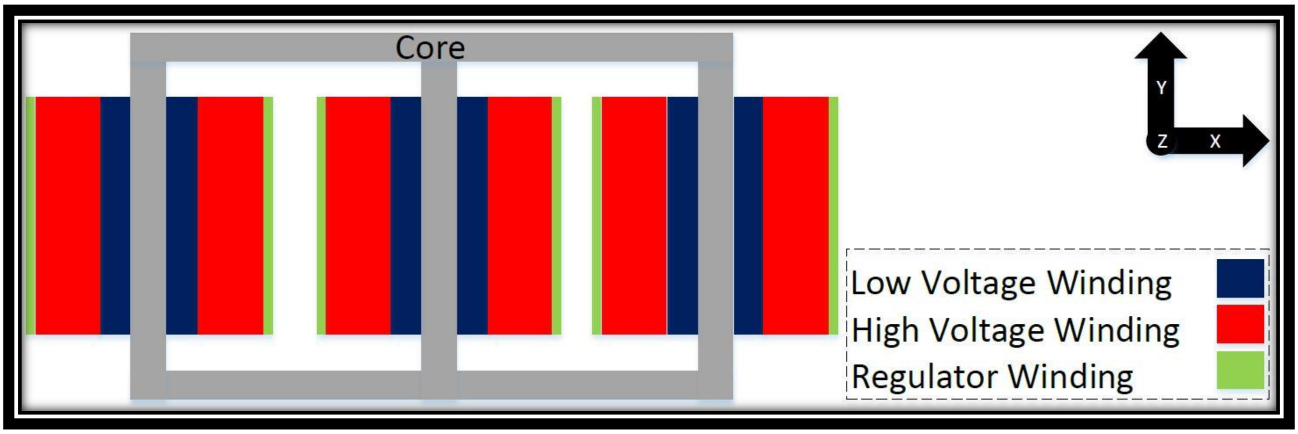

Figure 2-3: Cut through front view of a three phase transformer with a tap changer

Also note from Figure 2-3 that there is a coordinate system shown in the top right corner. This is the reference coordinate system that will be used throughout this dissertation. As can be seen from the coordinate system, the positive X, Y and Z axes are to the right, upwards and out of the page respectively.

The three images in Figure 2-4 below show the top view of one of the phases for the transformer shown in Figure 2-3. In Figure 2-4 an air gap is left between the LV, HV and regulator windings for illustrational purposes, but this air gap also represents the dielectric clearance or cooling ducts as previously mentioned. From top to bottom, these images are used to illustrate the following three situations for a transformer with a plus minus tap changer:

- Transformer delivers nominal voltage (NV), or in other words, the voltage if the regulator winding is out of the circuit. It is also important to note that this leakage flux pattern is that of a transformer with a tapped winding where the tapping range is symmetrically arranged around the nominal or rated voltage. For transformers where the tapping range is not symmetrically arranged around the nominal voltage, some of the turns of the regulator winding will be used to deliver the nominal voltage, but this will be discussed later.
- Transformer delivers the maximum voltage (MV), also known as the maximum plus voltage.
- Transformer delivers the reduced voltage (RV), also known as the minimum minus voltage.

Assume the images in Figure 2-4 represent one phase of a step up transformer with a plus minus tap changer. Firstly, consider the top image in Figure 2-4, in other words, the case where the regulator winding is out of the circuit. Seeing that it is a step up transformer the source will be connected to the LV winding and the load will be connected to the HV winding. The current from the source flows into the LV winding at the top and out of the LV winding at the bottom, thus it flows down the LV winding. By making use of the circular right hand rule for current flow in a solenoid, it is known that the flux created by the LV winding flows into the page inside the LV winding and out of the page outside the LV winding. This is indicated by the blue dots and crosses surrounding the LV winding. Two things must be noted from this:

- Most of the flux created by the LV winding will flow through the core, but there will be a small leakage flux that flows through the space surrounding the LV winding, as indicated by the blue dots and crosses. The same also goes for the other windings.
- The outer leakage flux of the LV winding is not only confined to the space within the HV winding, it flows around the LV, HV and regulator windings, but for illustrational purposes, it is only drawn around the LV winding. Once again, this also applies to the other windings.

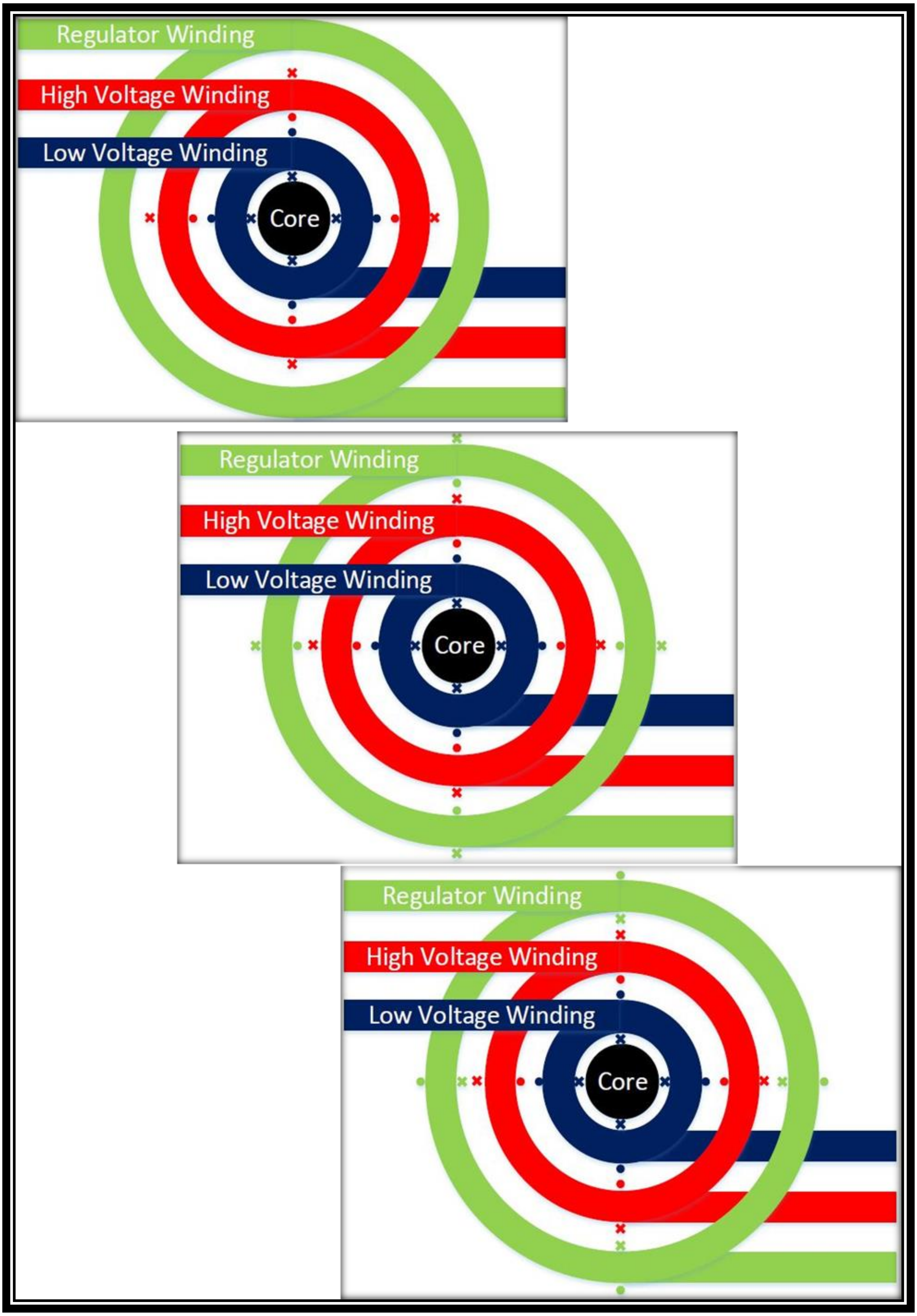

Figure 2-4: Top view of the core and winding configuration and leakage flux pattern of a single phase for a transformer with a plus minus tap changer delivering the NV, MV and RV

From Faraday’s and Lenz’s laws it is known that the induced emf over the HV winding will induce a current in the HV winding, if it is connected to a load, which will induce a magnetic field, thus magnetic flux which opposes the flux created by the LV winding. This means that the flux of the HV winding will flow out of the page inside the HV winding and into the page outside the HV winding as indicated by the red dots and crosses surrounding the HV winding. For this to be possible the current must flow up the HV winding, as is the case. This means that the currents in the LV and HV windings for this specific configuration will always flow in opposite directions.

In the case of the regulator winding, the flow of the current through it, and thus the flow of the magnetic flux can be manipulated to either deliver the nominal voltage, maximum voltage or reduced voltage. This is done by manipulating the number and orientation of electrical turns of the regulator winding which is connected to the HV winding. The three different drawings in Figure 2-5 show how the regulator and HV windings of a transformer with a plus minus tap changer must be connected so that the transformer can supply the nominal voltage, maximum voltage and the reduced voltage respectively. Once again, just note that Figure 2-5 also represents a transformer with a tapped winding where the tapping range is symmetrically arranged around the nominal or rated voltage. Although the windings in these representations are not drawn over one another, the flow of the magnetic flux still works exactly the same.

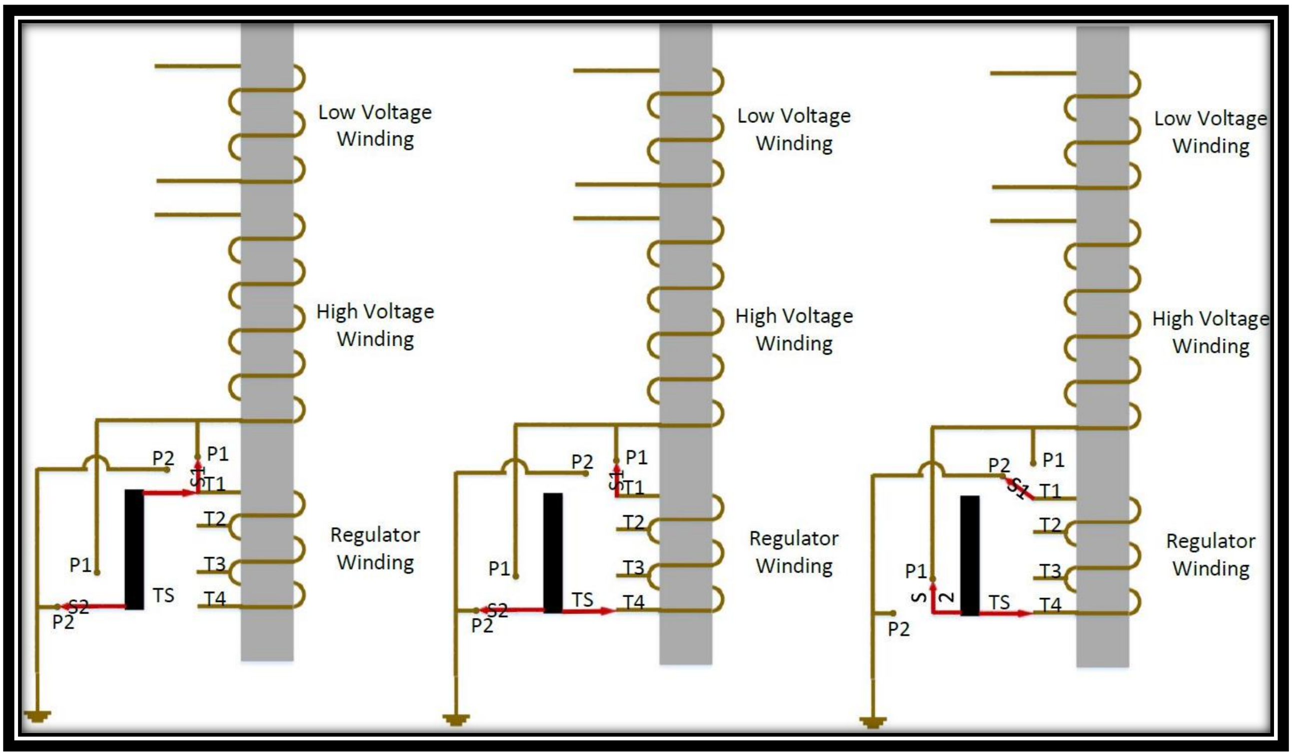

Figure 2-5: Regulator winding connections for a plus minus tap changer delivering the NV, MV and RV

For the situation where the transformer must supply the nominal voltage, consider the leftmost image in Figure 2-5. The tap selector (TS) moves to tap 1 (T1), switch 1 (S1) moves to position 1 (P1) and switch two (S2) moves to position 2 (P2). This ensures that no additional turns are added to the HV winding, thus the nominal voltage is delivered. In this case the mutual flux consists of the vector sum of the flux induced by the LV winding and the HV winding, or in other words, it is equal to the magnitude of the flux induced by the LV winding minus the magnitude of the flux induced by the HV winding. As can be seen from the top image in Figure 2-4, the regulator winding does not have a leakage flux. This is due to the fact that no current flows through the regulator winding seeing as it is out of the circuit.

For the situation where the transformer must supply the maximum voltage, consider the middle images in both Figure 2-4 and Figure 2-5. In order to deliver the maximum voltage, the HV and regulator windings must be connected in such a way that their emfs enhance one another. In order to ensure this, the tap selector is connected to tap 4, switch 1 is in position 1 and switch 2 is in position 2. For this specific setup, the source current flows down the LV winding and the load current flows up both the HV and regulator windings, which means that the flux created by both the HV and regulator windings opposes the flux created by the LV winding, as indicated by the dots and crosses.

For the situation where the transformer must supply the reduced voltage, consider the bottom image in Figure 2-4 and the rightmost image in Figure 2-5. In order to deliver the reduced voltage, the HV and regulator windings must be connected in such a way that their emfs oppose one another. In order to ensure this, the tap selector is connected to tap 4, switch 1 is in position 2 and switch 2 is in position 1. For this specific setup, the source current flows down the LV winding and the load current flows up the HV winding, but down the regulator winding, which means that the flux created by both the LV and regulator windings oppose the flux created by the HV winding, as indicated by the dots and crosses.

As said previously, for transformers where the tapping range is not symmetrically arranged around the nominal voltage, some of the turns of the regulator winding will be used to deliver the nominal voltage. For the case where the nominal voltage is closer to the maximum voltage than the reduced voltage, the leakage flux of the regulator winding will be exactly like the leakage flux of the HV winding when the transformer delivers the nominal voltage (inner leakage flux of regulator winding flows out of the page and outer leakage flux of the regulator winding flows into the page). For the case where the nominal voltage is closer to the reduced voltage than the maximum voltage, the leakage flux of the regulator winding will be exactly like the leakage flux of the LV winding when the transformer delivers the nominal voltage (inner leakage flux of the regulator winding flows into the page and outer leakage flux of the regulator winding flows out of the page).

In terms of the transformers with plus minus tap changers that are included in this study, only the first one's tapping range is symmetrically arranged around the nominal voltage and both the second and the third transformers with plus minus tap changers has tapping ranges that are asymmetrically arranged around the nominal voltage with the nominal tap being closer to the maximum voltage tap.

Now consider the three images in Figure 2-6 and Figure 2-7 that are used to illustrate the following three situations for a transformer with a plus tap changer:

- Transformer delivers reduced voltage.
- Transformer delivers nominal voltage. It is also important to note that this leakage flux pattern is that of a transformer with a plus tap changer that has both plus and minus tappings. For transformers with linear tap changers that only has plus tappings the leakage flux pattern for the nominal and reduced voltage tappings will be exactly the same. With this being said, none of the transformers with plus tap changers that are included in this study only has plus tappings and it would not affect the vibration characteristics, thus it is not of any concern.
- Transformer delivers maximum voltage.

As can be seen from the top image in Figure 2-6, or in other words the situation where the transformer delivers the reduced voltage, there is no flux surrounding the regulator winding which means that the regulator winding is out of the circuit. This is totally different from the situation where a transformer with a plus minus tap changer delivers the reduced voltage.

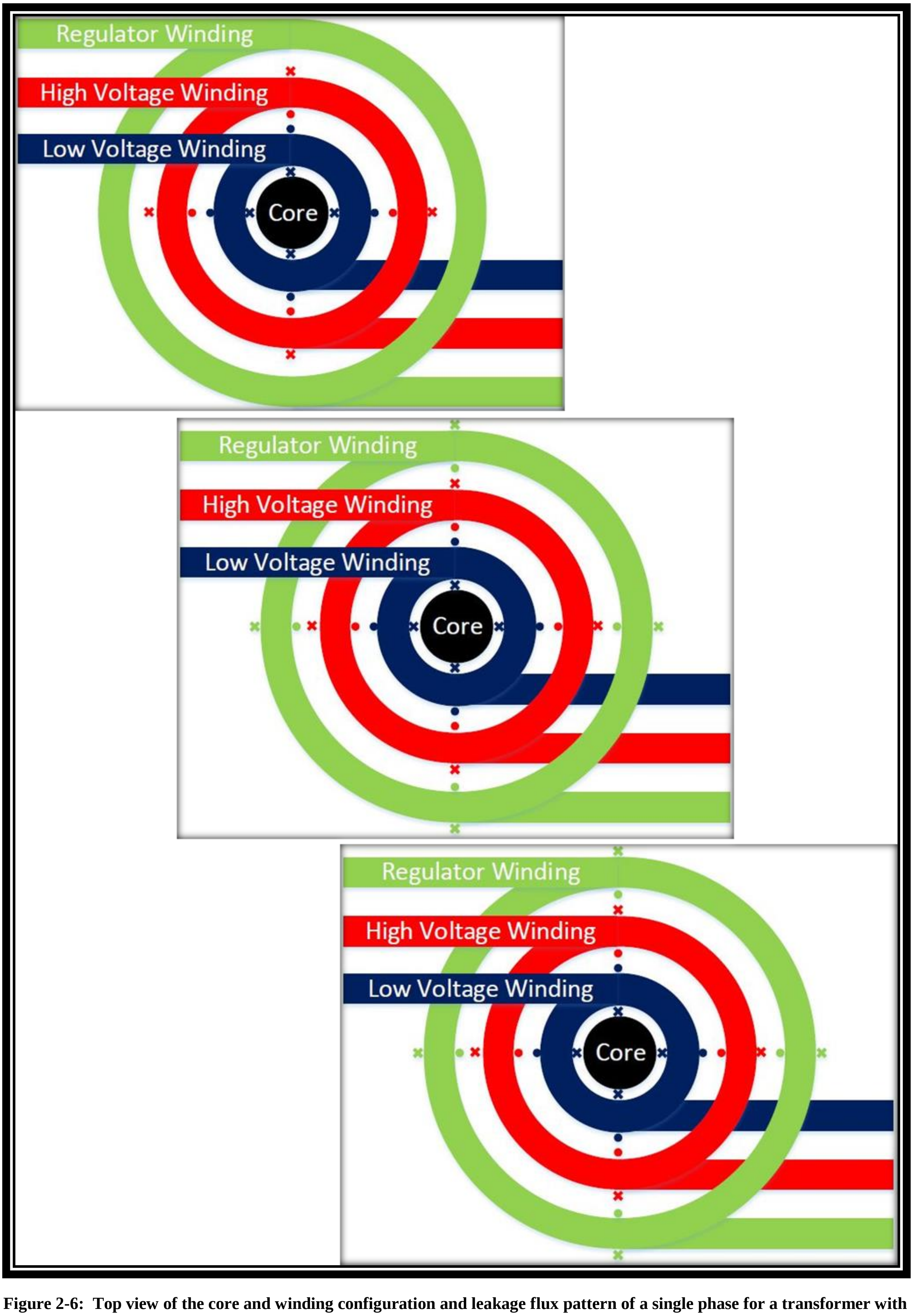

Figure 2-6: Top view of the core and winding configuration and leakage flux pattern of a single phase for a transformer with a plus tap changer delivering the RV, NV and MV

As can be seen from the middle and bottom images in Figure 2-6, or in other words, the situations where the transformer delivers the nominal and maximum voltages respectively, the flow of the leakage flux for these two situations are exactly the same. It is also the same as when a transformer with a plus minus tap changer delivers its maximum voltage. This means that the flow of flux for a transformer with a plus tap changer which is delivering the nominal or maximum voltage is the same as the flow of flux for a transformer with a plus minus tap changer which is delivering the maximum voltage.

This means that when a transformer with a plus tap changer with both plus and minus tappings delivers the nominal voltage of the transformer, some of the turns of the regulator winding is in use. This is clearly shown in the middle image in Figure 2-7. This means that it is totally different from the situation where a transformer with a plus minus tap changer where the tappings are symmetrically arranged around the nominal voltage, delivers its nominal voltage, but very similar to the situation where a transformer with a plus minus tap changer where the tappings are asymmetrically arranged around the nominal voltage, delivers its nominal voltage

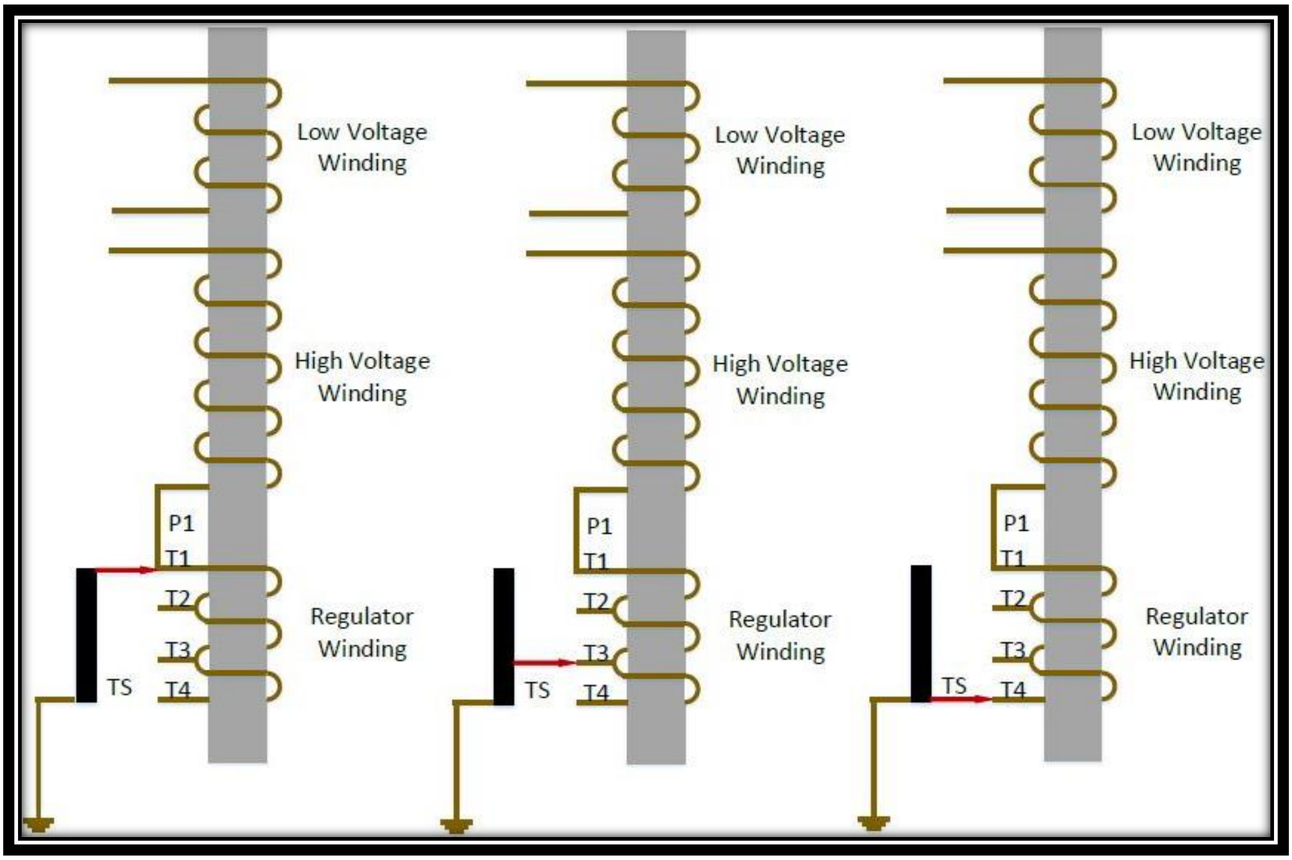

Figure 2-7: Regulator winding connections for a plus tap changer delivering the RV, NV and MV

Table 2-1 summarizes the differences between transformers with plus minus and plus tap changers in terms of delivering the maximum voltage, nominal voltage and reduced voltage.

Table 2-1: Comparison of voltages for transformers with plus minus and plus tap changers

	Plus minus tap changer		Plus tap changer	
	Symmetrical tapping range	Asymmetrical tapping range	Plus and minus tappings	Only plus tappings
Maximum voltage	All regulator turns are included, current in HV and regulator windings flow in same direction.		All regulator turns are included, current in HV and regulator windings flow in same direction.	
Nominal voltage	No regulator turns are included, no current flows through regulator winding.	Some regulator turns are included, current can flow up or down the regulator winding.	Some regulator turns are included, current in HV and regulator windings flow in same direction.	No regulator turns are included, no current flows through regulator winding.
Reduced voltage	All regulator turns are included, current in HV and regulator windings flow in opposite directions.		No regulator turns are included, no current flows through regulator winding.	

In Figure 2-5 and Figure 2-7 tap 1 is used as the lowest tap position, meaning that if tap 1 is selected, no extra turns are connected to the HV winding, but in practice and in all the transformers that are included in this study, if tap 1 is selected, the transformer will deliver the maximum voltage. Tap 17 or 21 usually delivers the reduced voltage, depending on the number of taps, and the nominal tap is anything between the HV and LV taps.

Furthermore, as was previously stated, of the transformers that are included in this study, four different winding types are used and they are helical, disk, layer(x) and loop layer and the three different conductor types are strip, continuously transposed conductor with epoxy (CTCE) and twin paper. Helical windings consists of one radial layer which is wound continuously along the length of a cylinder with spacers inserted between the turns. Layer(x) windings are basically x number of helical windings which are concentrically fitted over one another to form one winding. Disk type windings consist of disks with many radial layers that are connected with cross-overs between the disks and loop layer windings are used for the regulator windings. On the other hand, strip conductors are basically single copper cables, whereas twin paper conductors are two strip conductors fitted together. And last but not least, CTCE consists of many copper cables, bundled together, which are transposed continuously and treated with epoxy to form a rigid cable. Although the construction of the different winding and conductor types vary greatly, all of their leakage fluxes is as explained above.

2.2. Transformer vibrations excluding the effects of regulator windings

As mentioned in section 1.1, there are five main sources of vibration in transformers, but only the core and winding vibration sources are investigated here. The core and winding vibrations, which are caused by magnetostriction and electrodynamic forces respectively, are discussed in the next two subsections. It is important to note that the discussion on the core and winding vibrations as covered in the next two subsections does not cover the effects of the regulator windings.

2.2.1. Core vibrations

More often than not, transformer cores are made of ferromagnetic materials. In order to be able to understand how core vibrations are generated, the process of the magnetization of a ferromagnetic material, which causes magnetostriction, or in other words, the behavior of a ferromagnetic material when it is placed in an external magnetic field; needs to be explained. The simplest way to explain this process is to describe it in terms of magnetic domains.

A magnetic domain is a very small region in a ferromagnetic material in which all the magnetic dipoles are perfectly aligned as shown in Figure 2-8. As can be seen from Figure 2-8 the directions of the alignment of the magnetic dipoles vary from one domain to the next.

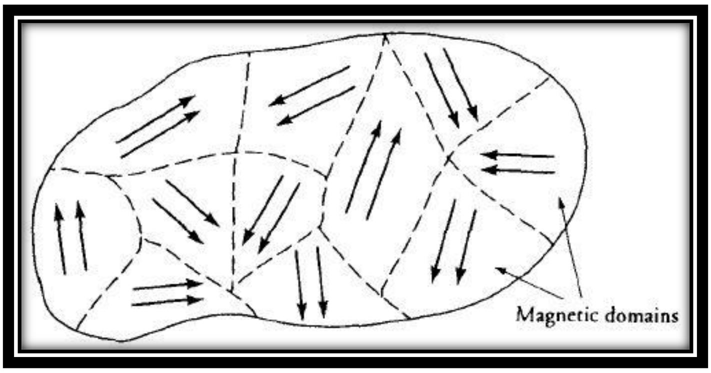

Figure 2-8: Magnetic domains with randomly oriented magnetic dipoles of a non-magnetized ferromagnetic material (Guru & Hiziroglu, 2001)

When this non-magnetized ferromagnetic material is placed in an external magnetic field, the magnetic domains that have the same orientation as the external magnetic field will grow in size which means that the neighbouring domains that do not have the same orientation as the external magnetic field will shrink. It is important to note that the growing or shrinking of a domain merely changes its boundaries. This means that the magnetization of a ferromagnetic material is realized without a rotation or reorientation of the magnetic dipoles (Mnyukh, 2014). Also this growing and shrinking is the cause of the core vibrations. This is described in more detail in the following paragraphs. To bring this back to transformers, consider Figure 2-9 below.

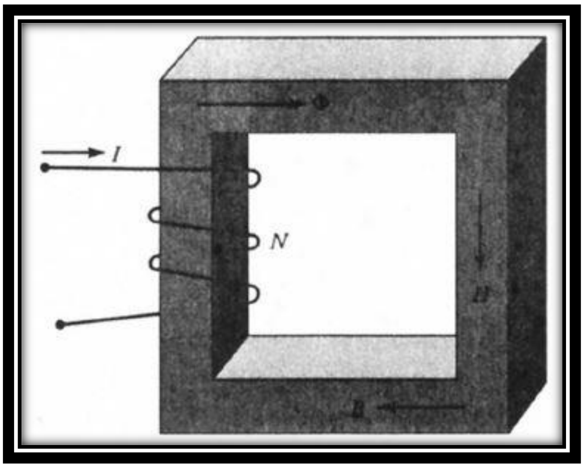

Figure 2-9: Ferromagnetism of transformer core (Guru & Hiziroglu, 2001)

When an AC carrying conductor is wound over a ferromagnetic core, the AC establishes an alternating magnetic field with a certain magnetic field intensity ($\vec{\boldsymbol{H}}$) within the material according to Faraday's law of electromagnetic induction. Then the alternating magnetic field creates an alternating magnetic flux with a certain magnetic flux density ($\vec{\boldsymbol{B}}$) in the material. To fully understand the vibration process, consider the full sinusoidal current waveform as shown in Figure 2-10.

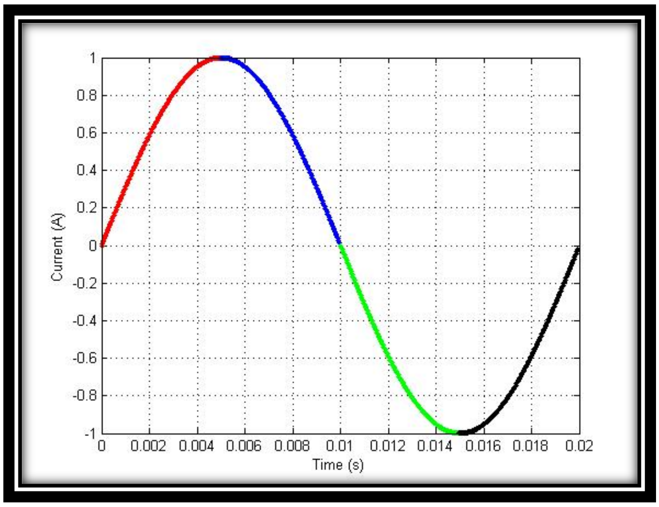

Figure 2-10: Full sinusoidal current waveform

As the AC increases in amplitude (first quarter of sinusoidal wave), the magnetic field intensity increases as stated in Ampère's law. This causes the magnetic flux density to increase which in turn causes the magnetic domains that are aligned with the applied $\vec{\boldsymbol{H}}$ field to grow at the expense of their neighbouring domains. If it is assumed that the sinusoidal waveform as shown in Figure 2-10 is the perfect waveform to extract the full hysteresis loop of the specific ferromagnetic material used to construct the core in Figure 2-9, the magnetic flux density inside the core will change as follows. The increase in the magnetic flux density is slow at first, then it increases more rapidly and when the current gets closer to its maximum value (saturation current), the increase in the magnetic flux density slows down until it finally flattens off. This phenomenon can be seen from Figure 2-11.

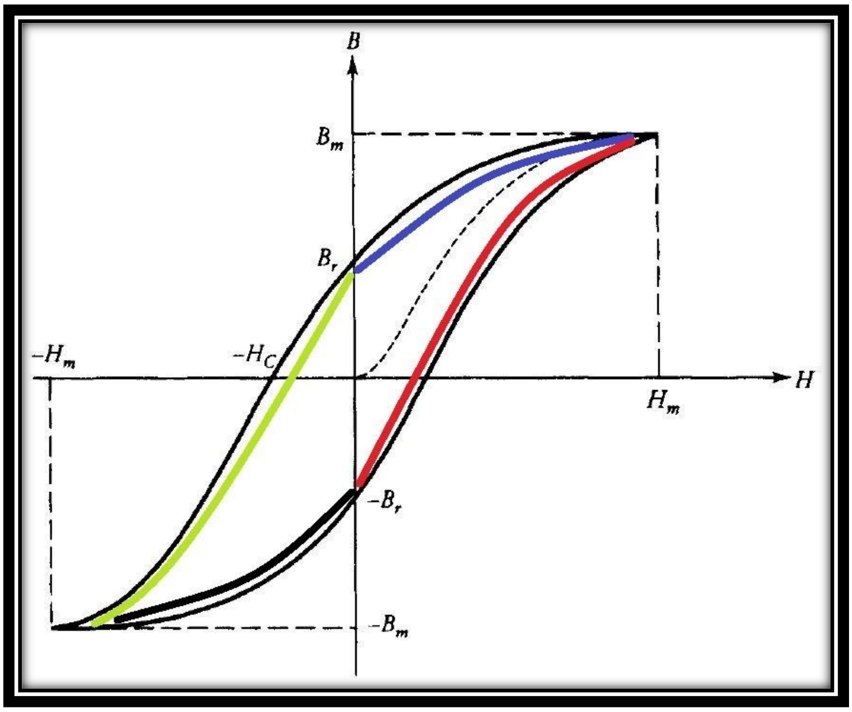

Figure 2-11: Hysteresis loop (Guru & Hiziroglu, 2001)

The curve shown in Figure 2-11 is known as a magnetization characteristic, hysteresis loop or simply a **B-H** curve. Each magnetic material has its own magnetization characteristic. The permeability of the magnetic material can be determined by calculating the ratio of the magnetic flux density to the magnetic field intensity at any point on the magnetization curve. Thus from this it can be deduced that the permeability of a magnetic material changes as it is subjected to a magnetic field.

Thus, from the above discussion for the first quarter of the sinusoidal waveform the following can be concluded: When the current starts to increase from zero, the magnetic domains that are aligned with the applied magnetic field very slowly start to increase in size and during this stage the permeability of the material is low. As the current increases the increase in the size of the magnetic domains happens more rapidly, thus during this stage the permeability of the material is very high. When the current gets closer to the saturation current the increase in the size of the magnetic domains that are aligned with the applied magnetic field slows down until it finally flattens off. Thus, during this stage the permeability is once again very low.

When the magnetization characteristic starts levelling off, it is assumed that the magnetic domains that are aligned with the applied magnetic field has grown to a maximum size and the other domains have shrunk to a minimum size. At this time the flux density and the magnetic field intensity are at their maximum values (B_m and H_m respectively) and the magnetic material is said to be fully saturated. When a magnetic material is fully saturated it has a permeability close to the permeability of free space, which means that the magnetic material now behaves like a nonmagnetic material. From this it should be clear that transformers should never be operated in a saturated condition.

When the AC reaches its maximum amplitude and starts to decrease, the magnetic field intensity decreases which causes the magnetic flux density to decrease. As the magnetic flux density decreases the magnetic domains that are aligned with the applied magnetic field shrink and the neighbouring domains increase in size. It can be seen from Figure 2-11 that the curve does not follow the same path as before. From Figure 2-11 it can be seen that the magnetic flux density decreases at a slower rate than at which it increased. This irreversibility is called hysteresis which simply means that **B** lags **H**. As can be seen from the magnetization curve, even if the magnetic field is reduced to zero by decreasing the current to zero, some magnetic flux density still exists in the material. This remaining flux density is called the residual flux density (B_r) and it is caused by the fact that magnetic domains that have been magnetized by an external magnetic field, shrink at a slower rate than it increases at.

In order to reduce the flux density in the magnetic material to zero, the applied current and thus the applied magnetic field must be reversed and this is where the third quarter of the full sinusoidal wave comes in. The magnetic field intensity value that brings the magnetic flux density to zero is known as the coercive force (H_c). If the current is further increased in the reverse direction, the magnetic field intensity is increased in the reverse direction and this will ensure that the magnetic material is magnetised with the opposite polarity. Once again as the amplitude of the AC increases, the magnetic field intensity increases which in turn causes the magnetic flux density to increase. As before the increase in the magnetic flux density is slow at first, then it rapidly increases and then finally it starts to flatten off again as saturation approaches. The magnitude of the maximum flux density is the same in either direction of magnetisation.

The last part of the magnetization curve is obtained when the fourth courter of the sinusoidal wave is in effect. As the current decreases the magnetic field intensity decreases which in turn causes the magnetic flux density to decrease. The decrease in the flux density is slow at first but it increases as the current goes to zero. Once again there is a residual flux in the material and in order to decrease this residual flux density to zero, the direction of the current has to be switched again which will then start the process all over again.

As stated previously, the growing of the domains that are aligned with the applied magnetic field and the shrinking of the domains that are not aligned with the applied magnetic field, cause slight deformations in the structure of the ferromagnetic material. Now seeing that alternating sources in South Africa have a frequency of 50 Hz, which means that there are 50 full sinusoidal waves in one second, it means that the ferromagnetic core of transformers will vibrate at a frequency of 100 Hz. This is due to the fact that each full sinusoidal wave establishes two opposing magnetic fields in the ferromagnetic core, which means that 50 full waves will establish 100 opposing magnetic fields.

From (Henshell, et al., 1965) it is known that if the core was a homogeneous body, the core vibrations will only have X and Y components as referred to Figure 2-3, or in other words, only in-plane vibrations. In practice however, the core is composed of thin magnetic sheets and the joints between the legs and yokes overlap. This overlapping causes irregular flux densities and the result of this is that the core vibration also has Z components or out of plane vibrations as discovered by (Weiser, et al., 1996). Moreover, each magnetic sheet has slight irregularities and there is friction between these sheets which also excites out of plane vibrations. Furthermore, due to the non-linearity of the magnetostriction phenomenon, the core vibrations also have integral multiple harmonics of the main frequency component.

It is important to note that during normal transformer operation the magnetic field intensity and magnetic flux densities never reach their maximum values (B_m and H_m), which means that the transformer is not operated in the saturation region. Thus the entire hysteresis loop is not used. Also, it can be proven that the hysteresis loss, which is equal to the surface area of the hysteresis loop and is caused by the magnetostriction, is only dependent on the source voltage, and thus the magnetization current, but independent of the load current. Thus, the current that was mentioned above and shown in Figure 2-10 is the magnetization current. The importance of this will become clearer in section 2.3.

2.2.2. Winding vibrations

The force that induces winding vibrations is known as the electrodynamic force and it is caused by the interaction of the currents flowing through the windings, with the leakage flux outside these windings as discovered by Ampère. In the next few paragraphs it will be shown that the main frequency component of the winding vibrations is also 100 Hz, that it too has integral multiple harmonics of its main frequency component and that transformer winding vibrations have both axial and radial vibration components.

The cause of the radial vibrations will be discussed in the next few paragraphs, but it is important to note that the radial vibrations are specific to transformers where the HV windings are spun over the LV windings as shown in Figure 2-3. As is shown in section 2.1, the currents in the LV winding (inner winding) and HV winding (outer winding) always flow in opposite directions, which ensures that the inner leakage flux of the HV winding and the outer leakage flux of the LV winding have the same polarities. These like polarities cause the windings to repel each other which cause the inner winding to compress and the outer winding to expand. This compression of the inner winding and the expansion of the outer winding causes the radial winding vibrations. It is important to note that the radial vibration component cause vibration in both the X and Z directions as shown in Figure 2-3.

Now seeing that transformers make use of alternating currents, the repulsion force will also alternate. Once again consider the full sinusoidal current waveform as shown in Figure 2-10. As the current increases in the first quarter of the current waveform, so does the repulsion force. When the current reaches its maximum value and starts to decrease, the repulsion force weakens until it finally reaches zero as the current becomes zero. In the third quarter of the current waveform the current starts to increase again, but although the current has changed polarity, the repulsion force does not become an attraction force, seeing that the current in both windings would now flow in the opposite direction. This means that the repulsion force will once again start to increase. As the fourth quarter of the sinusoidal wave is entered the repulsion force becomes weaker once more until it becomes zero at which time the process will start all over again.

Not only does the turns of the inner winding exert forces on the turns of the outer winding and vice versa, the turns of the inner winding also exert forces on each other, and the same goes for the outer winding. In this situation the force will be an attraction force seeing that the currents are moving in the same direction. These electrodynamic forces between the turns of each winding cause the axial vibrations. The axial vibration component causes vibrations in the Y direction as shown in Figure 2-3.

Once again, seeing that line frequency in South Africa is 50 Hz, the radial repulsion forces and the axial attraction forces alternate 100 times in one second, which means that the winding vibrations also have a vibration component at 100 Hz. The integral multiple harmonics of the main frequency component are caused by the magnetizing current and also some residual harmonic currents.

In the above discussion of the winding vibrations, it was assumed that the transformers are operated under normal operational conditions. The winding vibrations that are caused under normal operational conditions are not really of any concern, it is the winding vibrations that are caused under abnormal operational conditions such as short circuits and lightning strikes that really damage the windings and breaks down the insulation paper around the windings. According to (Skolov & Vanin, 2001) at least 12 to 15% of transformer failures are caused by winding deformations which are caused by very high electrodynamic forces appearing during short circuits. Furthermore, when winding deformations do occur as a result of large short circuit currents, there will be an increase in the winding vibration under normal operating conditions which will lead to an increase in the mechanical fatigue of the solid insulation. This results in the weakening of the insulation, leading to short circuits between turns.

Although the above discussion focuses on the winding vibrations under normal transformer operating conditions, the principles for short circuit winding vibrations are exactly the same, the only difference is that the short circuit current is much larger which causes the vibrations to be much more severe. Also, it can be proven that the winding vibrations are only dependent on the load current and independent of the source voltage. The importance of this will become apparent in section 2.3.

2.3. Previous transformer vibration monitoring studies

Several studies including (Shengchang, et al., 2006), (Shengchang, et al., 2011), (Nafar, et al., 2011), (Garcia, et al., 2005), (Garcia, et al., 2006), (Garcia, et al., 2006), (Yoon, et al., 2014) (Berler, et al., 2000) (Bartoletti, et al., 2004) have been conducted during which the core and winding vibrations of transformers were characterized. Although some of the transformers that were included in these studies did have tap changers, none of these studies explicitly looked at how the regulator winding, which is connected to the tap changer influences the vibrations. From these studies it was concluded that the characteristics of the core and winding vibrations of transformers without regulator windings can be summarized as shown in Table 2-2 below. The characteristics as summarized in Table 2-2 conform to the discussion of transformer vibrations excluding the effect of a regulator winding as summarized in section 2.2 above.

Table 2-2: Transformer core and winding vibration characteristics (excluding effects of regulator windings)

	Core vibrations	Winding vibrations
Phenomenon	Magnetostriction	Electrodynamic forces
Dependency	Excitation/source voltage	Load current
Directions	X, Y and Z	Axial (Y) and radial (X/Z)
Main frequency	100 Hz	100 Hz
Harmonics	Integral multiple harmonics	Integral multiple harmonics

As said previously, the core vibrations are dependent on the excitation voltage and independent of the load current and the winding vibrations are dependent on the load current and independent of the excitation voltage. To be more specific, for transformers that do not have regulator windings, it has been proven that the core vibrations are linearly related to the square of the excitation voltage and the winding vibrations are linearly related to the square of the load current. This is only true for the main frequency component (100 Hz) of the core and winding vibrations.

Due to the dependencies as summarized in Table 2-2 above, it is possible to excite the core and winding vibrations separately by performing the open and short circuit tests respectively. Most of the researchers as mentioned above did make use of the open and short circuit tests to characterize the transformer vibrations, but (Shengchang, et al., 2006) developed and proved a method that can be used to separate the core and winding vibrations of a transformer without running the transformer in the open or short circuit conditions. This is called the on load current method (OLCM). In the next three subsections the open circuit test, short circuit test and on load current method are discussed.

After the three tests as mentioned above have been discussed, a closer look will be taken at the best positions to place vibration measuring sensors on the tank of the transformer and then other factors that can influence the vibration measurements will also be discussed.

2.3.1. Open circuit test

During an open circuit test, one of the windings is left open while the other winding is excited by applying the rated voltage of that winding. It may be important to note that this discussion of open circuit tests is based on single phase transformers, but it can be proven that a three phase transformer works exactly like three single phase transformers. This means that for a three phase transformer, three windings will be left open while the other three windings are excited by applying the rated voltage of those windings.

The frequency of the applied voltage must be the rated frequency of the transformer and more often than not, the open circuit test is conducted by exciting the LV winding. The reasons for this are that it is safer and LV sources are more readily available. The open circuit test setup for a single phase transformer is shown in Figure 2-12. Normally the goal of an open circuit test is to determine the core losses, which are affected by the core loss resistance and magnetizing reactance, but in this instance, it will be used to isolate the core and winding vibrations. Nevertheless, the standard core loss resistance and magnetizing reactance equations will still be derived, seeing that they determine how much energy will be lost during the excitation of the core vibrations which is related to the amplitude of the vibrations.

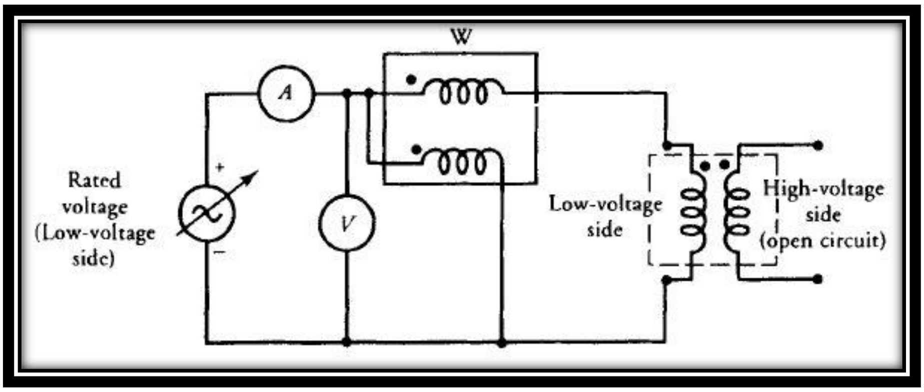

Figure 2-12: Open circuit test setup for single phase transformers (Guru & Hiziroglu, 2001)

As can be seen from Figure 2-12, a variable voltage source (variac), ammeter, voltmeter and wattmeter is connected on the LV side while the HV side is left open. By increasing the applied voltage carefully from 0 to the rated value of the LV winding and by taking the measurements of the ammeter, voltmeter and wattmeter when the applied voltage is at the rated voltage, the core losses can be determined.

Seeing that the HV side is left open, no current flows in the HV side, which means that the current that flows through the LV side is just enough to overcome the LV winding losses, the core losses and also to establish the required flux in the magnetic core. The current that flows through the LV side is known as the excitation, no load or the open circuit current (I_{oc}).

As previously discussed, the winding losses are linearly related to the square of the current, but seeing that the current that flows through the LV winding is so small during an open circuit test, the winding losses can be neglected. This means that the excitation current only has two components, that is the core loss current (I_c) and the magnetizing (I_m) current. Figure 2-13 shows the approximate equivalent circuit as viewed from the low LV for an open circuit test. Seeing that the only power loss in Figure

2-13 is the core loss, the wattmeter as shown in Figure 2-12 measures the core loss (P_{oc}) in the transformer.

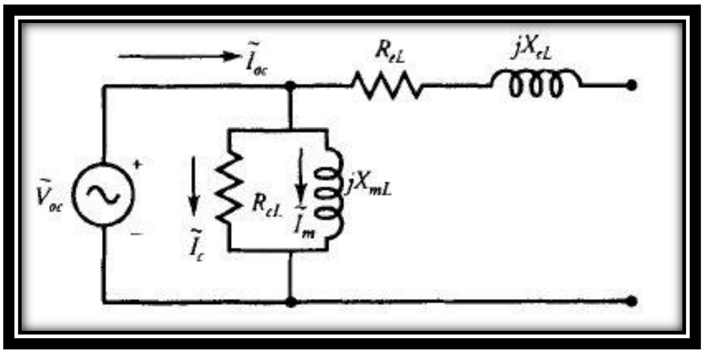

Figure 2-13: Approximate equivalent circuit of a single phase transformer for the open circuit test (Guru & Hiziroglu, 2001)

The core loss current is always in phase with the applied voltage and the magnetizing current lags the applied voltage by 90°. This is clearly illustrated in Figure 2-14 below.

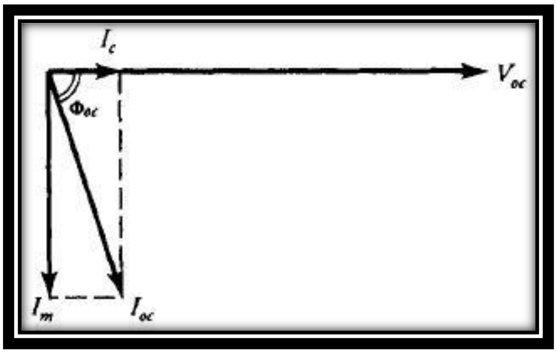

Figure 2-14: Phasor diagram of single phase transformer under open circuit test (Guru & Hiziroglu, 2001)

If the rated voltage (V_{oc}) is applied to the LV side, the voltmeter will measure V_{oc}, the ammeter will measure I_{oc} and the wattmeter will measure P_{oc}. From these readings it is possible to calculate the open circuit apparent power as follows (Guru & Hiziroglu, 2001):

$$S_{oc} = V_{oc} I_{oc} \tag{2.2}$$

The apparent power will have a lagging power factor and its angle can be calculated as follows (Guru & Hiziroglu, 2001):

$$\phi_{oc} = \cos^{-1}[\frac{P_{oc}}{S_{oc}}] \tag{2.3}$$

By making use of the power factor and the excitation current, the core loss and magnetizing currents can be calculated by making use of equations (2.4) and (2.5) below (Guru & Hiziroglu, 2001):

$$I_c = I_{oc} \cos(\phi_{oc}) \tag{2.4}$$

$$I_m = I_{oc}\sin(\phi_{oc}) \tag{2.5}$$

Now that the currents are known the core loss resistance and the magnetizing reactance as viewed from the LV side can be calculated as follows (Guru & Hiziroglu, 2001):

$$R_{cL} = \frac{V_{oc}}{I_C} = \frac{V_{oc}^2}{P_{oc}} \tag{2.6}$$

$$X_{mL} = \frac{V_{oc}}{I_m} = \frac{V_{oc}^2}{Q_{oc}} \tag{2.7}$$

Where Q_{oc} is the reactive power and it can be calculated as follows (Guru & Hiziroglu, 2001):

$$Q_{oc} = \sqrt{S_{oc}^2 - P_{oc}^2} \tag{2.8}$$

In order to calculate the core loss resistance and magnetizing reactance as referred to the HV side the following three equations can be used. First, the transformer ratio must be calculated and that can be done by dividing the primary winding voltage ratio by the secondary winding voltage ratio as shown in equation (2.9) (Guru & Hiziroglu, 2001).

$$a = \frac{V_P}{V_S} \tag{2.9}$$

With the transformer ratio known the core loss resistance and magnetizing reactance as referred to the HV side can be calculated as shown in equations (2.10) and (2.11) (Guru & Hiziroglu, 2001).

$$R_{cH} = a^2 R_{cL} \tag{2.10}$$

$$X_{mH} = a^2 X_{mL} \tag{2.11}$$

To further demonstrate how the core and winding vibrations are separated by performing the open circuit test, consider the following. Seeing that the core losses are only dependent on the excitation voltage and the frequency of the voltage, which means that it is independent of the load, the core losses will be generated even if there is no load, which is the case in the open circuit test. This means that the hysteresis loss, which is caused by magnetostriction will be present during the open circuit test which in turn means that the core will vibrate. Also, seeing that the winding vibrations are directly dependent on the load current, the winding vibrations are not induced during the open circuit test seeing that the current in the primary winding is very small and no current flows in the secondary winding.

2.3.2. Short circuit test

During the short circuit test of a single phase transformer, one of the windings is short circuited while the rated current is applied to the other winding. Although the discussion of the short circuit test is based on a single phase transformer, it works exactly the same in a three phase transformer. More often than not the short circuit test is used to determine the winding resistances and leakage reactances, but in this instance it will be used to only induce the winding vibrations. Nevertheless, the standard winding resistance and leakage reactance equations will still be derived seeing that they are inherent to the winding vibrations.

The rated current which is applied to the primary winding is obtained by carefully increasing the applied voltage of the variac that is connected to the primary side. The frequency of the applied voltage must be the rated frequency of the transformer. Once again it does not really matter which side is used as the primary and which is used as the secondary, but seeing that the primary winding should be operated at its rated current, for safety reasons it is suggested that the HV side should be used as the primary side. Figure 2-15 shows the short circuit test setup for a single phase transformer. As can be seen from Figure 2-15 an ammeter, voltmeter and wattmeter are also connected to the HV side.

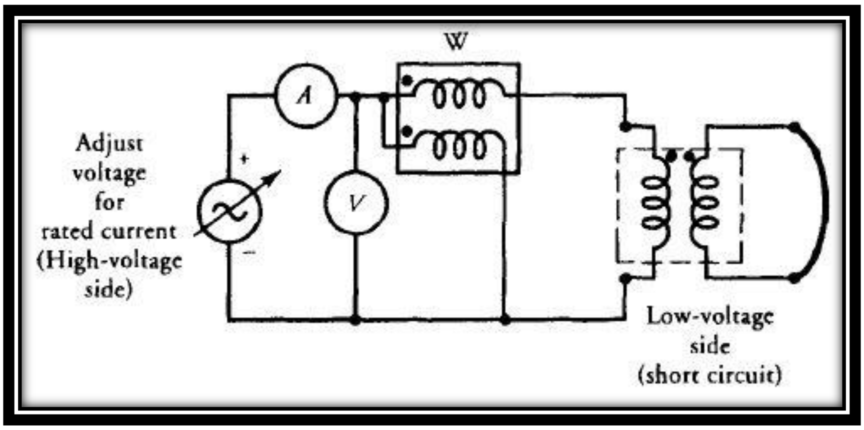

Figure 2-15: Short circuit test setup for a single phase transformer (Guru & Hiziroglu, 2001)

Seeing that the short circuit on the LV side ensures that the power output is zero, the power input to the transformer must be low. There may be a large current flowing through the short circuit, but there is no voltage over the short circuit, thus the power output is zero. The low power input at rated current means that the excitation voltage will have to be very low, thus extreme care must be taken when performing the short circuit test.

Seeing that the rated current of each winding flows through that winding, the full load leakage flux pattern of each winding is generated. This means that the full load winding vibrations are induced, or in other words, the maximum winding vibrations are induced. Also, seeing that the applied voltage is so small, the core loss and magnetizing current which are dependent on the source voltage and its frequency, are so small that they can be neglected. The approximate equivalent circuit of a single phase short circuited transformer as viewed from the HV side is shown in Figure 2-16.

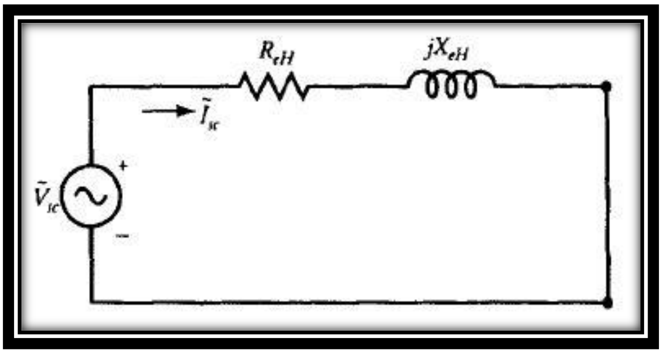

Figure 2-16: Approximate equivalent circuit of a single phase transformer for the short circuit test (Guru & Hiziroglu, 2001)

For the short circuit test the voltmeter measures the excitation voltage, the ammeter measures the excitation current and the wattmeter measures the copper loss at full load. If V_{sc}, I_{sc} and P_{sc} are the readings on the measurement devices, the total resistance of the two windings as referred to the HV side is given by (Guru & Hiziroglu, 2001):

$$R_{eH} = \frac{P_{sc}}{I_{sc}} \tag{2.12}$$

The magnitude of the impedance as referred to the HV side is given by (Guru & Hiziroglu, 2001):

$$Z_{eH} = \frac{V_{sc}}{I_{sc}} \tag{2.13}$$

This means that the total leakage reactance of the two windings as referred to the HV side is given by (Guru & Hiziroglu, 2001):

$$X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2} \tag{2.14}$$

The total resistance and leakage reactance of the two windings can be rewritten as follows (Guru & Hiziroglu, 2001):

$$R_{eH} = R_H + a^2 R_L \tag{2.15}$$

$$X_{eH} = X_H + a^2 X_L \tag{2.16}$$

where R_H and R_L are the resistances of the HV and LV windings respectively and X_H and X_L are the leakage reactances of the HV and LV windings respectively. In order to determine the resistances and leakage reactances of the HV and LV windings, it has to be assumed that the transformer has been designed in such a way that the power losses on the HV side are equal to the power losses on the LV side. This is known as the optimum design criterion and it implies that (Guru & Hiziroglu, 2001):

$$I_H^2 R_H = I_L^2 R_L \tag{2.17}$$

From this it is possible to derive the following equations for the resistances and leakage reactances (Guru & Hiziroglu, 2001):

$$R_H = a^2 R_L = 0.5 R_{eH} \tag{2.18}$$

$$X_H = a^2 X_L = 0.5 X_{eH} \tag{2.19}$$

2.3.3. On load current method

As previously said, many researchers have made use of the open and short circuit tests to separate the core and winding vibrations in order to determine the state of the core and windings. The disadvantage of this is that the transformer must be taken off line, which is not always possible in practice.

In a study conducted by (Shengchang, et al., 2006), an online condition monitoring technique was suggested. By making use of the same principles (core vibrations are dependent on excitation voltage and frequency and independent of the load current and the winding vibrations are only dependent on the load current and independent of the excitation voltage) as the researchers as mentioned above, (Shengchang, et al., 2006) suggested that as long as the excitation voltage and its frequency are kept constant, preferably at rated voltage and frequency, the core vibrations should not change. This means that if the load is changed while the excitation voltage is kept constant, any change in the tank vibrations must be caused by the winding vibrations. After conducting an experiment on a test transformer in a laboratory, (Shengchang, et al., 2006) set up a graph to show how the vibration signal will change if the excitation voltage is kept constant and the load is varied. This graph is shown in Figure 2-17.

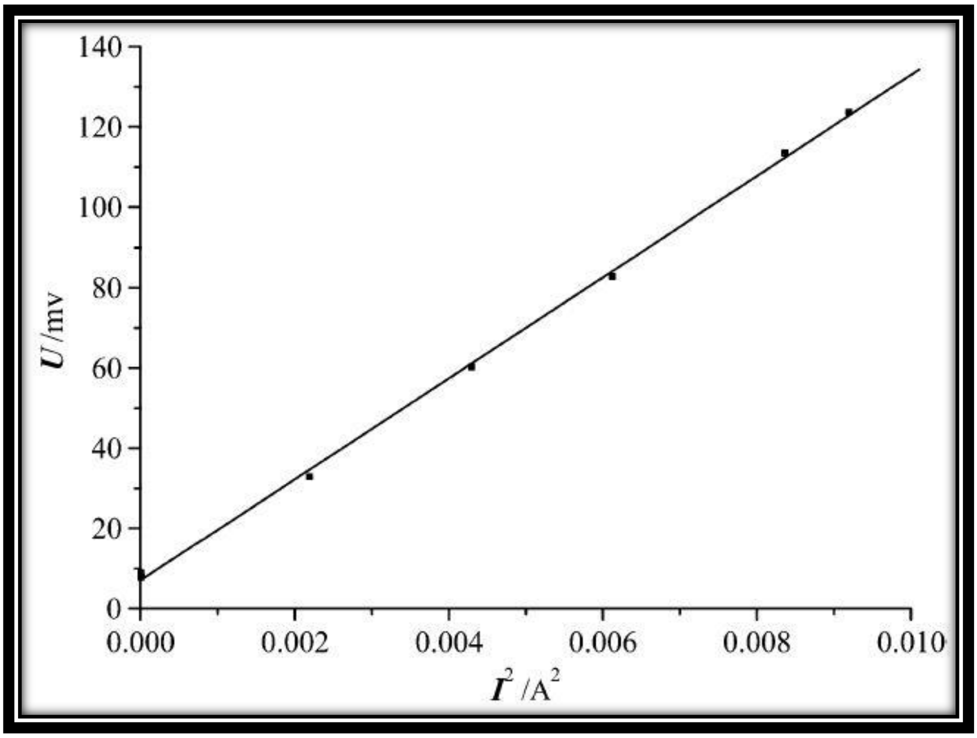

Figure 2-17: Fitted curve of on load current versus the fundamental frequency component of a vibration signal (Shengchang, et al., 2006)

Figure 2-17 shows the relationship curve of the on load currents squared (in Ampere) versus the magnitudes of the transformer tank vibration signals (in millivolt). What this graph implies is that by just measuring the transformer tank vibrations during its normal operation over a wide range of loads, it is possible to separate the contributions of the core and windings to the overall tank vibration signal by fitting the measured vibrations with a line of best fit. It has a small error seeing as a line of best fit is used, but by measuring the vibrations over longer periods and over a wider range of loads, the accuracy can be increased. The point where the line of best fit intersects the y axis shows the magnitude of the core vibrations seeing that the load current is zero at this point.

If the intersection point of the line of best fit with the y-axis changes drastically, there is a fault in the core and if the gradient of the line of best fit changes drastically, there is fault in the windings. (Shengchang, et al., 2006) proved that the on load current method works for a 5 KVA, 220 V/50 kV transformer, but warn that more research is needed before it can be applied on power transformers in practice.

As was mentioned in section 1.2 and as will be seen in section 4, all of the vibration measurements that were taken in this project were taken whilst the standard factory acceptance tests were conducted on the transformers. None of the standard factory acceptance tests require that a load be connected to the transformers. Thus during the standard factory acceptance tests the core and winding vibrations are always induced separately by performing the open and short circuit tests respectively. This means that for this project the OLCM method did not have to be used.

2.3.4. Vibration measuring sensor position on tank surface

There are two main factors that influenced the positioning and type of sensor used to measure the transformer tank vibrations in this study, and they are as follows. Firstly, the vibration measurements had to be taken during the standard factory acceptance tests under the normal production pressures. Secondly, due to the fact that this is only an exploratory investigation, a temporary transducer setup seemed to be the only logical choice. For these reasons the sensors that were used in this project could not be invasive in any way. To meet all of these requirements the vibration measurement sensors that were used included a portable laser Doppler vibrometer and a tri-axial accelerometer.

These sensors were not used at the same time, the laser Doppler vibrometer was only used to measure the vibrations of the first transformer and the accelerometer was used to measure the vibrations of the rest. The reasons for this are simple and they are as follows. Firstly, the vibration measurements of the first transformer were used as an exploratory session to get acquainted with the testing process. Secondly, the accelerometer attachment method had not yet been finalized by the time that the vibration measurements on the first transformer were taken.

After having decided which measuring equipment would be used, the next step was to determine the best location to measure the vibrations. (Shengchang, et al., 2011) conducted very thorough experiments to determine whether or not the attachment position of accelerometers on the tank of the transformer influences the measured vibrations. In the experiments, the accelerometer attachment positions are on the surface of the tank, above and below the windings on both the HV and LV sides as indicated by the numbers in Figure 2-18. From Figure 2-18 it can be seen that 12 accelerometers were used to determine whether or not the attachment positions affect the vibration measurements.

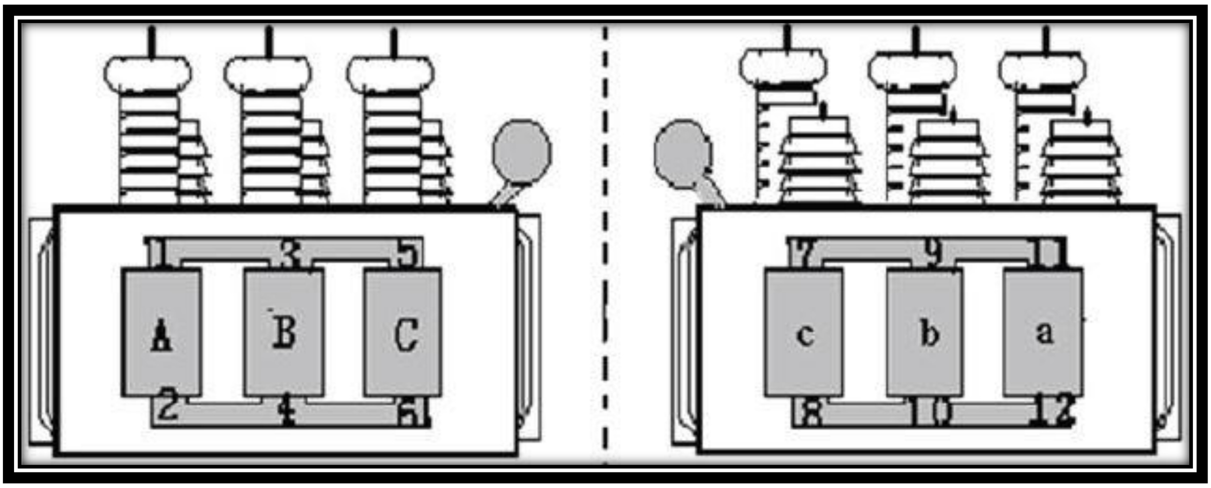

Figure 2-18: Accelerometer attachment positions (Shengchang, et al., 2011)

As said previously, the research conducted by (Shengchang, et al., 2011) is based on vibration measurements that were taken with accelerometers, but the principles discussed also apply to other vibration measuring sensors for example laser Doppler vibrometers. Although the main goal of the (Shengchang, et al., 2011) study was to determine if the attachment position influences the vibration measurement, for this project those results will be used to determine the best possible positions to place the tri-axial accelerometer and point the laser beam of the laser Doppler vibrometer.

The first test that (Shengchang, et al., 2011) conducted was to determine whether or not the vibration measurements of two different types of transformers will be the same if the accelerometers are placed in the same positions. After taking the measurements and doing the necessary post processing, which includes normalization of the results according to the square of the applied voltage and loading current, it was concluded that the amplitudes of the vibration signals were totally different, but the frequency characteristics were fairly similar. (Shengchang, et al., 2011) attributed the differences in the amplitudes to the different transmission paths, supporting structures and different clamping pressures in the windings and core. In this study seven totally different transformers were investigated, thus the vibration amplitudes cannot be compared to one another, but the frequency spectrums will be comparable.

The second test that (Shengchang, et al., 2011) conducted was to determine whether or not the vibration measurements of two of the same transformers are comparable if the accelerometers are placed in the same positions. After taking the measurements and doing the necessary post processing, it was concluded that the vibration signals were very similar. This means that the vibrations of the same type of transformers which are measured at the same positions can be compared to one another.

The third test that (Shengchang, et al., 2011) conducted was to determine whether or not the vibration measurements of the two accelerometers placed on the tank at the top and bottom of the same winding on the same side of the tank can be compared to one another. In other words, if the measurements of accelerometers 1 and 2 as shown in Figure 2-18 can be compared to one another. After taking the measurements and doing the necessary post processing it was concluded that the vibration signals vary slightly. (Shengchang, et al., 2011) attributed these slight variations to the differences in the transmission paths of the vibration signals. To be more specific, at the top of the tank the vibration signals can propagate through the HV and LV bushings and also the transformer oil. At the bottom of the tank the vibration signals can propagate through the supporting structures of the core that is fixed to the tank and the transformer oil. From this (Shengchang, et al., 2011) drew the conclusion that the top and bottom accelerometer measurements over the same phases should not be compared to one another.

The fourth test that (Shengchang, et al., 2011) conducted was to determine whether or not the vibration measurements of the two accelerometers that are at the same positions over a phase but on different sides of the transformer, can be compared to one another. In other words, if the vibration measurements of accelerometers 1 and 11 can be compared to one another. After taking the measurements and doing the necessary post processing it was concluded that the vibration signals vary slightly. (Shengchang, et al., 2011) attributed these slight variations to the differences in the transmission paths of the vibration signals. To be more specific, seeing that the top accelerometers over phase A are used as an example, the transmission paths that are of concern include the HV and LV bushings and also the transformer oil. The vibration signals that propagate through the transformer oil should not vary too much on the high and LV sides, but the vibration signals that propagate through the high and LV bushings should differ quite a lot. From this (Shengchang, et al., 2011) drew the conclusion that the left-right symmetrical accelerometer measurements should not be compared to one another.

The fifth test that (Shengchang, et al., 2011) conducted was to determine whether or not the vibration measurements of the accelerometers at the same positions, on the same side of the transformer of the three different phases can be compared to one another. In other words if the measurements of accelerometers 1, 3 and 5 can be compared to one another. After taking the measurements and doing the necessary post processing it was concluded that the vibration signals measured by accelerometers 1 and 5, in other words the vibration signals of phases A and C, are very similar, but they vary significantly from the vibration signal of accelerometer 3 or phase B.

(Shengchang, et al., 2011) attributed these differences to the symmetry of the transformer. To be more specific, positions 1 and 5 are symmetrical. By symmetrical it is meant that the structure of the tank at position 1 is the mirror image of the structure of the tank at position 5, and the influence that phase B and C has on A is the same as the influence that phase A and B has on C. For phase B (and therefore accelerometer 3), the structure and the influences that phases A and C have on B, vary quite a lot from the other two. From this (Shengchang, et al., 2011) drew the conclusion that only the vibration measurements of phases A and C at the same position on the same side of the transformer tank can be compared to one another. It is however very important to note that not all transformers are exactly symmetrical, especially ones with tap changers, which means that the fifth finding of (Shengchang, et al., 2011) is not directly applicable to this study.

The sixth and final test that (Shengchang, et al., 2011) conducted was to determine whether or not the vibration measurements of the accelerometers would change if the accelerometer was moved 5 or 10 centimetres upwards, downwards, left or right. After moving the accelerometers 5 cm upwards, downwards, left and right, the measurement results varied by ± 3.9%. After moving the accelerometers 10 cm upwards, downwards, left and right, the measurement results varied by ± 14.7%. (Leibfried & Feser, 1999) and (Lavalle, 1986) suggest that if the change in transformer tank vibrations is greater than 20%, the transformer should be taken out of the electrical energy grid and inspected thoroughly. However, observing that by moving the accelerometer attachment position by 10 cm causes the vibration signal to vary by 14.7% which is approaching 20%, (Shengchang, et al., 2011) recommend that the attachment position of the accelerometers should not vary by more than 5 cm.

From all these tests it can be concluded that the attachment position of the accelerometer does influence the vibration measurements significantly. (Shengchang, et al., 2011) suggest that the measuring positions should be marked on the transformer tank to ensure that the sensors are placed at the same positions every time the transformer tank vibrations are measured.

From the results obtained by (Shengchang, et al., 2011) it was decided that the best positions to measure the tank vibrations in this study is at the horizontal and vertical midpoint of each phase, as was also done in the practical measurements of (Shengchang, et al., 2006). Due to the fact that the vibration measurements for this study should not be invasive at all, it was decided that only one measuring sensor will be used to measure the core and winding vibrations, meaning that measurements will be taken over only one phase at a time. Also it was decided that it would be best if the sensor measured the tank vibrations at the horizontal and vertical midpoint of phase B if all the phases are excited at the same time, but if only one phase is excited, the sensor can measure the tank vibrations at the horizontal and vertical midpoint of that phase. Figure 2-19 graphically displays the measuring positions as discussed.

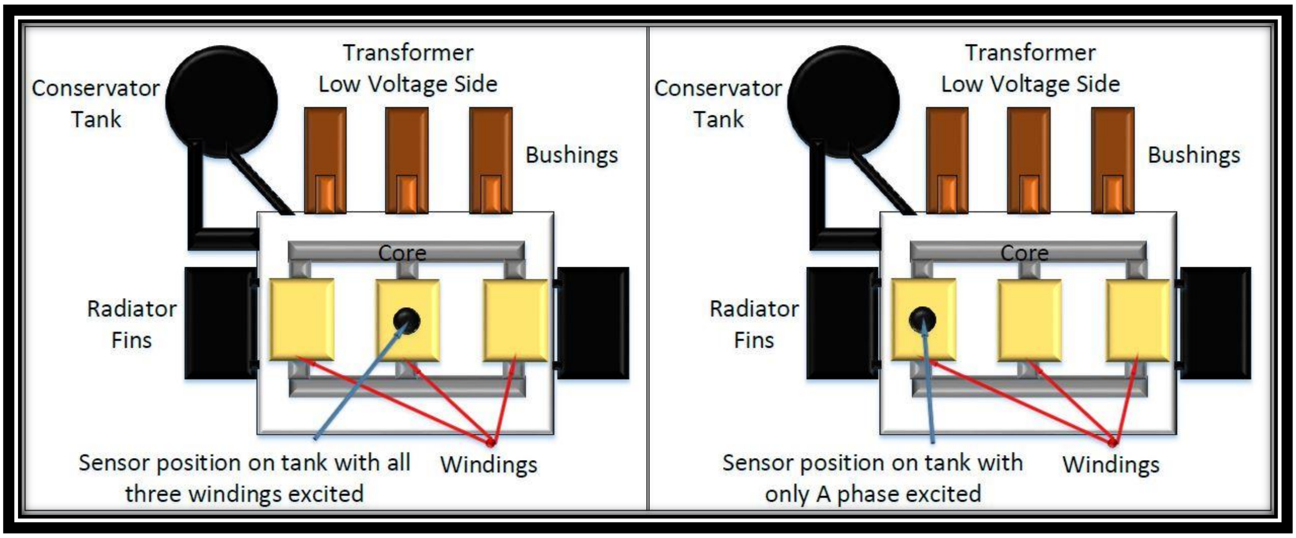

Figure 2-19: Sensor position

Also for safety and practicality reasons it was decided that the measurements will only be taken on the transformer LV side, or in other words the side where the LV bushings are situated, as can be seen from Figure 2-19.

In practice however it is not always possible to place the vibration measuring sensors at the positions as discussed above. This could be due to radiator fins that are in the way or because of the support ribs of the transformer tank, etc. If that is the case, the sensor measuring positions must be adjusted accordingly.

2.3.5. Other variables that can influence the measured tank vibrations

Besides the five main vibration sources as mentioned previously, the following variables can also influence the measured tank vibrations:

- Temperature.
- Power factor.
- Transmission path
    - Tank, support structures, clamping systems etc.
    - Transformer oil.

As summarized by (Garcia, et al., 2006), temperature variations can influence the measured tank vibrations in the following three ways:

- There is a nonlinear relationship between magnetostriction and temperature, thus the core vibrations depend on the temperature.
- The transformer oil viscosity is influenced by the temperature, which means that one of the propagation paths of the vibrations is influenced by temperature.
- Variations in the temperature could cause expansion or compression in some of the materials used to construct the transformer, which would change the natural frequencies of the system, the stiffness of the system and also the clamping pressures of the core and windings.

Although it is clear that temperature variation may have a significant impact on the vibrations, for this project it is assumed that the temperature does not affect the measured vibrations due to the fact that both the open and short circuit tests are performed so quickly that the temperature does not vary significantly.

The power factor only influences the measured vibrations when the transformer core and windings are excited simultaneously. Not one of the standard factory acceptance tests requires this, so it is clear that the power factor will not influence the measured vibrations.

In terms of the transmission path, as long as there is no failure in any of the transformers under investigation, it is safe to assume that the transmission path does not change over the course of the standard factory acceptance tests and thus the vibration measurements should not vary as a result of a change in the transmission path. At this point in time, it may also be useful to mention the refrigeration mode of the transformer. The only standard factory acceptance tests where the fans or oil pumps are operational are the temperature rise test and the sound pressure test, thus the refrigeration mode will also not influence the measured vibrations.

2.4. Expected transformer vibrations including the effects of regulator windings

As said previously, as long as the excitation voltage is kept constant, the core vibrations will remain constant. Therefore due to the fact that a tap changer does not affect the excitation voltage, the core vibrations are not influenced by the tap changer at all. This means that the theory for the core vibrations of all transformers is as follows:

The core vibrations (X, Y and Z components) of all transformers should be positively, linearly related to the normalized square of the excitation voltage.

The winding vibrations on the other hand are influenced by the regulator windings which is connected to the tap changer, and in the next few paragraphs the expected effects that the regulator windings have on the winding vibrations, are discussed.

Firstly, for transformers without regulator windings it has been proven that the winding vibrations are linearly related to the normalized square of the load current. This is also expected for transformers with regulator windings, but it is expected that the winding vibrations of each tap is only linearly related to that taps normalized square of the load current. The reason for this is that the leakage reactance characteristics for each tap differ due to the fact that each tap includes a different number of turns or is connected with a different orientation. The theory for this is as follows:

For transformers with plus and plus minus tap changers the radial and axial winding vibrations of a specific tap should be positively, linearly related to the normalized square of the load current of that specific tap.

In the rest of the discussions on the effects that the regulator windings have on the winding vibrations, the effects are only discussed for when the maximum current of the different taps are flowing through the windings. What this means is that in the following discussions, the linearity of the winding vibrations of the different taps with the normalized square of the load currents of those taps are not considered.

Seeing that transformers with regulator windings also have two different winding vibrations, namely radial and axial winding vibrations and also, seeing that there are differences between transformers with plus minus and plus tap changers in terms of delivering the nominal, maximum and reduced voltages, each type of transformer will have its own theories for the radial and axial winding vibrations. All of the factors that could affect the radial or axial winding vibrations for both transformers with plus and plus minus tap changers are summarized below:

- Connection orientation of the regulator and HV windings.
- Number of regulator taps included.
- Tap specific currents.
- Overall current carrying capacity of the transformer which is very closely related to the apparent power rating of the transformer.

The radial winding vibrations of transformers with both plus minus and plus tap changers are influenced by all of the factors as mentioned above, whereas the axial winding vibrations of transformers with plus minus and plus tap changers are only influenced by the last three factors as mentioned above. The reason why the connection orientation does not influence the axial winding vibrations is as follows. The axial winding vibrations are caused when the current flowing through the turns of an individual winding (for example the regulator winding) interact with the leakage flux of these turns, thus the connection orientation, which has to do with how the HV and regulator windings are connected relative to one another, does not make a difference.

The effect that the connection orientation of the regulator and HV windings, number of regulator taps included, tap specific currents and the overall current carrying capacity of the transformers have on the winding vibrations go hand in hand with each other, but what is meant by this will be explained separately.

In order to explain what is meant by the connection orientation of the regulator and HV windings, once again consider the middle and bottom images in Figure 2-4 and the middle and rightmost images in Figure 2-5 which were used to illustrate the situations where a transformer with a plus minus tap changer, where the tapping range is symmetrically arranged around the nominal tap, delivers the maximum and reduced voltages respectively.

First consider the situation where the transformer must deliver the maximum voltage. In this situation the regulator and HV windings are connected in such a way that the emfs enhance one another, which results in the leakage reactances of the regulator and HV windings to enhance one another. This means that if the regulator and HV windings were considered as a single component, its leakage reactance will be greater than the leakage reactance of the individual windings. The implication of this is that when the leakage flux of the regulator and HV windings interact with the current flowing through the LV winding, a greater radial vibration amplitude should be achieved. For convenience, this will be referred to as an *enhancing connection orientation*.

Now consider the situation where the transformer must deliver the reduced voltage. In this situation the regulator and HV windings are connected in such a way that their emfs oppose one another, which results in the leakage reactances of the regulator and HV windings to oppose one another. This means that if the regulator and HV windings were considered as a single component, its leakage reactance will be less than the leakage reactance of the individual windings. The implication of this is that when the leakage flux of the regulator and HV windings interact with the current flowing through the LV winding, a smaller radial vibration amplitude should be achieved. For convenience, this will be referred to as an *opposing connection orientation*.

From the discussions of transformers with plus tap changers in section 2.1 and the connection orientation as above, it should be clear that in the case of a transformer with a plus tap changer, the connection orientation can only be such that the emfs and thus also the leakage reactances of the regulator and HV windings enhance one another, or in other words it can only have an enhancing connection orientation.

In order to explain what is meant by the number of regulator taps included, consider the leftmost and middle images in Figure 2-5 which are used to illustrate the situations where a transformer with a plus minus tap changer, where the tapping range is symmetrically arranged around the nominal tap, delivers the nominal and maximum voltages respectively. For the situation where the transformer delivers the nominal voltage, no extra regulator turns are included, but the first tap is selected, and for the situation where the transformer delivers the maximum voltage, all the regulator turns are included, thus all the regulator taps are included. Thus it literally refers to the number of taps included.

The tap specific currents literally refers to the currents that will flow through the regulator and HV windings when a certain tap is selected. To explain what is meant by the overall current carrying capacity of the transformer consider the following three, single phase transformers as shown in Table 2-3. In Table 2-3 the abbreviation Trfr is used for transformer and the acronyms HVT, NVT and LVT are used and they refer to highest voltage tap, nominal voltage tap and lowest voltage tap respectively.

Table 2-3: Explanatory single phase transformers

Trfr	Apparent Power (kVA)	Voltage handling capacity of each winding (V)				Current handling capacity of each winding (A)			
		HV winding		LV winding		HV winding		LV winding	
		HVT	NVT	LVT	All taps	HVT	NVT	LVT	All taps
1	20	550	500	450	250	36.36	40	44.44	80
2	5	550	500	450	250	9.09	10	11.11	20
3	5	275	250	225	100	18.18	20	22.22	50

As can be seen from the specifications of the first two transformers, the rated currents of the first transformer are higher than that of the second transformer, thus it could be said that overall the first transformer has a higher current carrying capacity than the second transformer. The reasons why the rated currents of the first transformer are higher than the rated currents of the second transformer are as follows. The first transformer has a higher apparent power rating than the second and the two transformers have the same system voltages. Now consider the second and third transformers. The overall current carrying capacity of the third transformer is also greater than that of the second, even though it has the exact same apparent power rating. The reason for this is that the system voltage of the third transformer is half that of the second transformer. This means that the overall current carrying capacity is determined by two factors and they are the apparent power rating of the transformer and its system voltage.

Nevertheless, at this point in time it should be clear what is meant by the overall current carrying capacity of the transformer. Furthermore, for the transformers that are included in this study though, the higher the apparent power rating the higher the overall current carrying capacity of the transformer. Thus although the system voltage does impact the overall current carrying capacity, for the transformers that are included in this study the apparent power rating is the deciding factor in terms of the overall current carrying capacity.

It should be noted that the overall current carrying capacity of the transformers was not identified as a factor that can influence the axial and radial winding vibrations from the literature study, instead it was identified after having done the short circuit tests on all the transformers that are included in this study.

Now that all the factors that influence on the winding vibrations have been identified and explained, it is time to compose the theories for the different transformer and winding vibrations. It must be noted that in the discussion above and the theories below the terms higher and lower current carrying capacities were used. Higher and lower do not refer to specific values, instead they are relative to one another. Furthermore, the terms higher and lower have no relation to power transformers that are considered as high power or low power, power transformers in industry.

2.4.1. Transformers with plus minus tap changers

The theories for the amplitudes of the radial and axial winding vibrations at the main frequency component of transformers with plus minus tap changers are summarized below.

Radial vibrations

The theory for the amplitudes of the radial winding vibration at the main frequency component of transformers with plus minus tap changers is as follows:

For higher current carrying capacity transformers with plus minus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected.

Due to the fact that the above theory is specific to transformers with higher current carrying capacities, another theory is included which is specific to transformers with lower current carrying capacities and it is as follows:

For lower current carrying capacity transformers with plus minus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected.

It can be noted from the two theories above that the radial winding vibrations amplitudes at the main frequency component for the highest and lowest voltage taps just switched positions. The reason for this is as follows. It is expected that for transformers with plus minus tap changers and lower overall current carrying capacities, the importance of the number of regulator taps included will lower which will ensure that the importance of the connection orientation of the regulator and HV windings also lowers and thus the importance of the tap specific currents flowing through the HV winding would increase. In other words, for transformers with plus minus tap changers that has a lower overall current carrying capacity, it is expected that the vibration contribution of the included regulator taps decrease, and the vibration contribution of the HV windings which carries the tap specific currents would increase, which means that it behaves more like a transformer without regulator windings.

Axial vibrations

The theory for the amplitudes of the axial winding vibrations at the main frequency component of transformers with plus minus tap changers is as follows:

For all transformers with plus minus tap changers, the amplitude of the axial winding vibrations when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the axial winding vibrations when the highest voltage, thus lowest current tap is selected, given that there are not much more enhancing taps than opposing tap.

The theory for the axial winding vibrations of transformers with plus minus tap changers does have the condition that the transformer's highest voltage tap position cannot include much more taps than the transformer's lowest voltage tap position, in which case the axial winding vibrations for the highest voltage tap could exceed that of the lowest voltage tap. None of the transformers with plus minus tap changer that are included in this study have more plus taps than minus taps, thus the theory for the axial winding vibrations as stated above applies to all of the transformers with plus minus tap changers that are included in this study.

Furthermore, one of the main goals of using a plus minus tap changer in transformers is to achieve a wider voltage supply range with fewer winding turns, thus it does not really make sense to have much more plus taps than minus taps or vice versa, but just for interest sake, if a transformer with a plus minus tap changer has much more plus taps than minus taps, its axial vibrations would behave like the axial vibrations of a transformer with a plus tap changer.

2.4.2. Transformer with plus tap changers

The theories for the amplitudes of the radial and axial winding vibrations at the main frequency component of transformers with plus tap changers are summarized below.

Radial vibrations

The theory for the amplitudes of the radial winding vibrations at the main frequency component of transformers with plus tap changers is as follows:

For higher current carrying capacity transformers with plus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected.

Due to the fact that the above theory is specific to transformers with higher current carrying capacities, another theory is included which is specific to transformers with lower current carrying capacities and it is as follows:

For lower current carrying capacity transformers with plus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected.

It should be clear that the theories for the amplitude of the radial winding vibrations at the main frequency component for transformers with plus minus and plus tap changers are the same which means that the importance of the different factors that could influence the winding vibrations are the same. The only difference between them is that for transformers with plus tap changers it is expected that the amplitude of the radial winding vibrations at the main frequency component for the lowest voltage thus highest current tap should surpass the amplitude of the radial winding vibrations at the main frequency component of the highest voltage thus lowest current tap at a higher overall current carrying capacity than for transformers with plus minus tap changers. This is due to the fact that transformers with plus tap changers does not have the opposing connection orientation which could slightly reduce the amplitude of the radial winding vibration at the main frequency component when the lowest voltage, thus highest current tap is selected.

Axial vibrations

The theories for the amplitudes of the axial winding vibrations at the main frequency component of transformers with plus tap changers are as follows:

For higher current carrying capacity transformers with plus tap changers, the amplitude of the axial winding vibration at the main frequency component when the highest voltage, thus lowest current tap is selected, should be greater than the amplitude of the axial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected.

Once again, due to the fact that the above theory is specific to transformers with higher current carrying capacities, another theory is included which is specific to transformers with lower current carrying capacities and it is as follows:

For lower current carrying capacity transformers with plus tap changers, the amplitude of the axial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the axial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected.

It can be noted from the two theories above that the amplitudes of the axial winding vibrations at the main frequency component for the highest and lowest voltage taps just switched positions. The reason for this is as follows. It is expected that for transformers with plus tap changers and lower overall current carrying capacities that the importance of the number of regulator taps included will lower and the importance of the tap specific currents flowing through the HV winding would increase. In other words, for lower overall current carrying capacity transformers with plus tap changers, it is expected that the vibration contribution of the included regulator taps decrease, and the vibration contribution of the tap specific currents flowing through the HV windings increase, which means that it behaves more like a transformer without regulator windings.

From the different factors that could affect the radial and axial winding vibrations as well as the theories for the radial and axial winding vibrations for transformers with plus minus and plus tap changers as summarized above, it is clear that:

- It is not expected that the different LV and HV winding and conductor types have an influence on the radial winding vibrations of the highest voltage, thus lowest current tap relative to that of the lowest voltage, thus highest current tap for transformers with plus minus tap changers.
- It is not expected that the different LV and HV winding and conductor types have an influence on the radial and axial winding vibrations of the highest voltage, thus lowest current tap relative to that of the lowest voltage, thus highest current tap for transformers with plus tap changers.

3. Measuring equipment, data logger and setup

As previously said, the measuring equipment that was used in this project included a laser Doppler vibrometer and a tri-axial accelerometer. Due to the fact that the laser Doppler vibrometer measures velocity, all of the measurements taken by the accelerometer were integrated once so that its results are also given as velocities. One more integration could have been done so that all the results were given as displacements, but the more integration steps that are used, the more errors can be introduced. In the next three subsections the precise model for the measuring equipment and data logger used, the most important settings and also the vibration measuring setups for the two different measurement devices, are given. For all the other relevant characteristics of the measuring equipment and also the data logger which was used to log the vibration measurements, see Appendix A.

3.1. Laser Doppler vibrometer

The laser Doppler vibrometer that was used was the Polytec portable digital vibrometer (PDV100). A very important characteristic of the PDV100 is that it can only measure velocity in one direction at a time. This means that for the vibration measurements of the first transformer, only the Z vibrations as referred to Figure 2-3 were recorded.

The measurement range that was used was 500 mm/s which means that a velocity of 1 mm/s would generate a voltage of 8 mV and it can be calculated by using the equation as shown below:

$$\frac{Output\ swing}{Measurement\ range} = \frac{4000\ mV}{500\,\frac{mm}{s}} = \frac{8\ mV}{\frac{mm}{s}} \tag{3.1}$$

The cutoff frequency for the low pass filter was chosen as 1 kHz seeing that previous transformer vibration research studies suggest that the frequencies of note in transformers are below 1 kHz, and the high pass filter was disabled.

As previously said, the vibrations of only the first transformer was measured by making use of the PDV100. The setup for the vibration measurements of the first transformer was as shown in Figure 3-1 below. From Figure 3-1 it can be seen that the PDV100 was mounted on a tripod which provided a stable measuring surface. Also, from Figure 3-1 it can be seen that the laser beam was pointed at a piece of reflective tape attached to the transformer tank, this was done to increase the signal strength of the reflected laser beam.

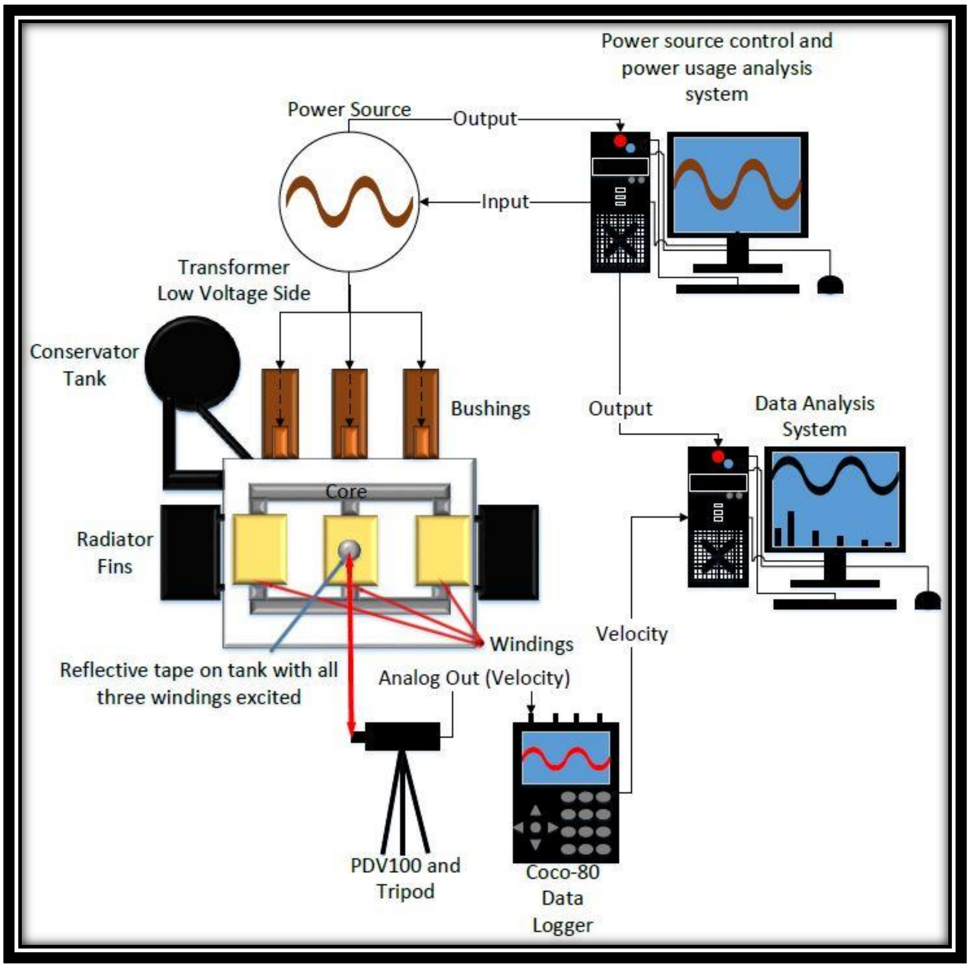

Figure 3-1: Measurement setup for the PDV100

The sampling frequency (f_s) for the vibration measurement with the PDV100 was chosen to be 10.24 kHz and the sampling time (T) was chosen to be 5 seconds, this ensures that the frequency resolution (f_{res}) will be 0.2 Hz and can be calculated by making use of equation (3.2) below:

$$f_{res} = \frac{f_s}{fs \times T} = \frac{1}{T} \tag{3.2}$$

Although the frequency resolution is not very fine, its influence on the results is minimal seeing that the main frequency component and its integral multiple harmonics are 100 Hz apart. As can be seen from equation (3.2), the frequency resolution only depends on the sampling time, thus to decrease the frequency resolution the sampling time must be increased. This also means that although a different sampling frequency was used for the accelerometer vibration measurements, the frequency resolution remained the same.

The main reason for the 5 second sampling time was to ensure that the vibration measurements did not interfere with the outcome of the standard factory acceptance tests. Specifically, the short circuit test requires that the windings are not heated too much seeing as this will increase the power consumption of the windings which could then mean that the transformer does not meet the specifications as set by the client. To ensure that the windings are not heated to much the short circuit test is performed as follows. The short circuit current is increased as fast as is possibly safe to the rated current of the transformer, then all of the necessary results are recorded within a matter of split seconds and then the current is decreased to zero as fast as is possibly safe. To accommodate this project, the test department agreed that the rated current will be supplied for 5 seconds to allow enough time for the vibration measurements.

3.2. Accelerometer

The accelerometer that was used is a Dytran tri-axial accelerometer. The setup for the vibration measurements where the accelerometer was used is as shown in Figure 3-2 below. From Figure 3-2 it can be seen that the accelerometer was attached to the transformer tank by means of a magnetic mount. Due to the fact that a magnetic mount was used, the sampling frequency for the accelerometer vibration measurements was very limited. (Ewins, 2000) and (Saeed & Farhad, 2014) suggest that when using a magnetic mount to take vibration measurements the sampling frequency should not be much greater than 2 kHz, thus the sampling frequency was chosen as 2.056 kHz.

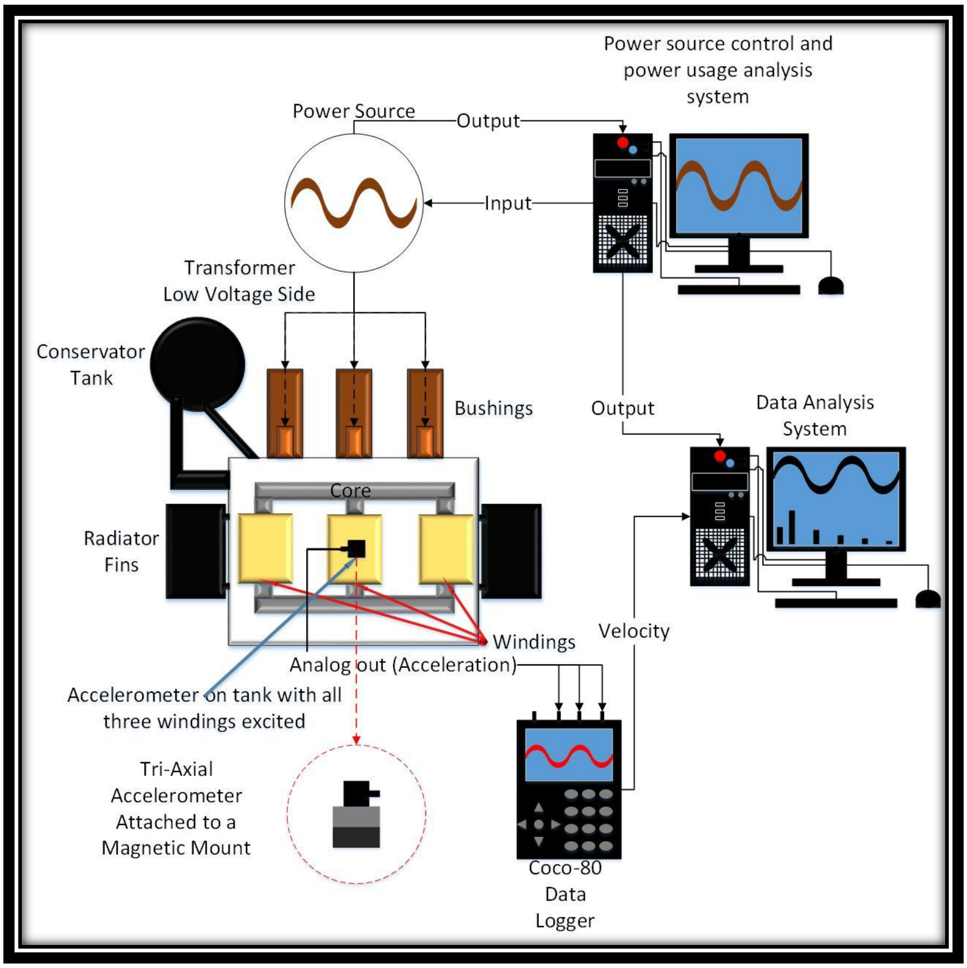

Figure 3-2: Measurement setup for the accelerometer

3.3. Data logger

The data logger that was used for this project is the CoCo-80. As previously stated, the main motivating factor for the selection of the equipment as mentioned above is their lack of invasiveness. All of the equipment can be set up quite easily and very fast, and it does not require that much space, which ensures that it does not interfere with the outcome of the standard factory acceptance tests.

4. Practical measurements

As previously indicated, the vibration measurements were conducted during the standard factory acceptance tests. Powertech Transformers performs three different types of standard factory acceptance tests, they are routine, type and special tests. Routine tests have to be performed on all transformers, type tests are only performed on representatives of other transformers and special tests are tests other than routine or type tests that has to be performed on the transformers as agreed upon by the manufacturer and purchaser. A transformer is considered as a representative of others if it is built to the same drawings, using the same techniques and materials, in the same manufacturing plant. The different routine, type and special tests are listed below.

- Routine tests.
    - Winding resistance measurement.
    - Voltage ratio and phase displacement measurement.
    - Short circuit impedance and load loss measurements (Short circuit test).
    - No load loss and current measurements (Open circuit test).
    - Dielectric routine tests.
    - Tests on on-load tap changers.
    - Leak testing with pressure for liquid-immersed transformers.
    - Tightness tests and pressure tests for tanks for gas-filled transformers.
    - Ratio and polarity of internal current transformers.
    - Check of core and frame insulation for liquid immersed transformers with core or frame insulation.
    - Determination of capacitances (windings to earth and between windings)
    - Measurement of direct current (DC) insulation resistance between each winding to earth and between windings.
    - Measurement of the dissipation factor (tan δ) of the insulation system capacitances.
    - Measurement of dissolved gasses in dielectric liquid from each separate oil compartment except diverter switch compartment.
    - Measurement of no load loss and current at 90% and 110% of rated voltage.
- Type tests.
    - Temperature rise test.
    - Dielectric type tests.
    - Determination of sound level for each method of cooling for which a guaranteed sound level is specified.

    - Measurement of the power absorbed by refrigeration system.
- Special tests.
    - Dielectric special tests.
    - Winding hotspot temperature rise measurements.
    - Determination of transient voltage transfer characteristics.
    - Measurement of zero sequence impedance on three phase transformers.
    - Short circuit withstand test.
    - Vacuum deflection test on liquid immersed transformers.
    - Pressure deflection test on liquid immersed transformers.
    - Vacuum tightness test on site on liquid immersed transformers.
    - Measurement of frequency response.
    - Check of external coating.
    - Measurement of dissolved gasses in dielectric liquid.
    - Mechanical test.
    - Determination of weight with transformer arranged for transport.

To prove the theories for the core and winding vibrations as summarized in section 2.4, the following tests had to be done.

- To prove the theory for the core vibrations, the magnetizing reactance characteristics for the transformers under investigation had to be determined, which means that the open circuit test had to be performed at different voltages for the transformers. These tests are performed as part of the standard factory acceptance tests, thus it was not a problem to get the vibration measurements that are required. In the discussion of the results, this specific test is referred to as the open circuit test.
- To prove the theory that for transformers with regulator windings, the winding vibrations of each tap is positively, linearly related to that tap's normalized square of the load current, the leakage reactance characteristics for the different taps have to be determined. Normally this is not done during the standard factory acceptance tests so a special request had to be made in order to prove this theory. Due to the fact that this is an expensive test and that it requires quite some time to complete, it was only done on one transformer and it was also only done on the highest, nominal and lowest voltage taps. In the discussion of the results, this specific test is referred to as the leakage reactance curve test.
- To prove the rest of the theories for the radial and axial winding vibrations, only the maximum leakage reactance had to be induced on the highest, nominal and lowest voltage taps. These

tests are performed in the standard factory acceptance test, thus it was not a problem to get the vibration measurements that were required. In the discussion of the results, this specific test is referred to as the short circuit test.

Seeing that the expected vibrations for plus minus and plus tap changers are slightly different and because their highest, nominal and lowest tap voltages are slightly different, they are discussed separately. Also, to ensure that the report is not too lengthy, in the case of the open circuit test, only the results of the Z vibrations are displayed, but the results of the X, Y and Z vibrations are discussed. Furthermore, the open circuit test results for only the first tested transformers with plus minus and plus tap changers are shown, but the discussion of their results will also include a discussion of the other transformers with plus minus and plus tap changers, core vibrations. The reasoning behind this is as follows. Except for the magnitude, all the other characteristics of the core vibration components are exactly the same. Thus, to include all those results would be redundant and it would increase the length of the report unnecessarily. In the case of the short circuit test, only the results of the Y and Z vibrations are displayed and discussed seeing that the X vibrations, when it comes to the winding vibrations are basically the same as the Z vibrations.

The reasoning behind the selective display of results as discussed above is so that the first transformers with plus minus and plus tap changers serve as the baselines or standards for the transformers with plus minus and plus tap changers respectively. This ensures that the differences in the results of the remaining transformers are emphasized. As will be seen from the results, the transformers with plus minus and plus tap changers are arranged in descending order in terms of the overall current carrying capacity. Both the first transformers with plus minus and plus tap changers fall within the category of transformers with higher overall current carrying capacity and the remaining transformers with plus minus and plus tap changers fall within the category of transformers with lower overall current carrying capacities. This arrangement makes it possible to clearly indicate the effects that the lower overall current carrying capacity have on the radial and axial winding vibrations for both transformers with plus minus and plus tap changers.

4.1. Plus minus tap changers

Three different transformers with plus minus tap changers are included in this study.

4.1.1. Plus minus 1

The first transformer with a plus minus tap changer is a generator step up transformer with the following specifications:

- 180 MVA, 161/15 kV.
- Plus minus tap changer (161 + 10(-10) × 1%).
- YNd.
- HV – disk type twin paper / LV – helical CTCE / regulator – loop layer strip

The first bullet shows the apparent power rating (APR) of the transformer and also the voltage handling capacity of the HV and LV windings. The voltage handling capacity of the HV winding, 161 kV, is the nominal voltage. The second bullet shows the tapping range of the transformer, thus it shows that this specific transformer has a plus minus tap changer, that is symmetrically arranged around the nominal voltage and which is connected to the HV winding that can increase or decrease the voltage in ten steps, and each step increases or decreases the voltage by 1%. The third bullet shows the vector group or connection types of the HV and LV windings respectively, thus the HV windings are connected in the star (Y) configuration, with the neutral brought out and the LV windings are connected in the delta (Δ) configuration. The fourth bullet shows that the HV winding is a disk type winding wound with twin paper conductor, the LV winding is a helical winding wound with CTCE conductor and the regualor winding is a loop layer winding wound with strip conductor. The specifications of all the other transformers will be summarized in the same format.

In section 2.1 it was mentioned that for the transformers that are included in this study, tap 1 is always the highest voltage tap, the lowest voltage tap is usually tap 17 or tap 21 depending on the number of taps and the nominal voltage tap is somewhere in between the highest and lowest voltage taps. Now for this specific transformer tap 1 is the highest voltage tap, tap 21 is the lowest voltage tap and tap 11 is the nominal voltage tap.

The way the taps are numbered is as follows: Always begin with the highest voltage tap at tap position 1. Then just continue counting upwards until all of the plus taps, in this case 10, have a tap position assigned to them. For this specific transformer the maximum voltage plus tap, otherwise known simply as the highest voltage tap (HVT) is at tap position 1 and the minimum voltage plus tap, which has a voltage that is only slightly larger than the voltage of the nominal tap, is at tap position 10. Then the next tap position will be the nominal tap, thus tap position 11 is the nominal voltage tap (NVT). Then last but not least, just continue counting upwards until all of the minus taps, also 10 taps for this specific transformer, have a tap position assigned to them. For this specific transformer the maximum voltage minus tap is at position 12 and its voltage is only slightly smaller than the voltage of the nominal tap, and the lowest voltage minus tap, or simply the lowest voltage tap (LVT) is at position 21.

Now it is very important to note that the tap position is not the same as the number of taps that are included. Consider the following examples. To deliver the highest voltage, the tap selector should select tap position 1, which means that all ten taps are included. To deliver the second highest voltage, the tap selector should select tap position 2, which means that only nine taps should be included and so on. To deliver the nominal voltage, the tap selector should select tap position 11, which means that no extra taps are connected and last but not least, to deliver the lowest voltage, the tap selector should select tap position 21, which once again means that all ten taps are included. Remember, this is a plus minus tap changer which means that it makes use of the same winding turns to increase or decrease the voltage and current.

By making use of the specifications as summarized above the voltage and current handling capabilities of each tap position can be calculated. To calculate the voltage handling capabilities of the taps, equation (4.1) can be used (Guru & Hiziroglu, 2001).

$$V_{tap1} = NV \times \frac{100 + Tap\%(\#Taps)}{100} = 161 \times \frac{100 + 1(10)}{100} = 177.1\ kV \qquad (4.1)$$

where NV is the nominal voltage, Tap% is the percentage by which a single tap can increase or decrease the voltage and #Taps is the number of taps that are included. As can be seen from equation (4.1), the voltage handling capability of tap 1 was calculated to be 177.1 kV. In order to calculate the tap voltage handling capabilities for the minus taps, the plus sign in equation (4.1) will change to a minus sign. To calculate the current handling capability of the taps, equation (4.2) can be used (Guru & Hiziroglu, 2001).

$$I_{tap1} = \frac{\frac{APR}{3}}{\frac{V_{tap1}}{\sqrt{3}}} = \frac{\frac{180 \times 10^6}{3}}{\frac{177.1 \times 10^3}{\sqrt{3}}} = 586.80\ A \qquad (4.2)$$

where APR is the apparent power rating of the transformer. When doing these calculations it is important to remember the rules for the star and delta connections which are summarized below. For star connections (Guru & Hiziroglu, 2001):

$$V_{LL} = \sqrt{3}V_p \tag{4.3}$$

$$I_{LL} = I_P \tag{4.4}$$

Equations (4.3) and (4.4) simply state that for star connections, the line to line voltage is equal to the phase voltage times the square root of three and the line to line current is equal to the phase current. For delta connections (Guru & Hiziroglu, 2001):

$$V_{LL} = V_P \tag{4.5}$$

$$I_{LL} = \sqrt{3}I_P \tag{4.6}$$

Equations (4.5) and (4.6) simply state that for delta connections, the line to line voltage is equal to the phase voltage and the line to line current is equal to the phase current times the square root of three. So to summarize all of the information as mentioned above, for this specific transformer, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:
  - Tap position: 1.
  - Number of taps included: 11.
  - Voltage handling capability: 177.1 kV.
  - Current handling capability: 586.80 A.
- Nominal voltage tap:
  - Tap position: 11.
  - Number of taps included: 1.
  - Voltage handling capability: 161 kV.
  - Current handling capability: 645.48 A.
- Lowest voltage tap:
  - Tap position: 21.
  - Number of taps included: 11.
  - Voltage handling capability: 144.9 kV.

- Current handling capability: 717.21 A.

- LV winding specifications:
    - Voltage handling capability: 15 kV.
    - Current handling capability: 6928.2 A.

It is important to take note of which tap number corresponds to the highest, nominal and lowest voltage taps seeing that in the discussion of the results, only the tap number will be mentioned. For the complete specifications for this and all the other transformers that are included in this study, see Appendix B. This specific transformer was the first transformer to be tested, thus as previously stated, the PDV100 was used to record the vibrations of this transformer which means that only the Z vibrations were recorded. The vibrations for both the open and short circuit tests were recorded and the results are presented below.

Open circuit test

Figure 4-1 shows the open circuit test Z vibrations velocity versus time for the first transformer with a plus minus tap changer. The axis system and legend for this figure is as follows:

- X-axis: Time in seconds (s).
- Y-axis: Velocity in millimeters per second (mm/s).
- Legend: Percentage of excitation voltage (%).

The open circuit test Z vibrations versus time graph of the first transformer with a plus tap changer has the same axis system and legend. The top image in Figure 4-1 shows the measured vibrations over the entire measurement period (5 seconds) and the bottom image in Figure 4-1 shows only the first 0.025 seconds.

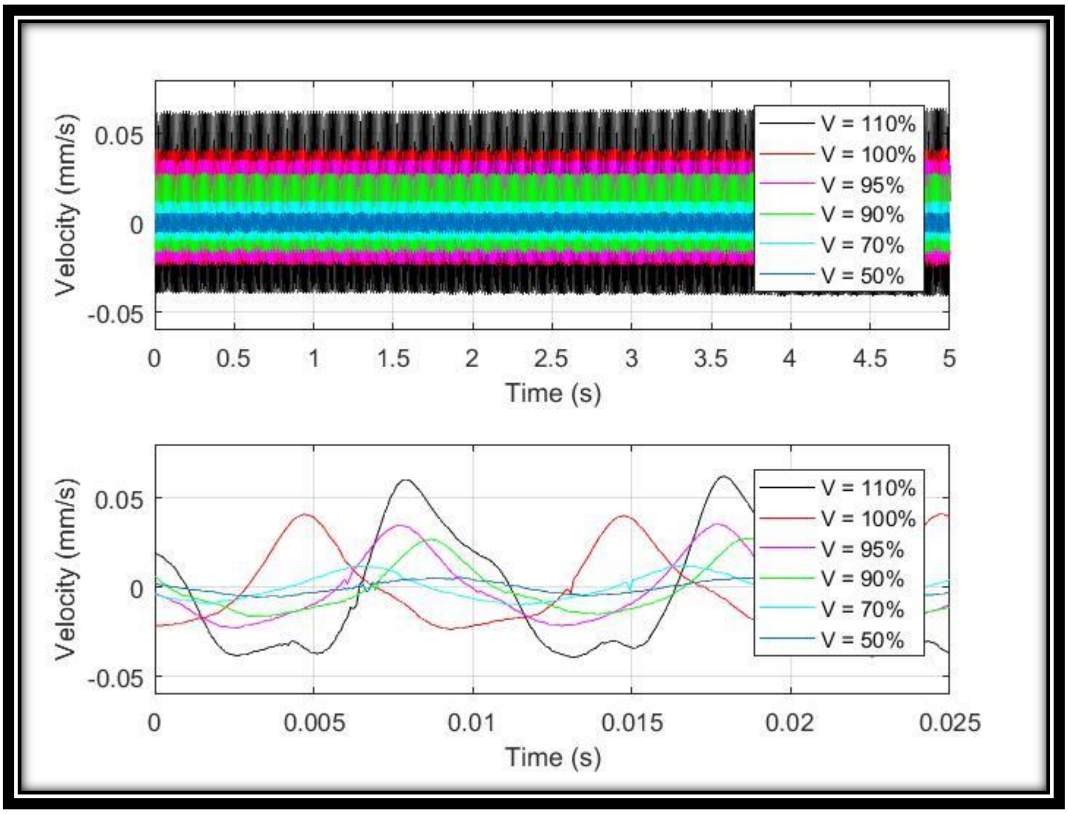

Figure 4-1: Plus minus 1 open circuit test Z vibration velocity vs time

From Figure 4-1 it appears that the velocity of the vibrations increases as the percentage of the excitation voltage increases. This is to be expected seeing that the theory for the core vibrations of all transformers states that all of the transformer core vibration components (X, Y and Z) should be positively, linearly related to the square of the excitation voltage, which basically means that if the excitation voltage increases, the vibration amplitude should also increase.

Figure 4-2 shows the frequency spectrum of the open circuit test Z vibrations. The axis system and legend for this figure is as follows:

- X-axis: Frequency in Hertz (Hz).
- Y-axis: Vibration amplitude in millimeters squared per second squared per Hertz ($[mm/s]^2/Hz$).
- Legend: Percentage of excitation voltage (%).

The frequency spectrum of the open circuit test Z vibrations for the first transformer with a plus tap changer has the same axis system and legend. The frequency in the top image in Figure 4-2 ranges from 0 to 1000 Hz and the bottom image zooms in on only the main frequency component (100 Hz) as determined in the literature study.

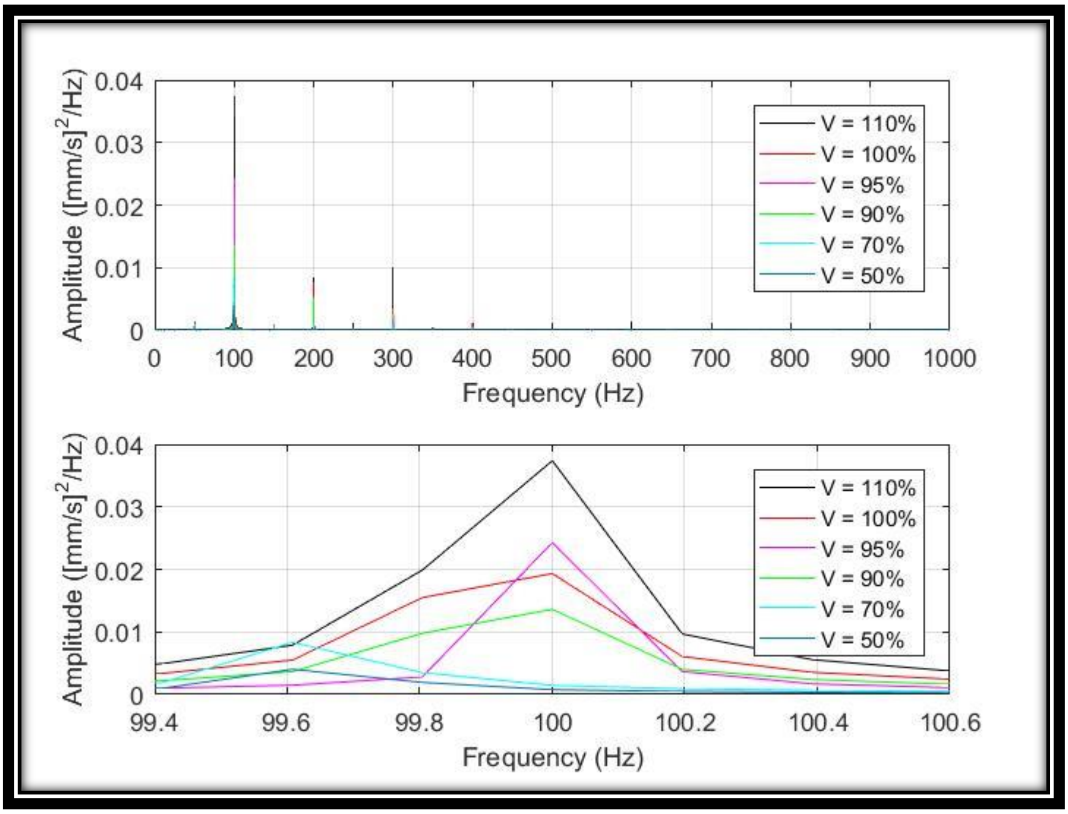

Figure 4-2: Plus minus 1 open circuit test Z vibration frequency spectrum

With regards to the frequencies, as can be seen from the top image in Figure 4-2, the main frequency component is 100 Hz as was expected, but it does also have integral multiple harmonics (200, 300 Hz etc.). This too was expected. With regards to the vibration amplitudes, overall it does appear that the vibration amplitudes increase as the excitation voltage increases, the only exception is at 100% of the excitation voltage the vibration amplitude is slightly lower than at 95% of the excitation voltage. There are five factors that could explain why the vibration amplitude at 95% of the excitation voltage is greater than the vibration amplitude when the excitation voltage is at 100%, but they will be explained at a later stage.

At this point in time it might be useful to have another look at the frequency resolution. As was stated previously and as can be seen from the bottom image in Figure 4-2, the frequency resolution is 0.2 Hz. Although the frequency resolution is quite coarse, the results are still clear enough in order to draw sensible conclusions. As will be seen from the frequency spectra of all the other transformers, the 100 Hz components show up in the spectra from 99.6 to 100.4 Hz.

Figure 4-3 shows the open circuit test Z vibration amplitude versus the normalised square of the excitation voltage. The axis system and legend for this figure is as follows:

- X-axis: Normalized square of excitation voltage (unity).

- Y-axis: Vibration amplitude in millimeters squared per second squared per Hertz ($[mm/s]^2/Hz$).
- Legend: Percentage of excitation voltage (%) and the line of best fit (LOBF).

Once again, the open circuit test Z vibration amplitude versus the normalised square of the excitation voltage for the first transformer with a plus tap changer will have the same axis system and legend.

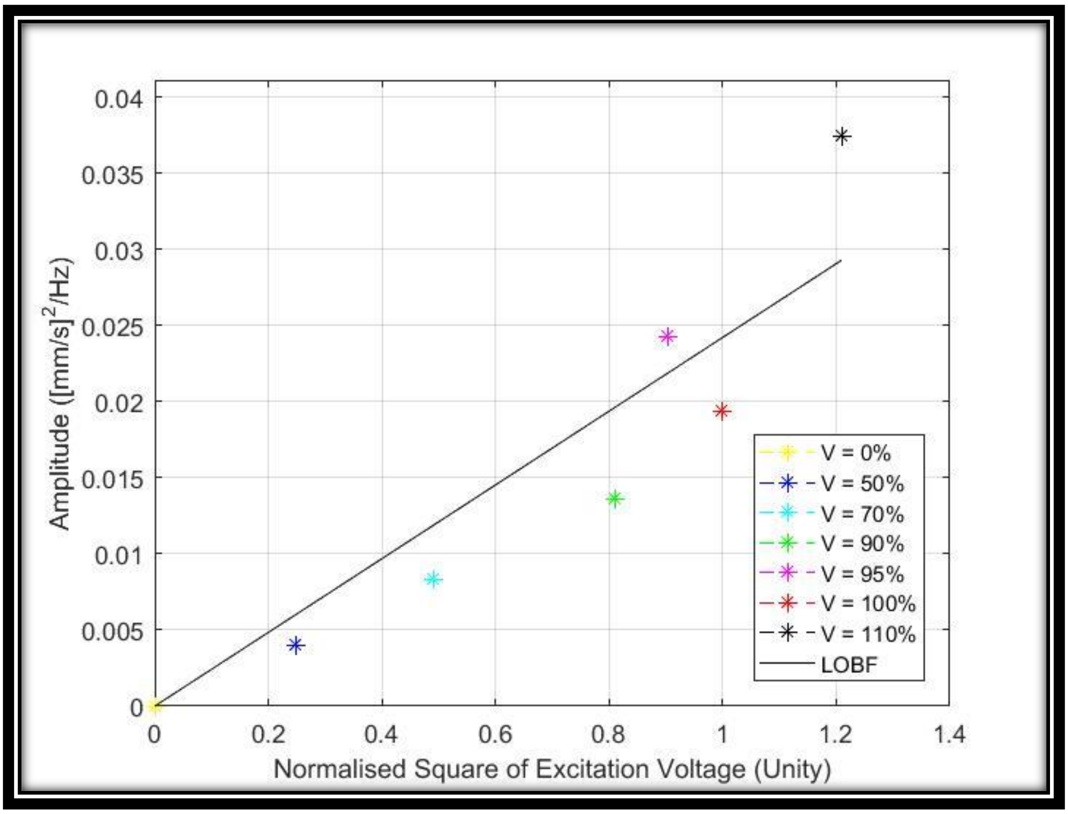

Figure 4-3: Plus minus 1 open circuit test Z vibration amplitude vs normalised square of the excitation voltage

As can be seen from Figure 4-3, the vibration amplitudes appear to be linearly related to the normalised square of the excitation voltage as was theorised in section 2.4. The black line that is included in Figure 4-3 is a line of best fit that is superimposed on the vibration amplitude data points. The line of best fit was obtained by making use of the least squares method.

As can be seen from Figure 4-3, the only vibration amplitude data point that varies greatly from the line of best fit is the data point where the excitation voltage is at 110%. This is due to the fact that at this point the transformer core is completely saturated and from the literature study it is known that the transformer should not be operated in this state, thus this data point is not of real concern. The factors that were identified that could possibly cause the deviation in the data points and the line of best fit are as follows:

- Factory noise.

- Inability to set the voltage (and current) to the exact value.
- Sensitivity of measuring equipment.
- Sampling period.
- Sampling frequency.

Although only the core vibrations in the Z direction were recorded for this specific transformer, from the core vibration measurements of the second transformer with a plus minus tap changer it was concluded that the characteristics of the X and Y core vibrations are very similar to the characteristics of the Z vibrations. To be more specific, the frequencies of note are exactly the same and both the X and Y core vibrations are also positively linearly related to the normalised square of the excitation voltage, the only difference between the vibrations in the three different directions is in the magnitude of the signals.

Short Circuit Test

Figure 4-4 shows the short circuit test radial (Z) vibrations velocity versus time for the first transformer with a plus minus tap changer. The axis system and legend for this figure is as follows:

- X-axis: Time in seconds (s).
- Y-axis: Velocity in millimeters per second (mm/s).
- Legend: Tap number at rated current.

The short circuit test radial vibrations velocity versus time for all the other transformers will have the same axis system and legend. The top image in Figure 4-4 shows the measured vibrations over the entire measurement period (5 seconds) and the bottom image in Figure 4-4 only shows the first 0.025 seconds.

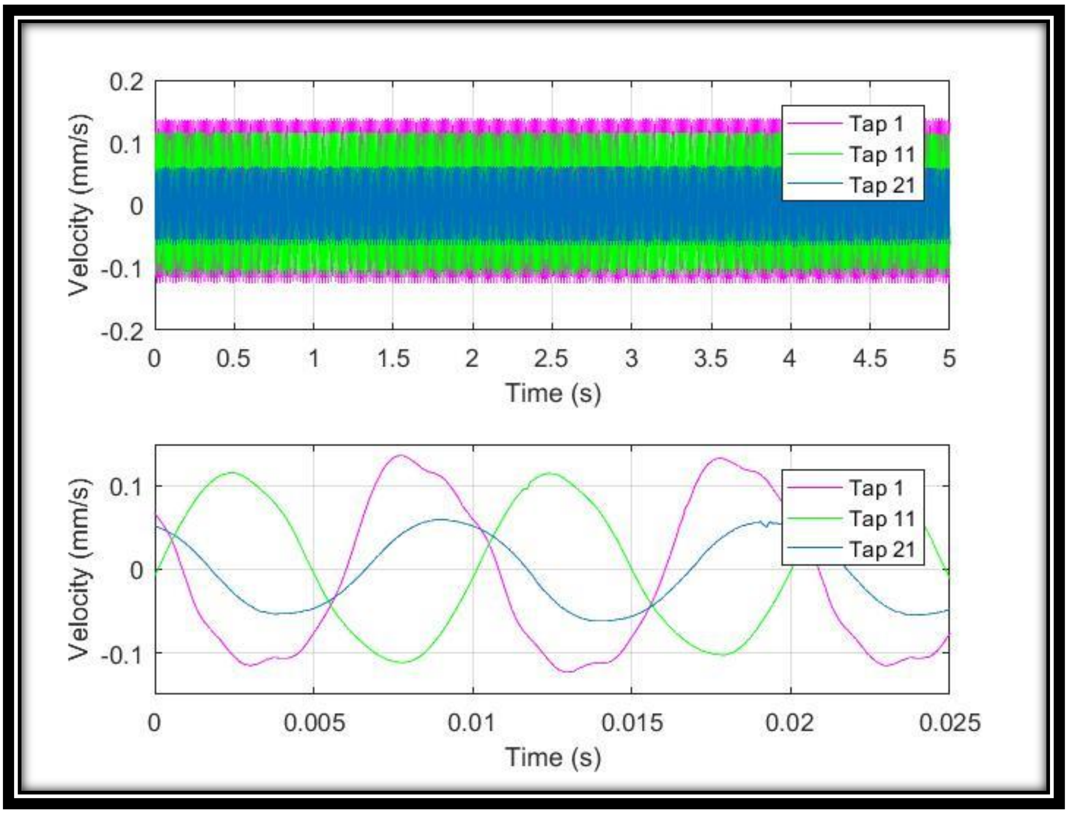

Figure 4-4: Plus minus 1 short circuit test radial (Z) vibration velocity vs time

From Figure 4-4 it can be noted that tap 1, which is the highest voltage, thus lowest current tap has the highest velocity. Tap 21 which is the lowest voltage thus highest current tap has the lowest velocity and the velocity of tap 11 which is the nominal voltage and current tap is more or less in the middle of tap 1 and tap 21.

Figure 4-5 shows the frequency spectrum of the short circuit test radial vibrations. The axis system and legend for this figure is as follows:

- X-axis: Frequency in hertz (Hz).
- Y-axis: Vibration amplitude in millimeters squared per second squared per Hertz ($[mm/s]^2/Hz$).
- Legend: Tap number at rated current.

Once again, the frequency spectrum of the short circuit test radial vibrations for all the other transformers will have the same axis system and legend. The frequency in the top image in Figure 4-5 ranges from 0 to 1000 Hz and the bottom image zooms in on only the main frequency component (100 Hz) as determined in the literature study.

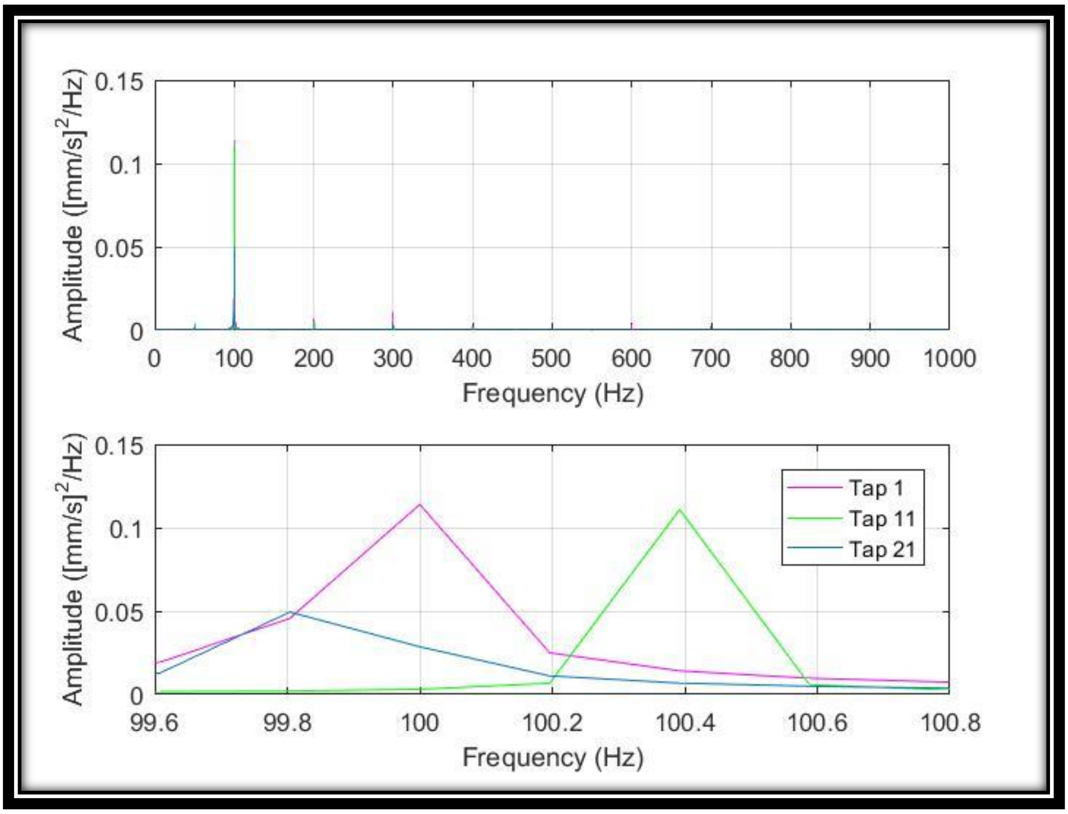

Figure 4-5: Plus minus 1 short circuit test radial (z) vibration frequency spectrum

From Figure 4-5 it is quite clear that the main frequency component of the radial winding vibrations is 100 Hz and that it does have integral multiple harmonics (200, 300 Hz etc.) but their amplitudes are insignificant compared to the main frequency component. Also, it can be seen that, at the main frequency component of the radial winding vibrations, tap 1's vibration amplitude is greater than tap 11's vibration amplitude which is greater than tap 21's vibration amplitude which proves the theory for the radial winding vibrations of transformers with plus minus tap changers with higher overall current carrying capacities as summarized in section 2.4.1.

The results as shown above for the first transformer with a plus minus tap changer completely supports both the theory for the core vibrations in the Z direction of all transformers as well as the theory for the radial winding vibrations of transformers with plus minus tap changers with higher overall current carrying capacities. If the axial winding vibrations of this transformer were recorded, the expectation would be that the vibration amplitude when the lowest voltage, thus highest current tap is selected, would be greater than the vibration amplitude when the highest voltage, thus lowest current tap is selected.

4.1.2. Plus minus 2

The second transformer with a plus minus tap changer is a distribution transformer with the following specifications:

- 45 MVA, 88/11 kV.
- Plus minus tap changer (88 + 7(-9) × 1.5%).
- YNyn.
- HV – disk type twin paper / LV – helical strip / regulator – loop layer strip

As was previously stated and as can be seen from the specifications above, the second transformer with a plus minus tap changer has a tapping range that is asymmetrically arranged around the nominal voltage. Furthermore, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:
  - Tap position: 1.
  - Number of taps included: 9.
  - Voltage handling capability: 97.24 kV.
  - Current handling capability: 267.18 A.
- Nominal voltage tap:
  - Tap position: 8.
  - Number of taps included: 2.
  - Voltage handling capability: 88 kV.
  - Current handling capability: 295.24 A.
- Lowest voltage tap:
  - Tap position: 17.
  - Number of taps included: 9.
  - Voltage handling capability: 76.12 kV.
  - Current handling capability: 341.31 A.
- LV winding specifications:
  - Voltage handling capability: 11 kV.
  - Current handling capability: 2361.89 A.

The vibrations for this transformer for both the open and short circuit tests were recorded in the X, Y and Z directions, but only the winding vibration results are shown seeing as the characteristics of its core vibrations are the same as that of the first transformer with a plus minus tap changer.

Short Circuit Test

Figure 4-6 shows the short circuit test radial (Z) vibrations velocity versus time for the second transformer with a plus minus tap changer. As can be seen from Figure 4-6, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 8.

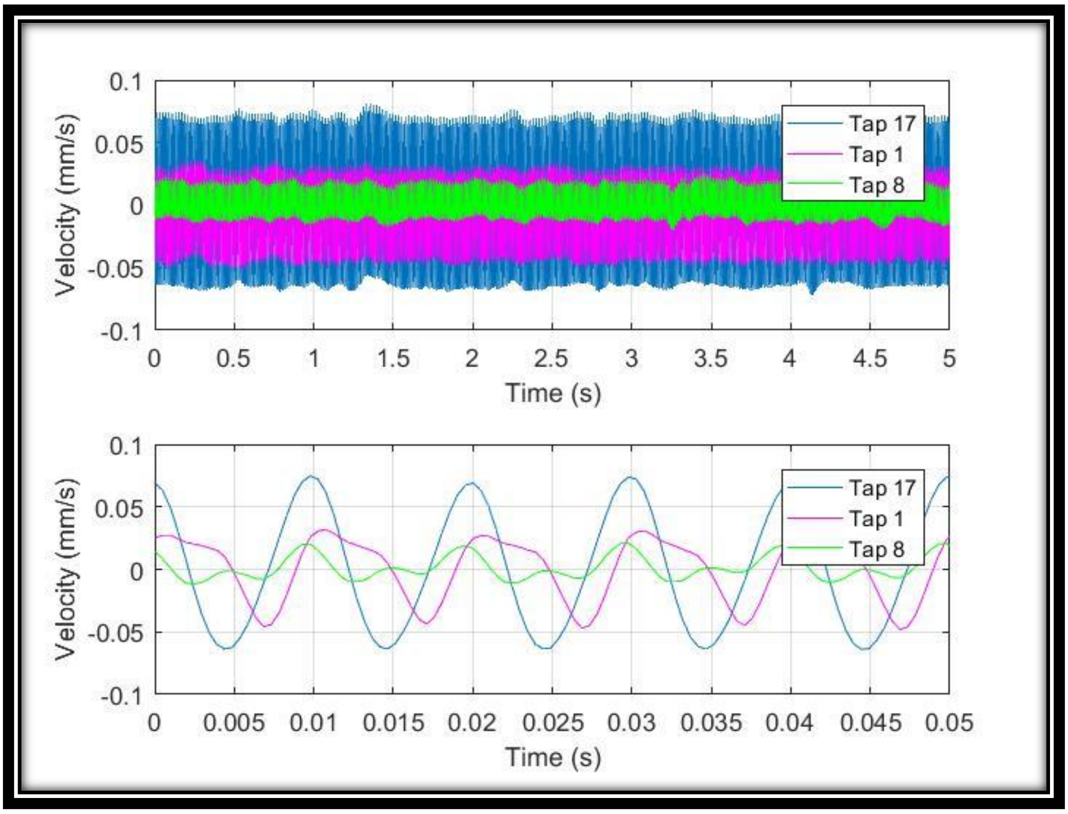

Figure 4-6: Plus minus 2 short circuit test radial (Z) vibration velocity vs time

Figure 4-7 shows the frequency spectrum of the short circuit test radial vibrations. As can be seen from Figure 4-7, the main frequency component of the radial winding vibrations is 100 Hz, that it does have integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component, the vibration amplitude of tap 17 is greater than the vibration amplitude of tap 1 which is greater than the vibration amplitude of tap 8.

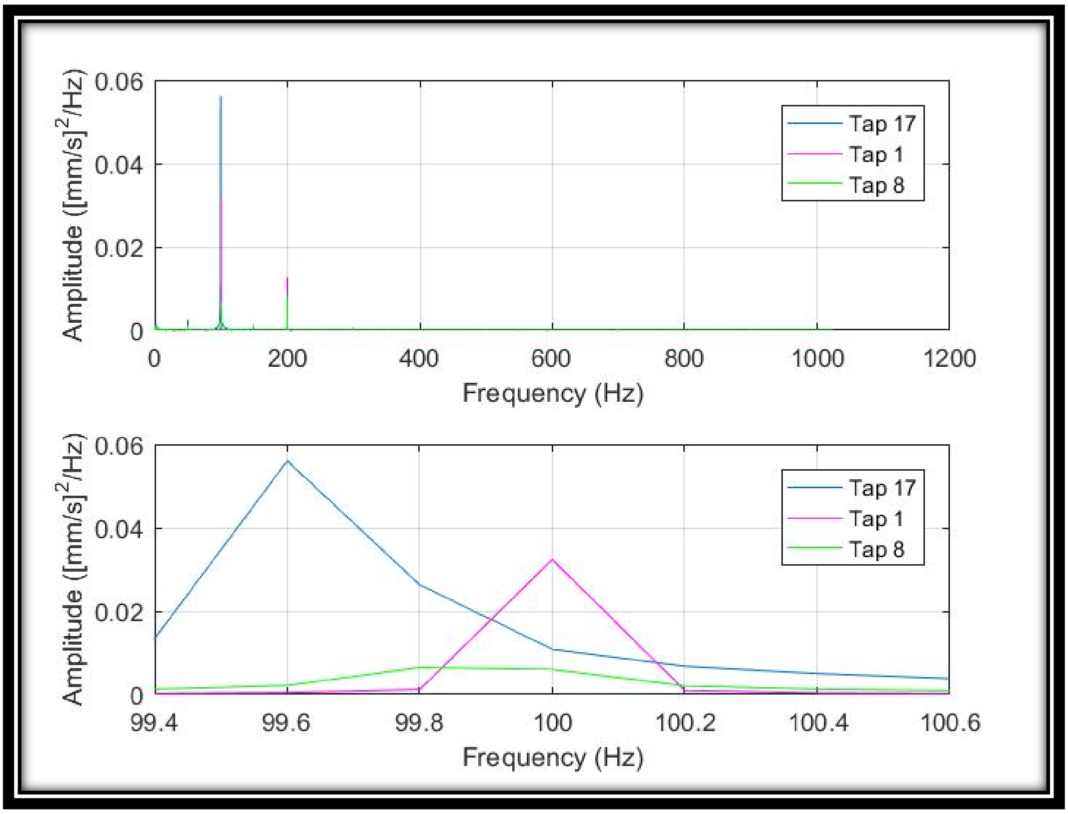

Figure 4-7: Plus minus 2 short circuit test radial (Z) vibration frequency spectrum

From the figures and the discussions above it should be clear that the radial winding vibrations at the main frequency component for the second transformer with a plus minus tap changer conforms to the theory for the radial winding vibrations of transformers with plus minus tap changers with lower overall current carrying capacities as summarized in section 2.4.1. This makes sense seeing that it was said that only the first transformers with plus minus and plus tap changers falls within the category of transformers with higher overall current carrying capacities.

Just to recap, because the second transformer with a plus minus tap changer has a lower overall current carrying capacity than the first, the following events take place:

- The vibration contribution of the regulator taps decrease, which means that the enhancing connection orientation and the number of included taps when tap 1 is selected increases the vibration amplitude of the HV winding which carries the rated current of tap 1 by less, and the opposing connection orientation and the number of taps included when tap 17 is selected decreases the vibration amplitude of the HV winding which carries the rated current of tap 17 by less.
- The vibration contribution of the HV windings which carries the tap specific currents increase.
- Then overall, tap 17's vibration amplitude is higher and tap 1's vibration amplitude is lower.

By considering only the radial vibration amplitudes of tap 1 and tap 8 in Figure 4-7, or in other words the radial vibration amplitudes of the highest and nominal voltage taps, it can be noted that the contribution of the enhancing connection orientation is still big enough to ensure that tap 1's vibration amplitude is greater than tap 8's vibration amplitude. Although this specific transformer does fall within the category of transformers with lower overall current carrying capacities, its overall current carrying capacity is not yet low enough to ensure that the radial vibration amplitude of the nominal tap is greater than that of the highest voltage tap.

Figure 4-8 shows the short circuit test axial (Y) vibrations velocity versus time for the second transformer with a plus minus tap changer. As can be seen from Figure 4-8, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 8.

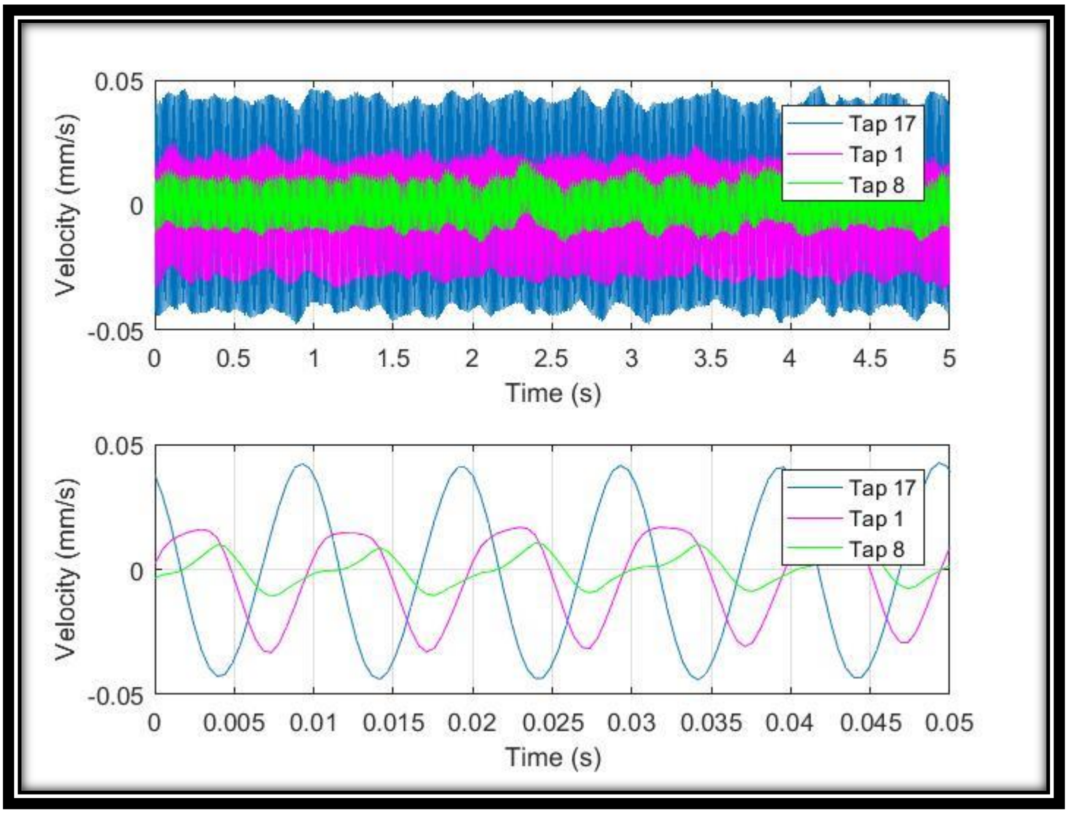

Figure 4-8: Plus minus 2 short circuit test axial (Y) vibration velocity vs time

Figure 4-9 shows the frequency spectrum of the short circuit test axial vibrations. From Figure 4-9 it is quite clear that the main frequency component of the axial winding vibrations is 100 Hz and that it too has integral multiple harmonics, but its amplitudes are insignificant compared to the main frequency component. It can also be seen that the vibration amplitude of the axial winding vibrations at the main frequency component of tap 17 is greater than that of tap 1 which is greater than that of tap 8.

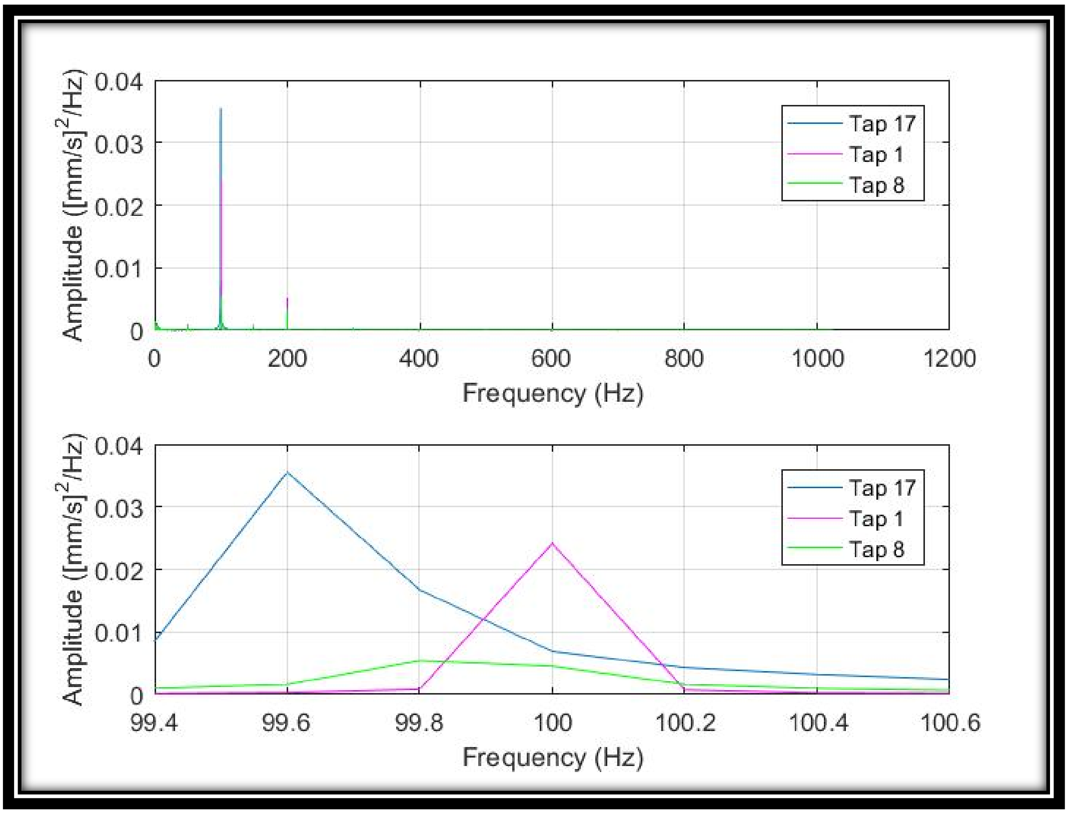

Figure 4-9: Plus minus 2 short circuit test axial (Y) vibration frequency spectrum

It should be clear that the axial winding vibrations at the main frequency component for the second transformer with a plus minus tap changer conforms to the theory for the axial winding vibrations of transformers with plus minus tap changers as summarized in section 2.4.1.

4.1.3. Plus minus 3

The third transformer with a plus minus tap changer is also a distribution transformer with the following specifications:

- 20 MVA, 33/11.5 kV.
- Plus minus tap changer (33 + 4(-12) × 1.25%).
- Dyn.
- HV – disk type strip / LV – disk CTCE / regulator – loop layer strip

As was previously stated and as can be seen from the specifications above, the third transformer with a plus minus tap changer also has a tapping range that is asymmetrically arranged around the nominal voltage. Furthermore, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:
    - Tap position: 1.

- Number of taps included: 9.
- Voltage handling capability: 34.65 kV.
- Current handling capability: 333.25 A.

- Nominal voltage tap:
  - Tap position: 5.
  - Number of taps included: 5.
  - Voltage handling capability: 33 kV.
  - Current handling capability: 349.91 A.
- Lowest voltage tap:
  - Tap position: 17.
  - Number of taps included: 9.
  - Voltage handling capability: 28.05 kV.
  - Current handling capability: 411.66 A.
- LV winding specifications:
  - Voltage handling capability: 11.5 kV.
  - Current handling capability: 1004.09 A.

The vibrations for this transformer for both the short circuit and leakage reactance characterization tests were recorded in the X, Y and Z directions and its results are presented below. The results for the short circuit tests will be discussed first and thereafter the results of the leakage reactance characterization tests will be discussed.

Short circuit test

Figure 4-10 shows the short circuit test radial vibrations velocity versus time for the third transformer with a plus minus tap changer. Although it is not that clear, it can be seen from Figure 4-10 that tap 17's vibration velocity is higher than tap 5's vibration velocity which is higher than tap 1's vibration velocity.

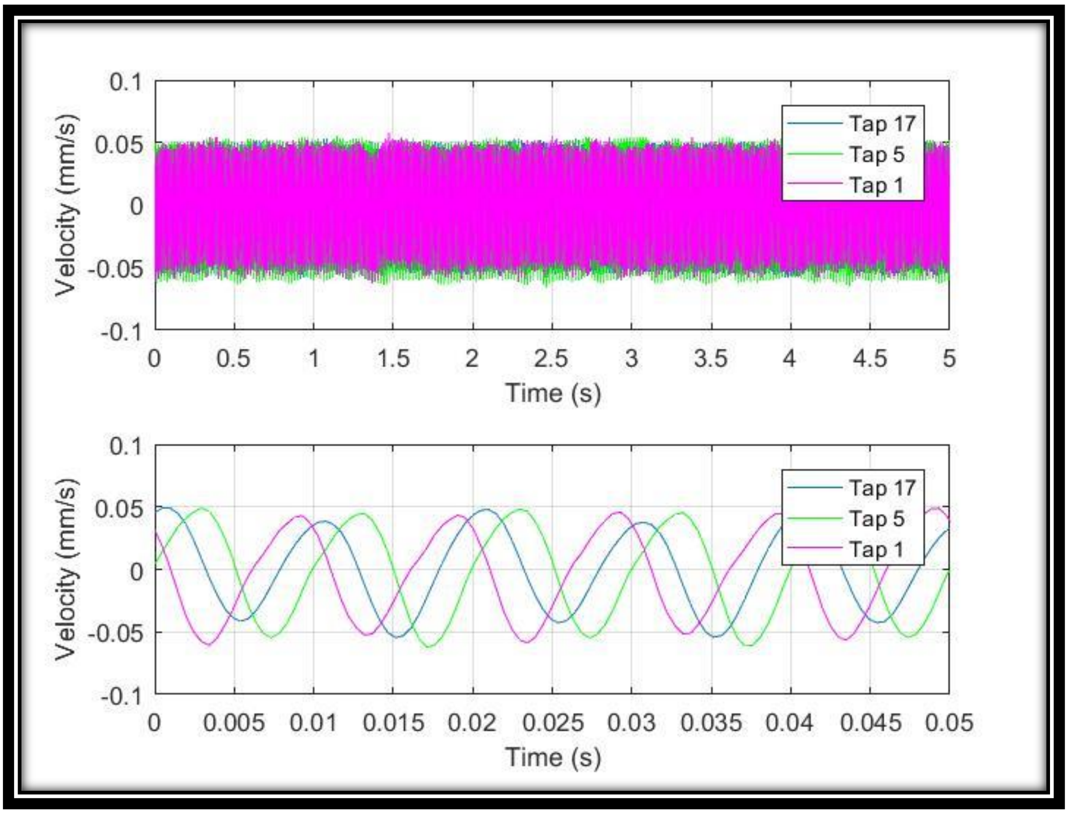

Figure 4-10: Plus minus 3 short circuit test radial (Z) vibration velocity vs time

Figure 4-11 shows the frequency spectrum of the short circuit test radial vibrations. From Figure 4-11 it is quite clear that the main frequency component of the radial winding vibrations is 100 Hz and that it does have integral multiple harmonics, but their amplitudes are insignificant compared to the main frequency component. From the figure it can also be seen that the 100 Hz vibration amplitude component of tap 17 is greater than the 100 Hz vibration amplitude component of tap 5 which is greater than the 100 Hz vibration amplitude component of tap 1.

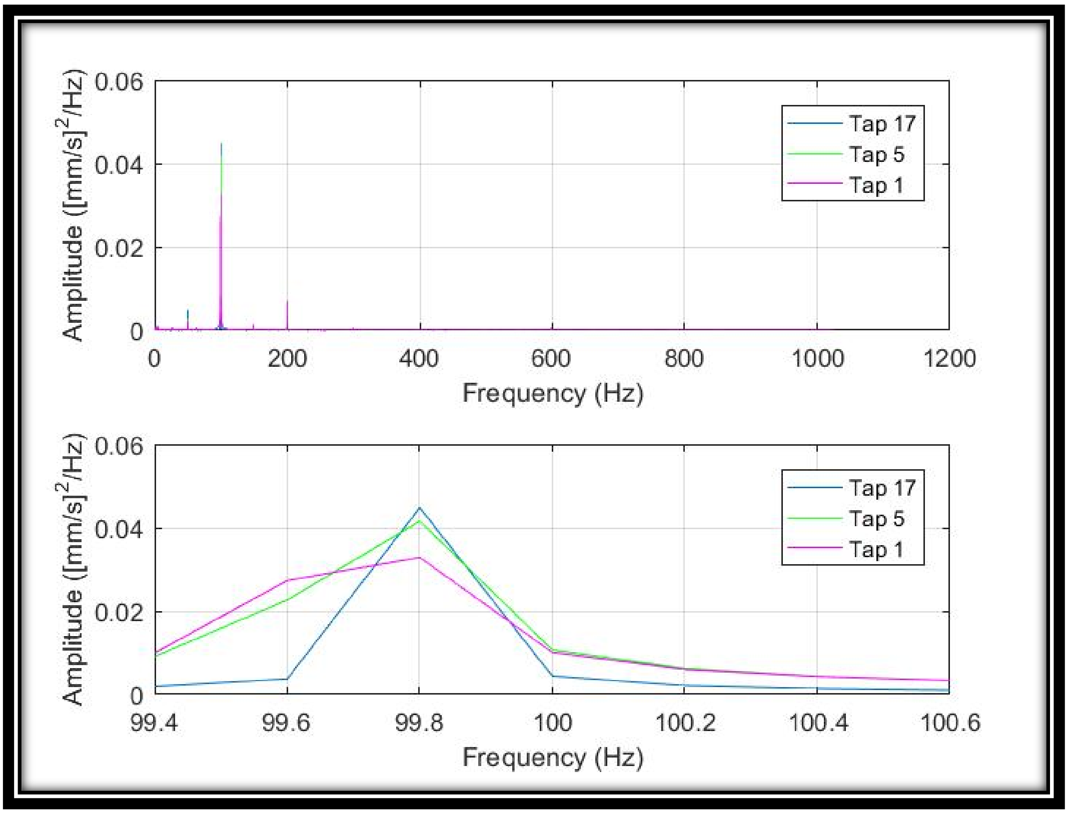

Figure 4-11: Plus minus 3 short circuit test radial (Z) vibration frequency spectrum

This means that the third transformer with a plus minus tap changer also conforms to the theory for the radial winding vibrations of transformers with lower overall current carrying capacities. Once again, consider only the vibration amplitudes of the nominal (tap 5) and highest voltage (tap 1) taps. The vibration amplitude of the nominal tap has now surpassed the vibration amplitude of the highest voltage tap. This means that the overall current carrying capacity of this transformer is low enough to ensure that the vibration contribution of the enhancing connection orientation and the regulator windings is too small to ensure that the radial vibrations of the highest voltage tap is greater than that of the nominal voltage tap. This is also due to the fact that the nominal and highest voltage taps aren't that far from each other seeing that the third transformer with a plus minus tap changer has a tapping range that is asymmetrically arranged around the nominal tap.

Figure 4-12 shows the short circuit test axial vibrations velocity versus time for the third transformer with a plus minus tap changer. In terms of the vibration velocities, it appears as if the velocities of taps 1 and 5 are the greatest, but more information will be given in the frequency spectrum of the axial vibrations.

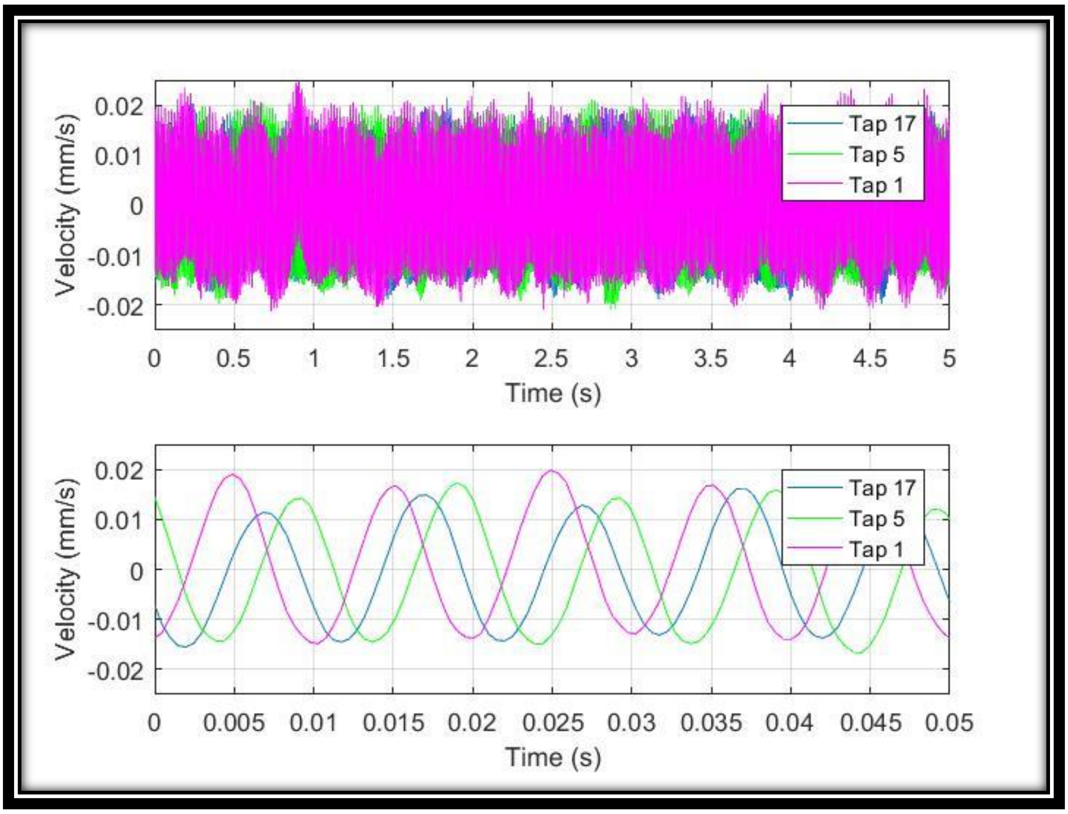

Figure 4-12: Plus minus 3 short circuit test axial (Y) vibration velocity vs time

Figure 4-13 shows the frequency spectrum of the short circuit test axial vibrations. From Figure 4-13 it is quite clear that the main frequency component of the axial winding vibrations is 100 Hz and that it too has integral multiple harmonics, but its amplitudes are insignificant compared to the main frequency component. It can also be seen that the vibration amplitude of the axial winding vibrations at the main frequency component of tap 17 is greater than that of tap 5 which is greater than that of tap 1.

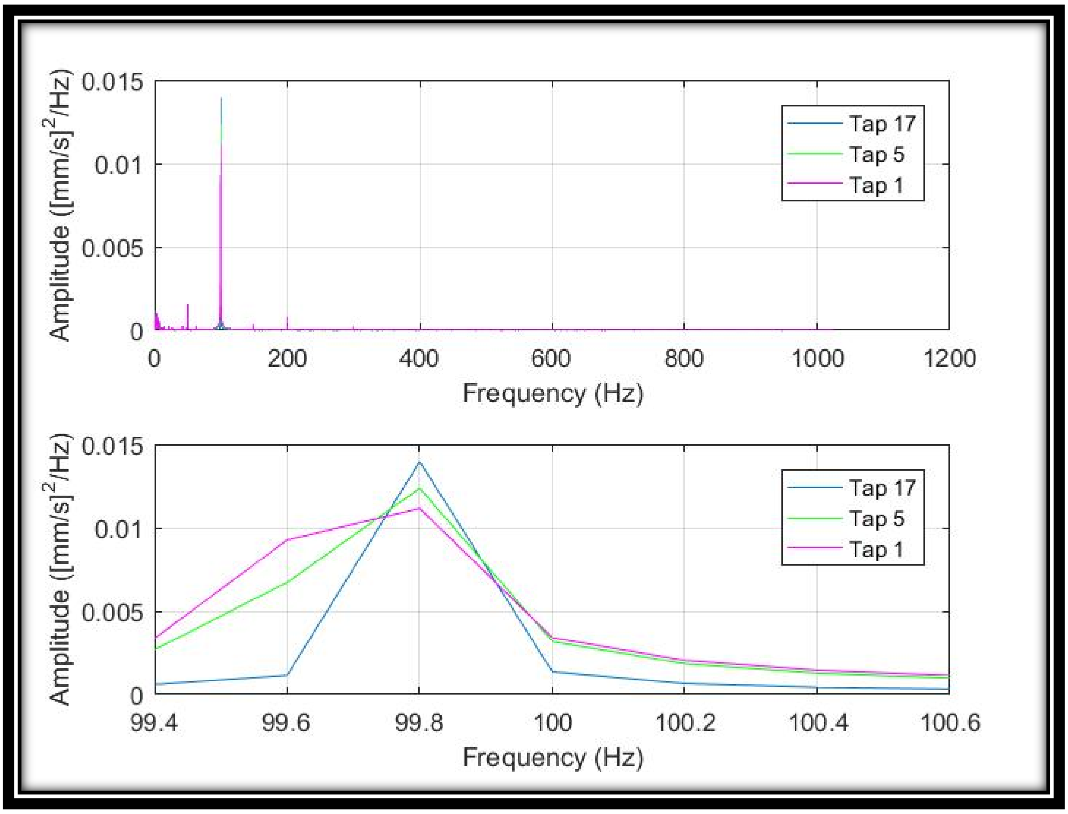

Figure 4-13: Plus minus 3 short circuit test axial (Y) vibration frequency spectrum

This means that the axial winding vibrations of the third transformer with a plus minus tap changer also conforms to the theory for the axial winding vibrations of transformers with plus minus tap changers as summarized in section 2.4.1. Although the overall current carrying capacity can never ensure that the axial vibration amplitude of the highest voltage tap is greater than that of the lowest voltage tap, its effect can still be seen on the axial vibration amplitudes of the highest and nominal voltage taps. For the second transformer with a plus minus tap changer (which has a higher overall current carrying capacity than the third transformer with a plus minus tap changer), the highest voltage tap's axial vibration amplitude is greater than that of the nominal voltage tap as can be seen from Figure 4-9. But as can be seen from Figure 4-13, for the third transformer with a plus minus tap changer, the axial vibration of the nominal voltage tap is greater than that of the highest voltage tap. This is also due to the fact that for the third transformer with a plus minus tap changer the nominal voltage tap is closer to the highest voltage tap than for the second transformer with a plus minus tap changer.

Leakage reactance curves test

Once again, to ensure that the report is not to lengthy, only the vibration amplitude versus the normalized square of the load current curves of the radial and axial winding vibrations for only the lowest voltage tap will be shown, but the results of the leakage reactance curve tests for the highest and nominal voltage taps will also be discussed.

Figure 4-14 shows the leakage reactance curve test radial vibration amplitude versus the normalised square of the load current for tap 17. The axis system and legend for this figure is as follows:

- X-axis: Normalized square of load current (unity).
- Y-axis: Vibration amplitude in millimeters squared per second squared per Hertz ($[mm/s]^2/Hz$).
- Legend: Percentage of load current (%) and the line of best fit (LOBF).

From Figure 4-14 it can be seen that the vibration amplitude at the main frequency component of the radial winding vibrations does appear to be linearly related to the normalised square of the load current, the only exception is that the 90% component is slightly greater than the 95% component.

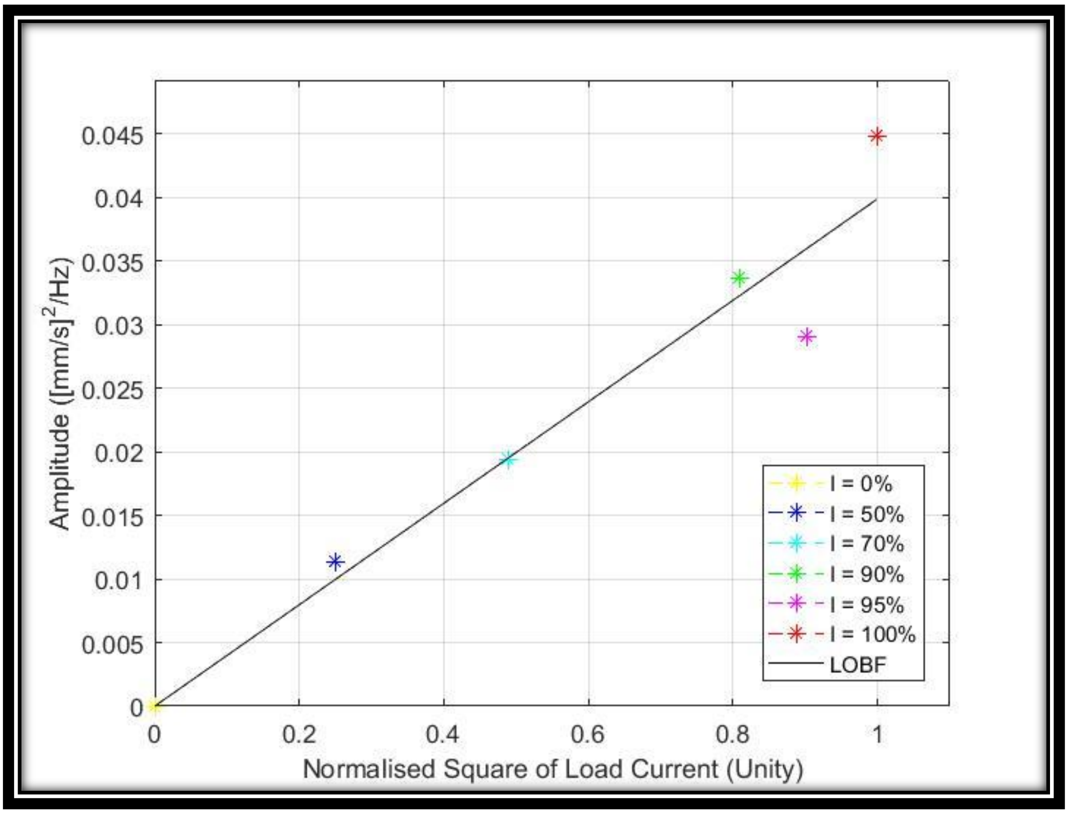

Figure 4-14: Plus minus 3 tap 17 leakage reactance curve test radial (Z) vibration amplitude vs normalised square of the load current

Figure 4-15 shows the leakage reactance curve test axial vibration amplitude versus the normalised square of the load current for tap 17. From Figure 4-15 it can be seen that the vibration amplitude at the main frequency component of the axial winding vibrations does appear to be linearly related to the normalised square of the load current, once again the only exception is that the 90% component is slightly greater than the 95% component.

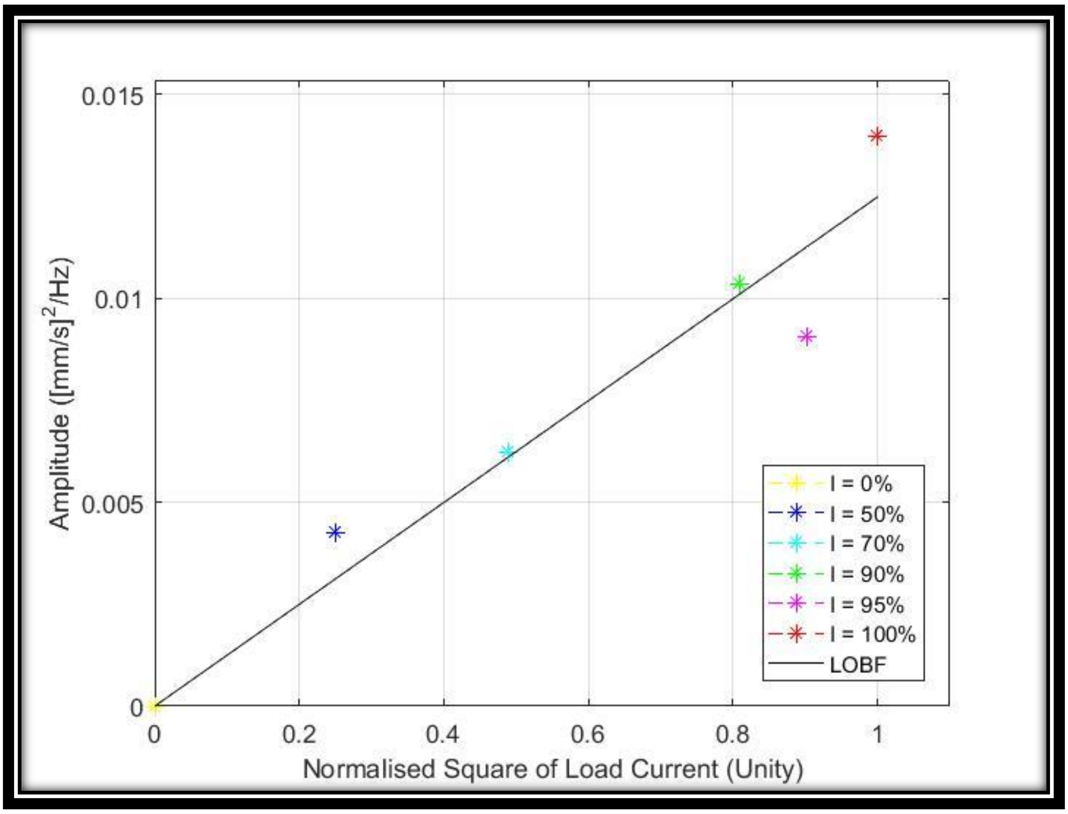

Figure 4-15: Plus minus 3 tap 17 leakage reactance curve test axial (Y) vibration amplitude vs normalised square of the load current

Although the leakage reactance curve tests for the highest and nominal voltage taps are not shown, from their results and the results of the leakage reactance curve tests of the lowest voltage tap as shown above it is clear that both the radial and axial winding vibration amplitudes of each tap is linearly related to that taps normalized square of the load current, thus the theory as summarized in section 2.4 is correct.

4.2. Plus tap changers

Four different transformers with plus tap changers are investigated in this study. Before the investigation is started, just remember that transformers with plus tap changers vary from transformers with plus minus tap changers in terms of delivering the nominal, maximum and reduced voltage as summarized in Table 2-1.

4.2.1. Plus 1

The first transformer with a plus tap changer is a distribution transformer with the following specifications:

- 80 MVA, 132/33 kV.
- Plus tap changer (132 + 8(-8) × 1.25%).
- YNd.
- HV – disk type twin paper / LV – disk strip / regulator – loop layer strip

Furthermore, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:
    - Tap position: 1.
    - Number of taps included: 17.
    - Voltage handling capability: 145.2 kV.
    - Current handling capability: 318.1 A.
- Nominal voltage tap:
    - Tap position: 9.
    - Number of taps included: 9.
    - Voltage handling capability: 132 kV.
    - Current handling capability: 349.91 A.
- Lowest voltage tap:
    - Tap position: 17.
    - Number of taps included: 1.
    - Voltage handling capability: 118.8 kV.
    - Current handling capability: 388.79 A.
- LV winding specifications:
    - Voltage handling capability: 33 kV.
    - Current handling capability: 1399.64 A.

The vibrations for both the open and short circuit tests were recorded in the X, Y and Z directions for this transformer and its results are presented below.

Open circuit test

Figure 4-16 below shows the open circuit test Z vibrations velocity versus time for the first transformer with a plus tap changer. From Figure 4-16 it appears that the velocity of the vibrations increases as the percentage of the excitation voltage increases.

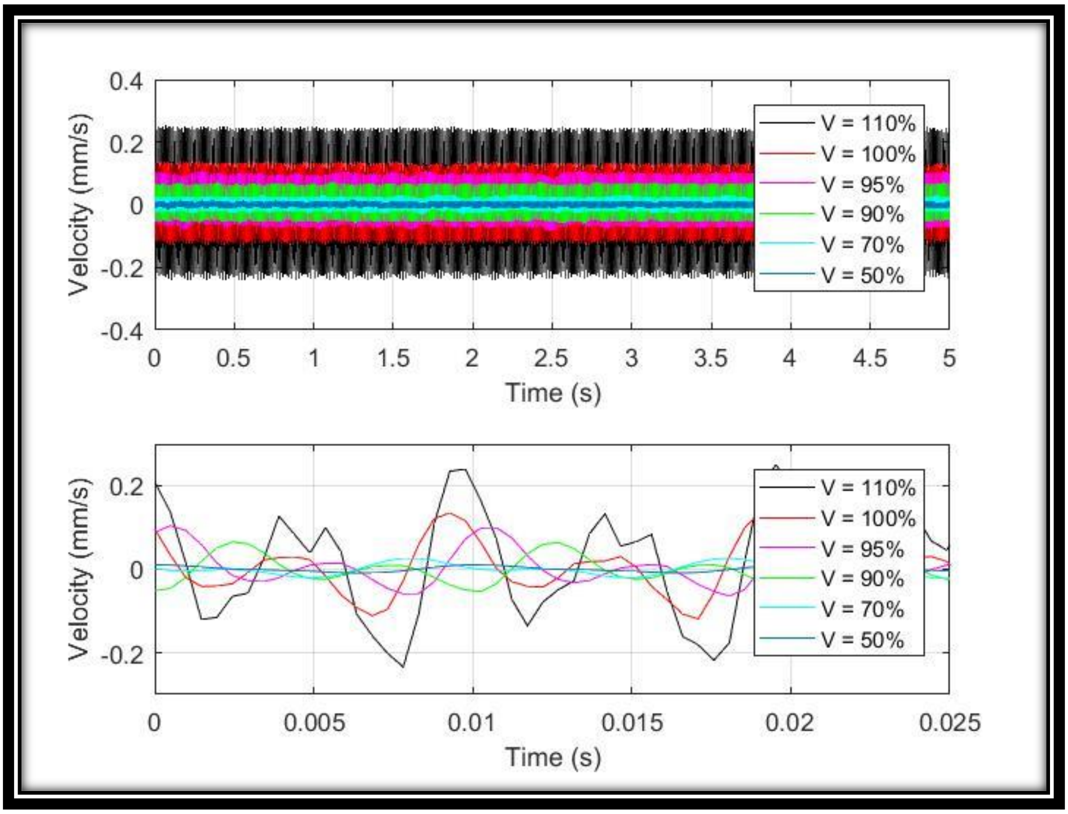

Figure 4-16: Plus 1 open circuit test Z vibration velocity vs time

Figure 4-17 shows the frequency spectrum of the open circuit test Z vibrations. With regards to the frequencies, as can be seen from Figure 4-17, it appears that 200 Hz is the main frequency component, but this is not the case. It is believed that the 200, 300 and 600 Hz components have such high amplitudes because they are close to some of the approximated natural frequencies of the core. These approximated natural frequencies were not measured, they were calculated by making use of empirical equations as is accustomed in industry. This means that the 100 Hz component is still the main frequency component for the core vibrations in the Z direction, and that it’s integral multiple harmonics are over emphasized by the approximated natural frequencies of the core.

With regards to the vibration amplitudes at the main frequency component, overall it does appear that the vibration amplitudes increases as the excitation voltage increases, the only exception is that the vibration amplitude when the excitation voltage is at a 110% is slightly smaller than the vibration amplitude when the excitation voltage is at a 100%.

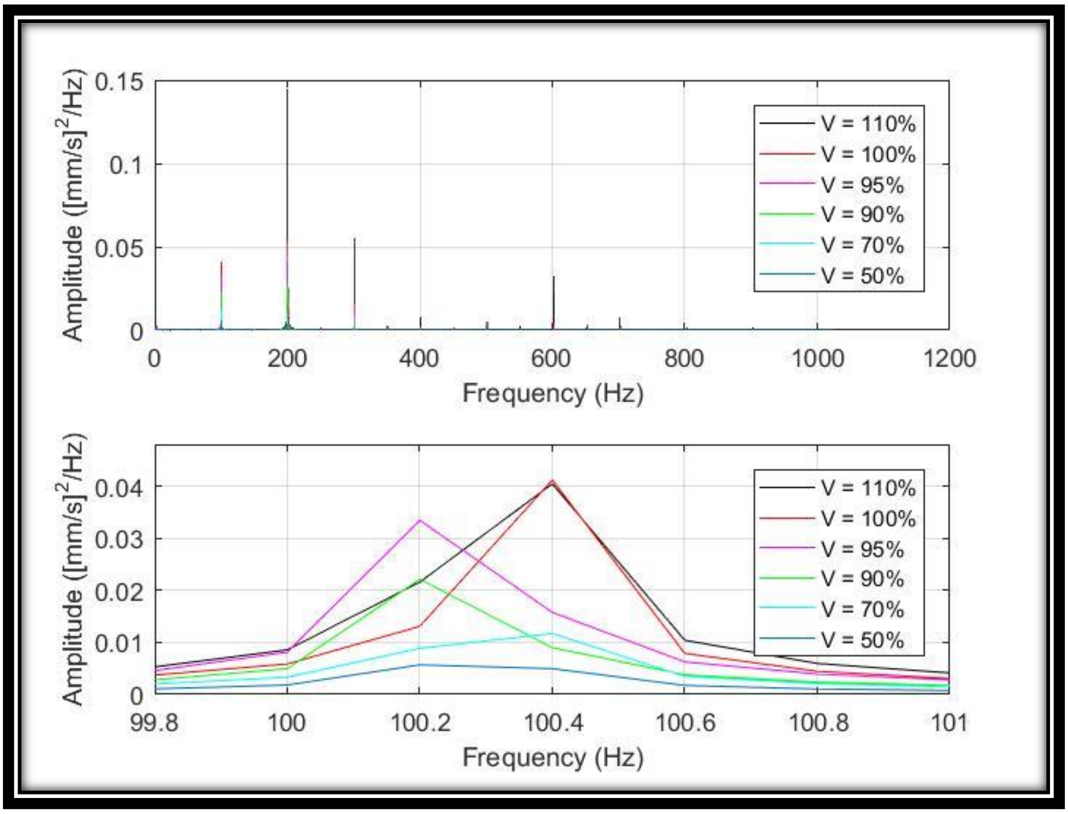

Figure 4-17: Plus 1 open circuit test Z vibration frequency spectrum

Figure 4-18 shows the open circuit test Z vibration amplitude versus the normalised square of the excitation voltage. As can be seen from Figure 4-18, even though the vibration amplitude when the excitation voltage is at a 110% is slightly smaller than the vibration amplitude when the excitation voltage is at a 100%, the vibration amplitudes still appears to be linearly related to the normalised square of the excitation voltage.

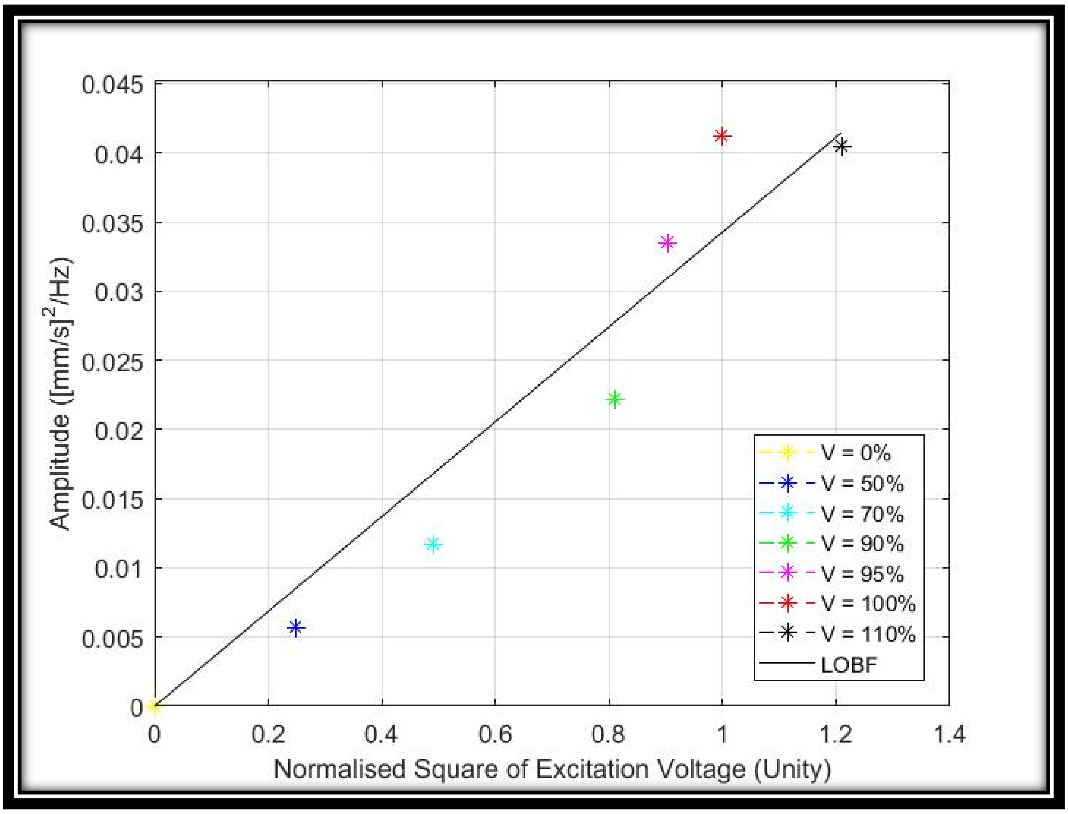

Figure 4-18: Plus 1 open circuit test Z vibration amplitude vs normalised square of the excitation voltage

The characteristics of the X and Y core vibrations for this specific transformer is very similar to the characteristics of its Z vibrations, to be more specific, the frequencies of note are exactly the same, the only difference between the vibrations in the three different directions is in the magnitude of the signals. From all of the results of the open circuit test as discussed above it is clear that the core vibrations of this transformer conforms to the theory of the core vibrations as summarized in section 2.4.

Although the results of the open circuit tests for the remaining transformers with plus tap changers are not shown, it was concluded from their results that except for the magnitude of the vibrations and obviously the approximated natural frequencies of the core, all the other characteristics of the core vibrations in the X, Y and Z directions were exactly the same as for the first transformer with a plus minus tap changer.

Short circuit test

Figure 4-19 below shows the short circuit test radial vibrations velocity versus time for the first transformer with a plus tap changer. As can be seen from Figure 4-19 the vibration velocity of tap 1 is greater than the vibration velocity of tap 9 which is greater than the vibration velocity of tap 17.

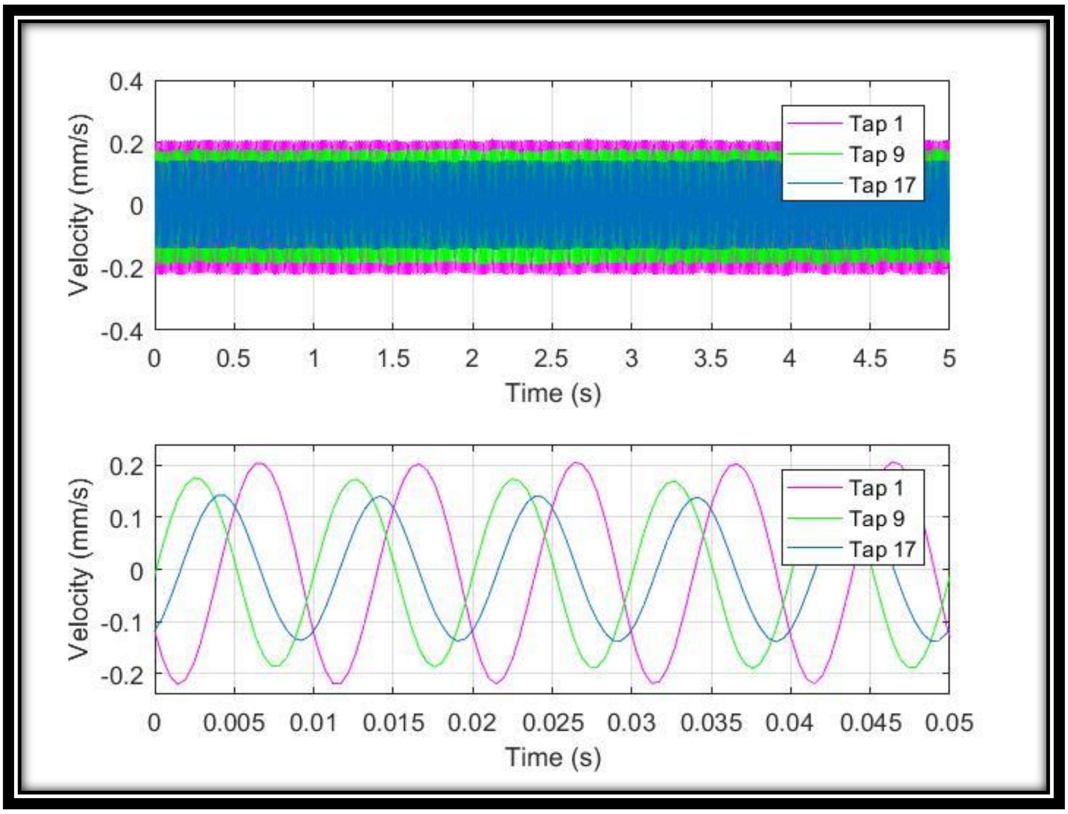

Figure 4-19: Plus 1 short circuit test radial (Z) vibration velocity vs time

Figure 4-20 shows the frequency spectrum of the short circuit test radial vibrations. As can be seen from Figure 4-20, the main frequency component of the radial winding vibrations is 100 Hz, that it does have integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component of the radial vibrations, the vibration amplitude of tap 1 is greater than the vibration amplitude of tap 9 which is greater than the vibration amplitude of tap 17. This conforms to the theory for the radial winding vibrations of transformers with plus tap changers with higher current carrying capacities as summarized in section 2.4.2.

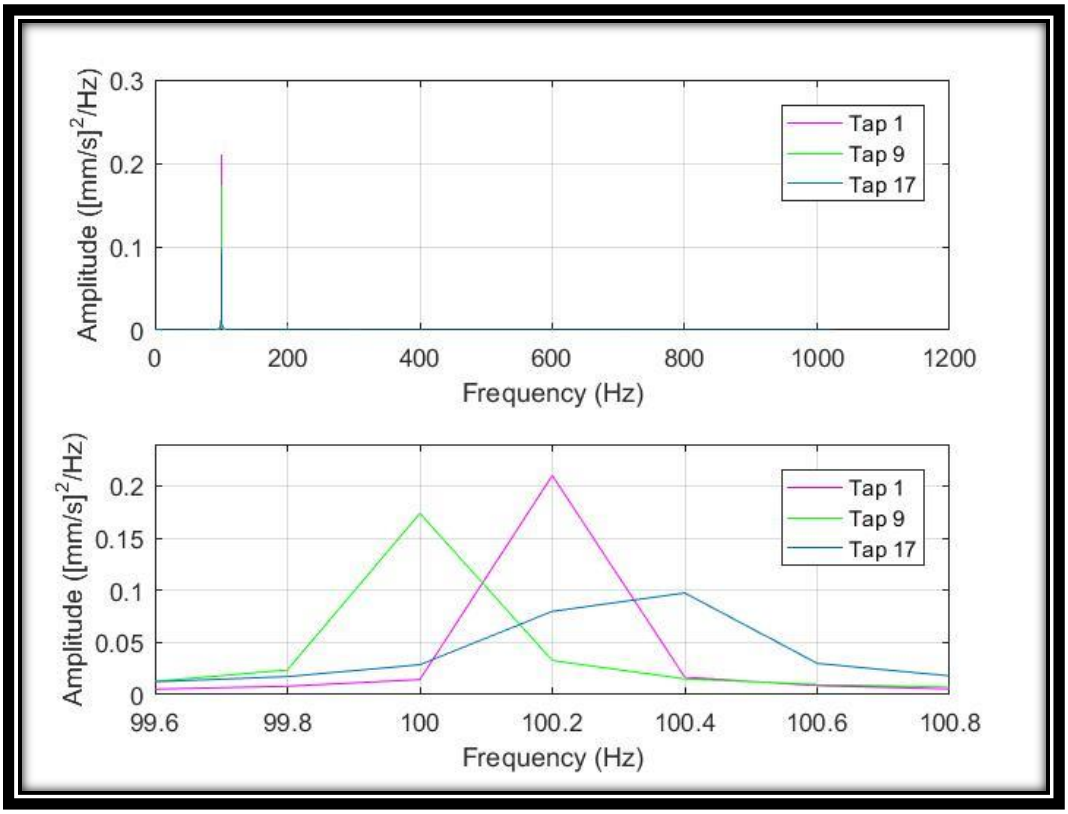

Figure 4-20: Plus 1 short circuit test radial (Z) vibration frequency spectrum

Figure 4-21 shows the short circuit test axial vibrations velocity versus time for the first transformer with a plus tap changer. As can be seen from Figure 4-21 the vibration velocity of tap 1 is greater than the vibration velocity of tap 9 which is greater than the vibration velocity of tap 17.

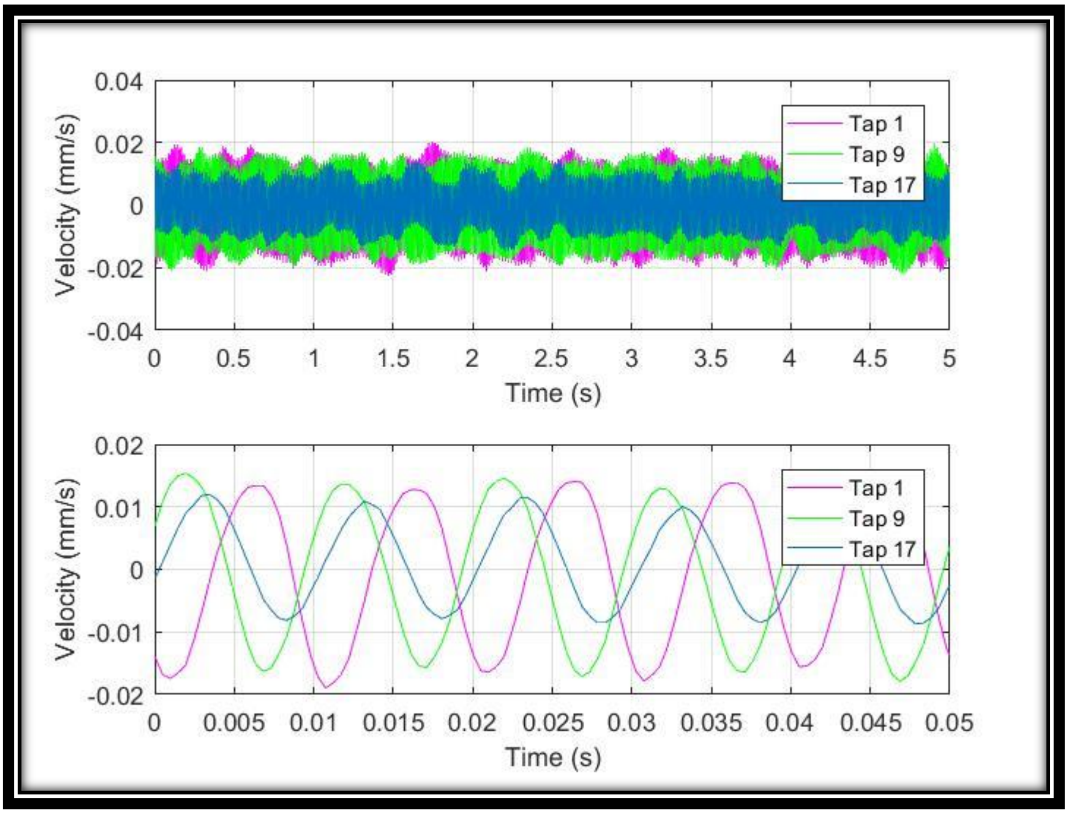

Figure 4-21: Plus 1 short circuit test axial (Y) vibration velocity vs time

Figure 4-22 shows the frequency spectrum of the short circuit test axial vibrations. As can be seen from Figure 4-22, the main frequency component of the axial winding vibrations is also 100 Hz, that it too has integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component of the axial vibrations, the vibration amplitude of tap 1 is greater than the vibration amplitude of tap 9 which is greater than the vibration amplitude of tap 17. This means that this specific transformer conforms to the theory for the axial winding vibrations of transformers with plus tap changers with higher current carrying capacities as summarized in section 2.4.2.

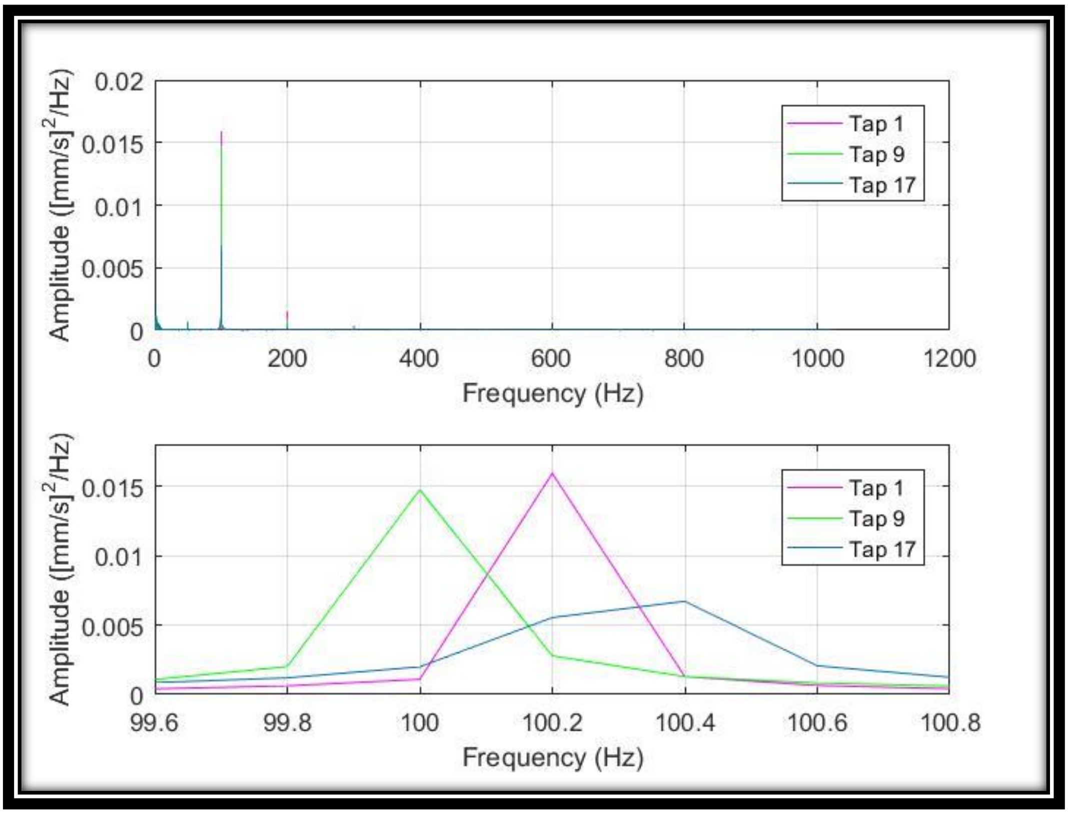

Figure 4-22: Plus 1 short circuit test axial (Y) vibration frequency spectrum

4.2.2. Plus 2

The second transformer with a plus tap changer is a distribution transformer with the following specifications:

- 60 MVA, 132/33 kV.
- Plus tap changer (132 + 8(-8) × 1.25%).
- YNd.
- HV – disk type strip / LV – disk strip / regulator – loop layer strip

Furthermore, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:
  - Tap position: 1.
  - Number of taps included: 17.
  - Voltage handling capability: 145.2 kV.
  - Current handling capability: 238.57 A.
- Nominal voltage tap:
  - Tap position: 9.
  - Number of taps included: 9.
  - Voltage handling capability: 132 kV.
  - Current handling capability: 262.43 A.
- Lowest voltage tap:
  - Tap position: 17.
  - Number of taps included: 1.
  - Voltage handling capability: 118.8 kV.
  - Current handling capability: 291.59 A.
- LV winding specifications:
  - Voltage handling capability: 33 kV.
  - Current handling capability: 1049.73 A.

The vibrations for both the open and short circuit tests were recorded in the X, Y and Z directions for this transformer but only the results of the short circuit test are presented.

Short circuit test

Figure 4-23 below shows the short circuit test radial vibrations velocity versus time for the second transformer with a plus tap changer. As can be seen from Figure 4-23, the vibration velocity of tap 1 is greater than the vibration velocity of tap 17 which is greater than the vibration velocity of tap 9.

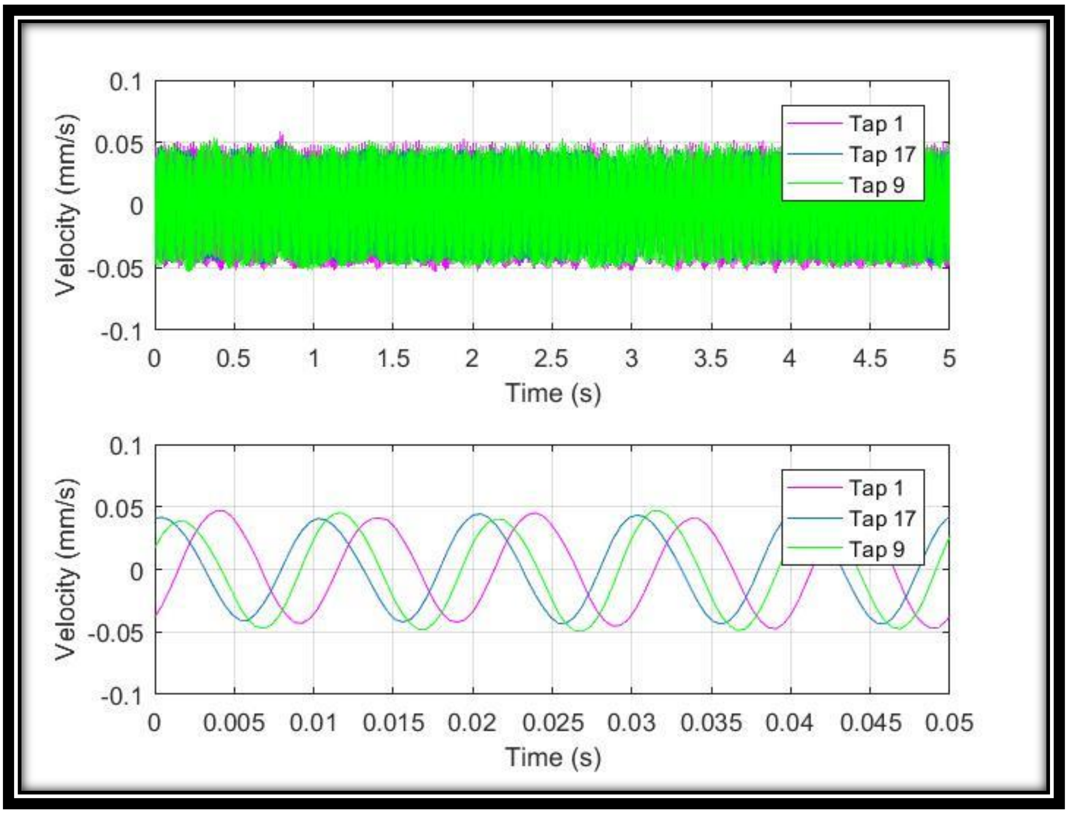

Figure 4-23: Plus 2 short circuit test radial (Z) vibration velocity vs time

Figure 4-24 shows the frequency spectrum of the short circuit test radial vibrations. As can be seen from Figure 4-24, the main frequency component of the radial winding vibrations is 100 Hz, that it does have integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component of the radial vibrations, the vibration amplitude of tap 1 is slightly greater than the vibration amplitude of tap 17 which is greater than the vibration amplitude of tap 9.

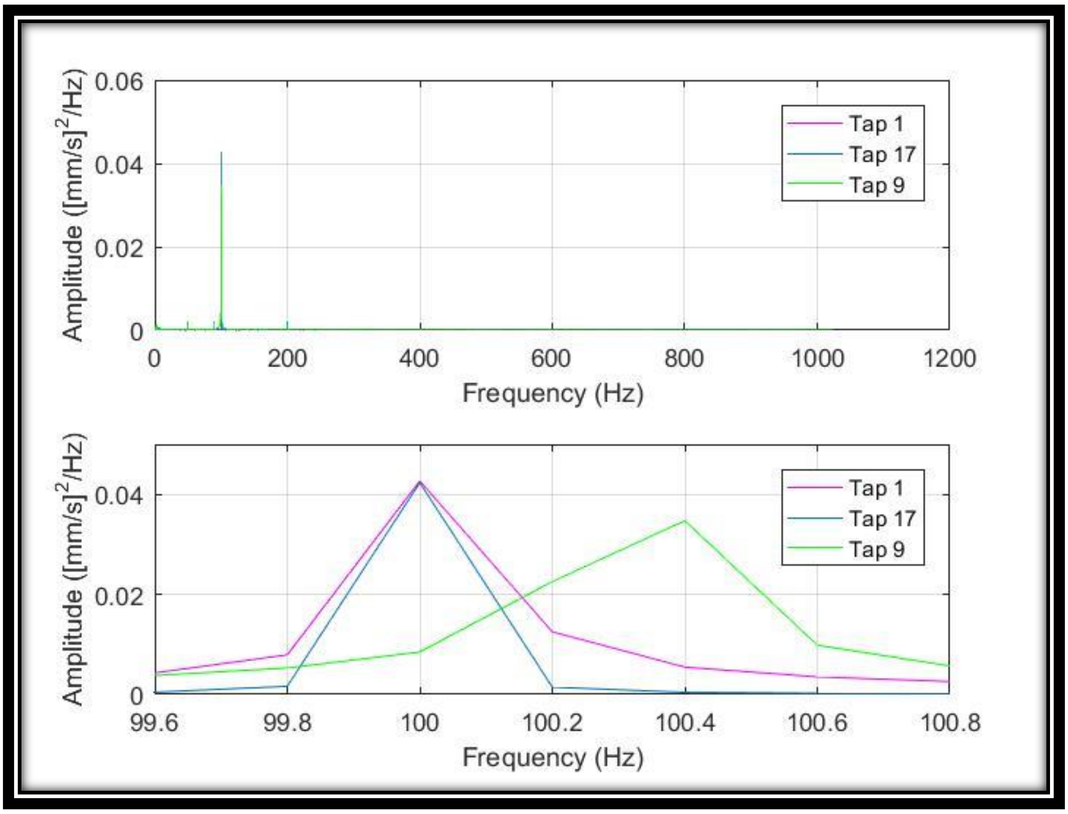

Figure 4-24: Plus 2 short circuit test radial (Z) vibration frequency spectrum

Although the second transformer with a plus tap changer does have a lower overall current carrying capacity than the first transformer with a plus tap changer, at the main frequency component of the radial winding vibrations, the vibration amplitude of tap 1 is still slightly greater than that of tap 17. This means that the overall current carrying capacity of this transformer is just big enough so that it falls within the range of transformers with higher current carrying capacities in terms of the radial winding vibrations. With this being the case, this specific transformer also conforms to the theory for the radial winding vibrations of transformers with plus tap changers with higher current carrying capacities as summarized in section 2.4.2.

Figure 4-25 shows the short circuit test axial vibrations velocity versus time for the second transformer with a plus tap changer. As can be seen from Figure 4-25, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 9.

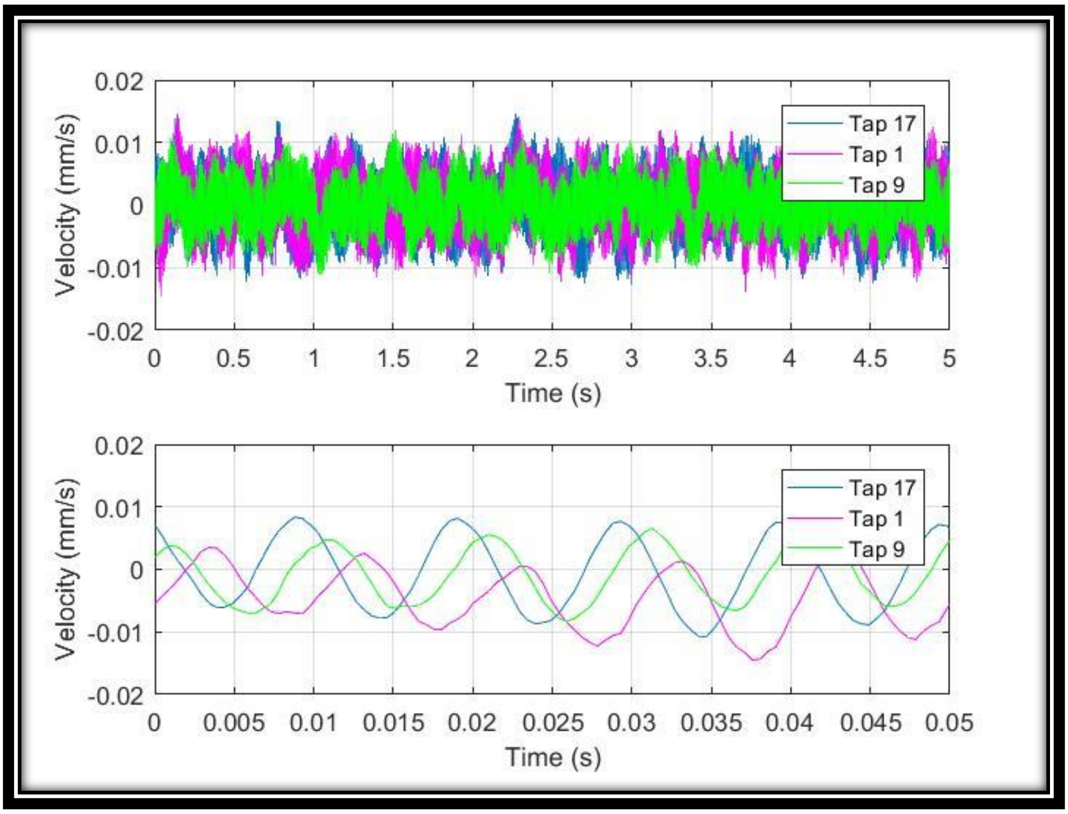

Figure 4-25: Plus 2 short circuit test axial (Y) vibration velocity vs time

Figure 4-26 shows the frequency spectrum of the short circuit test axial vibrations. As can be seen from Figure 4-26, the main frequency component of the axial winding vibrations is also 100 Hz, that it too has integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component of the axial vibrations, the vibration amplitude of tap 17 is greater than the vibration amplitude of tap 1 which is greater than the vibration amplitude of tap 9.

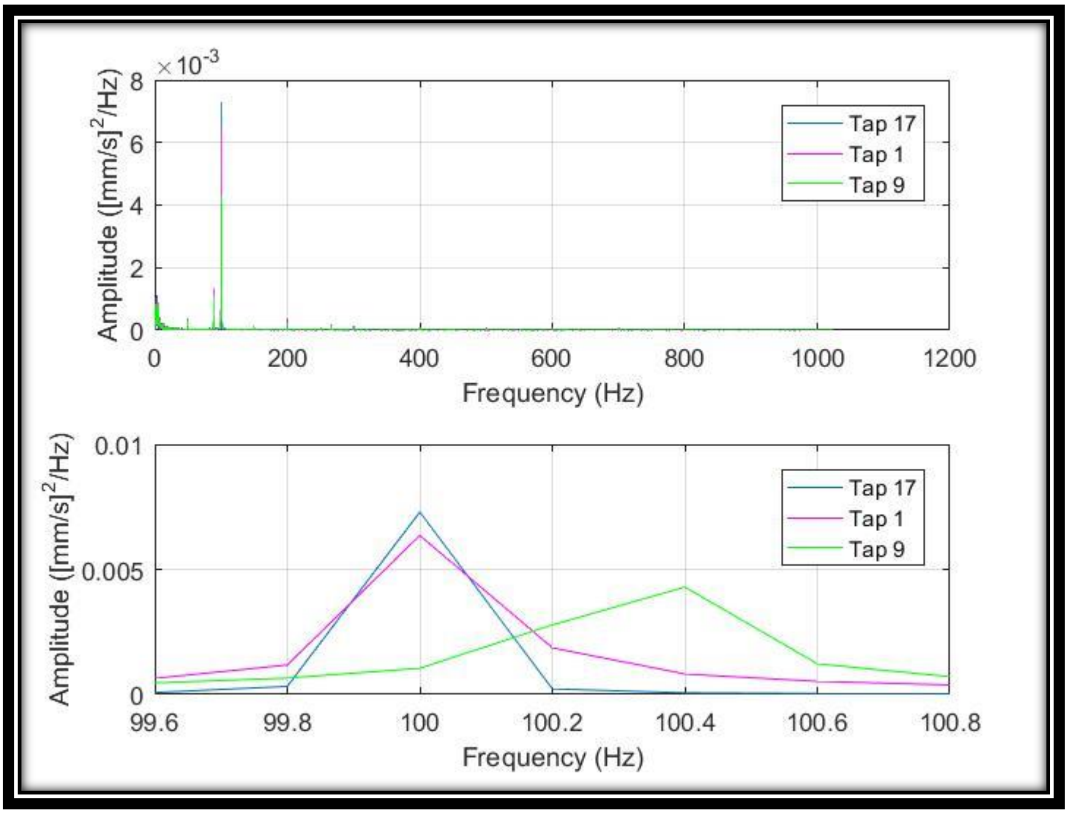

Figure 4-26: Plus 2 short circuit test axial (Y) vibration frequency spectrum

The axial vibrations at the main frequency component of this specific transformer conforms to the axial winding vibration theory for transformers with plus tap changers with lower current carrying capacities as summarized in section 2.4.2. This means that the overall current carrying capacity of the second transformer with a plus tap changer is low enough so that it falls within the range of transformers with lower current carrying capacity transformers in terms of the axial winding vibrations.

4.2.3. Plus 3

The third transformer with a plus tap changer is a distribution transformer with the following specifications:

- 40 MVA, 132/33 kV.
- Plus tap changer (132 + 4(-12) × 1.25%).
- YNd.
- HV – disk type twin paper / LV – disk strip / regulator – loop layer strip

Furthermore, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:

- Tap position: 1.
- Number of taps included: 17.
- Voltage handling capability: 138.6 kV.
- Current handling capability: 166.62 A.

- Nominal voltage tap:
  - Tap position: 5.
  - Number of taps included: 13.
  - Voltage handling capability: 132 kV.
  - Current handling capability: 174.95 A.
- Lowest voltage tap:
  - Tap position: 17.
  - Number of taps included: 1.
  - Voltage handling capability: 112.2 kV.
  - Current handling capability: 205.83 A.
- LV winding specifications:
  - Voltage handling capability: 33 kV.
  - Current handling capability: 699.82 A.

The vibrations for both the open and short circuit tests were recorded in the X, Y and Z directions for this transformer but only the results of the short circuit test are presented. The third transformer with a plus tap changer has an even lower overall current carrying capacity than the second transformer with plus tap changer, thus it is expected that the third transformer falls into the category of transformers with plus tap changers with lower overall current carrying capacities in terms of both the radial and axial winding vibrations.

Short circuit test

Figure 4-27 below shows the short circuit test radial vibrations velocity versus time for the third transformer with a plus tap changer. As can be seen from Figure 4-27, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 5.

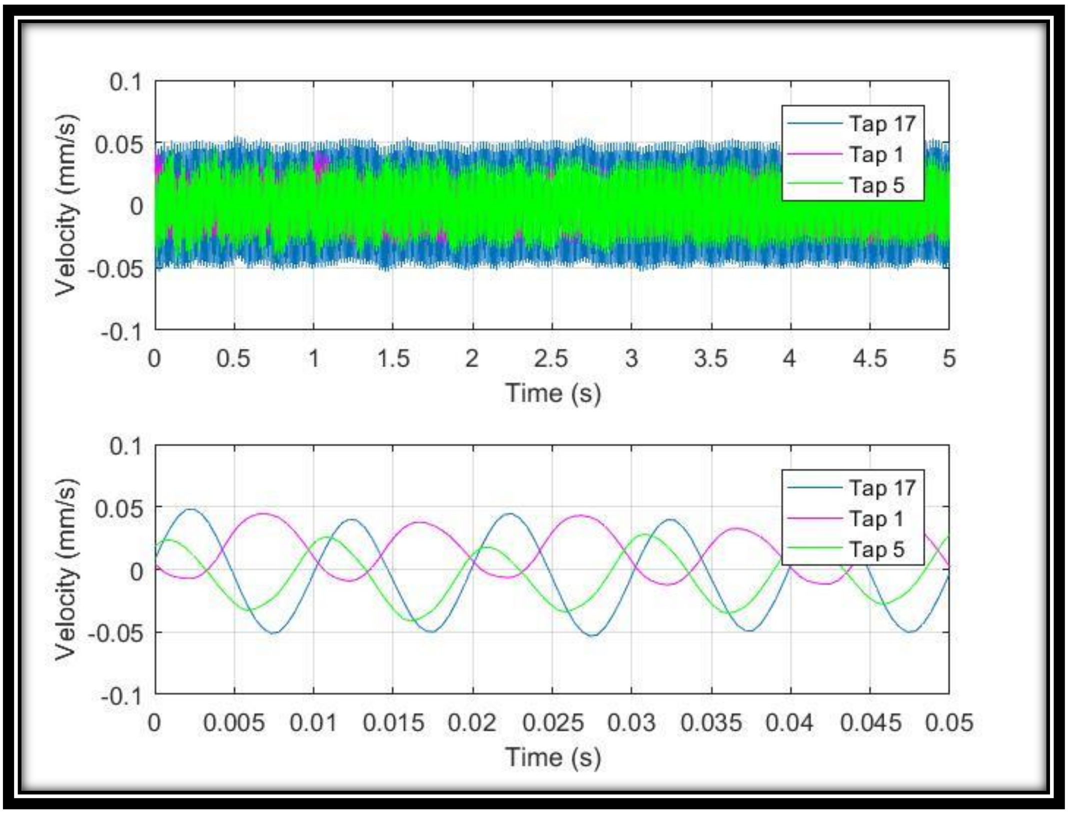

Figure 4-27: Plus 3 short circuit test radial (Z) vibration velocity vs time

Figure 4-28 shows the frequency spectrum of the short circuit test radial vibrations. As can be seen from Figure 4-28, the main frequency component of the radial winding vibrations is 100 Hz, that it does have integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component, the vibration amplitude of tap 17 is much greater than the vibration amplitude of tap 1 which is slightly greater than the vibration amplitude of tap 5.

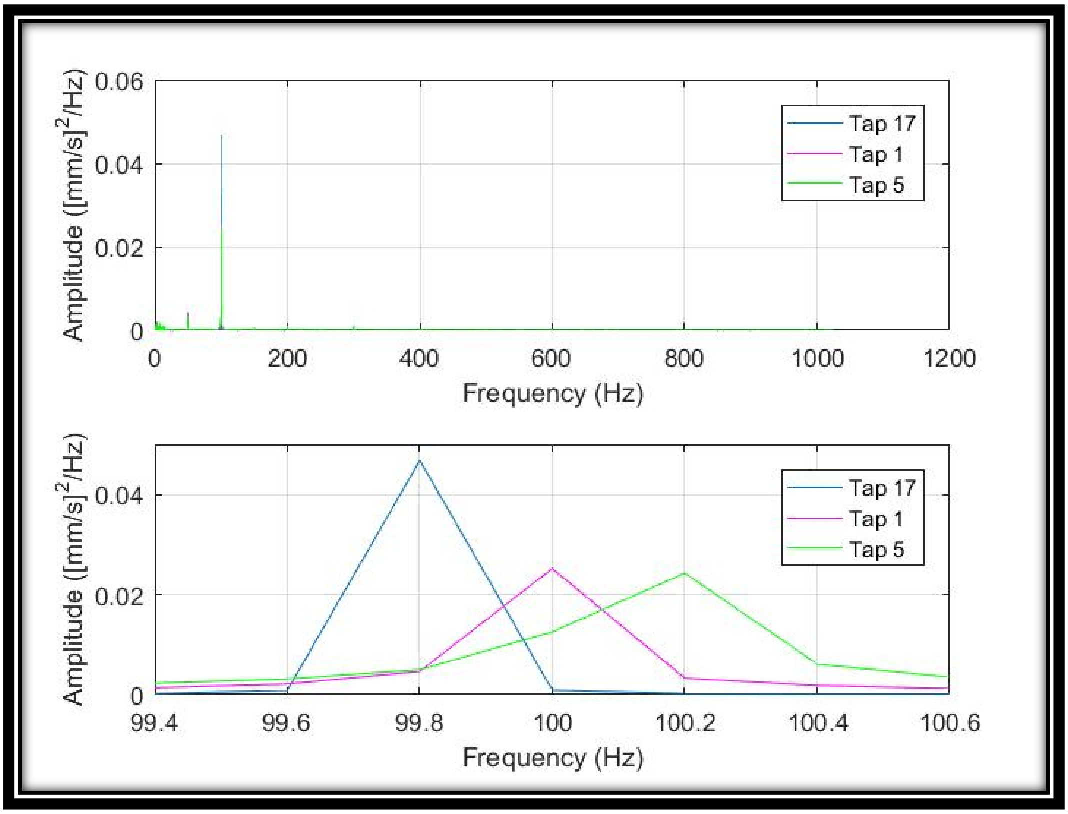

Figure 4-28: Plus 3 short circuit test radial (Z) vibration frequency spectrum

Figure 4-29 shows the short circuit test axial vibrations velocity versus time for the third transformer with a plus tap changer. As can be seen from Figure 4-29, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 5.

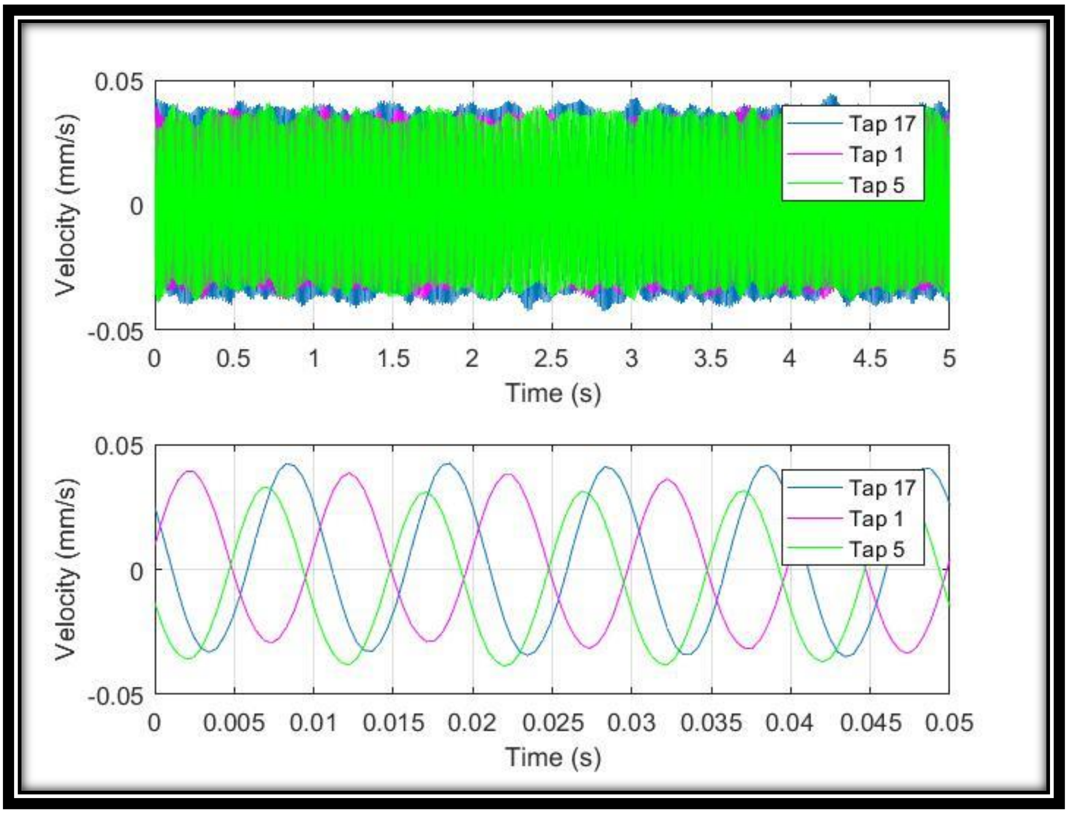

Figure 4-29: Plus 3 short circuit test axial (Y) vibration velocity vs time

Figure 4-30 shows the frequency spectrum of the short circuit test axial vibrations. As can be seen from Figure 4-30, the main frequency component of the axial winding vibrations is also 100 Hz, that it too has integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component, the vibration amplitude of tap 17 is greater than the vibration amplitude of tap 1 which is greater than the vibration amplitude of tap 5.

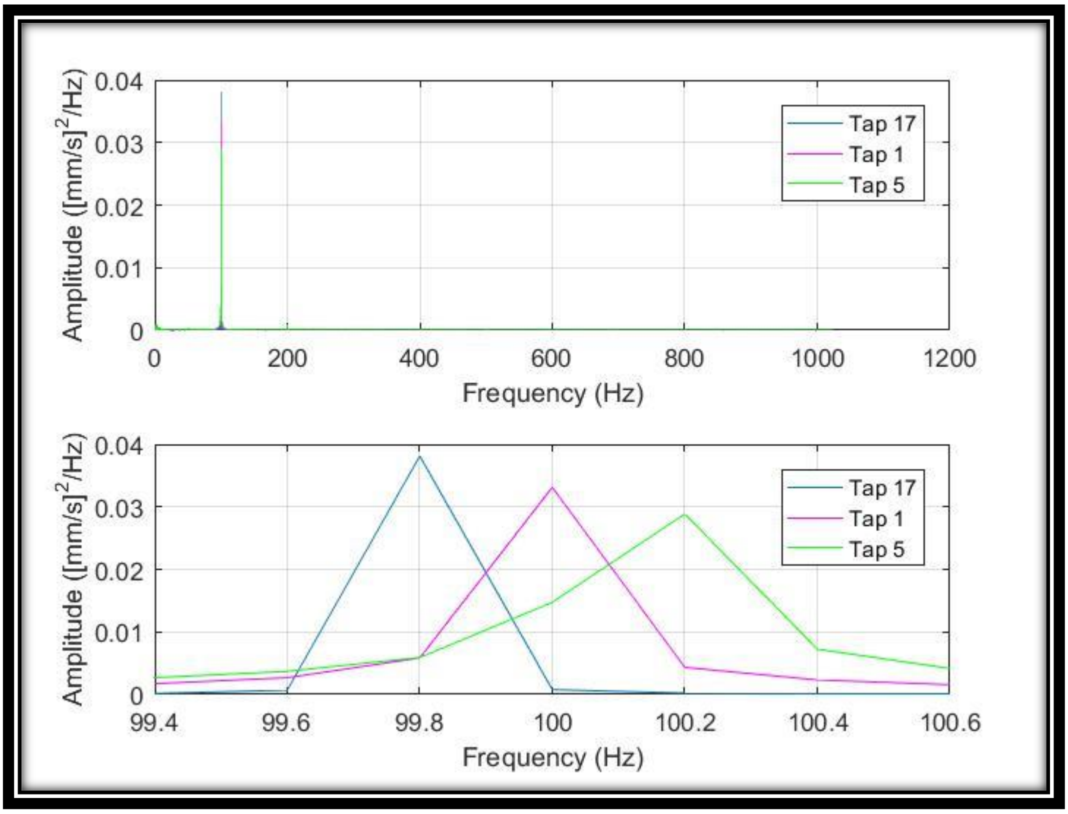

Figure 4-30: Plus 3 short circuit test axial (Y) vibration frequency spectrum

From all of the results of the short circuit test as discussed above it is clear that the radial and axial winding vibrations of the third transformer with a plus tap changer conforms to the theories of the radial and axial winding vibrations for transformers with plus tap changers with lower current carrying capacities as summarized in section 2.4.2.

4.2.4. Plus 4

The fourth transformer with a plus tap changer is also a distribution transformer with the following specifications:

- 5 MVA, 22/11 kV.
- Plus tap changer (22 + 4(-12) × 1.25%).
- Dyn.
- HV – layer(8) strip / LV – layer(4) strip / regulator – loop layer strip

Furthermore, the specifications for the highest, nominal and lowest voltage taps as well as the LV winding specifications are as follows:

- Highest voltage tap:
  - Tap position: 1.
  - Number of taps included: 17.
  - Voltage handling capability: 23.1 kV.
  - Current handling capability: 124.97 A.
- Nominal voltage tap:
  - Tap position: 5.
  - Number of taps included: 13.
  - Voltage handling capability: 22 kV.
  - Current handling capability: 131.22 A.
- Lowest voltage tap:
  - Tap position: 17.
  - Number of taps included: 1.
  - Voltage handling capability: 18.7 kV.
  - Current handling capability: 154.37 A.
- LV winding specifications:
  - Voltage handling capability: 11 kV.
  - Current handling capability: 262.43 A.

The vibrations for both the open and short circuit tests were recorded in the X, Y and Z directions for this transformer but only the results of the short circuit test are presented.

Short circuit test

Figure 4-31 below shows the short circuit test radial vibrations velocity versus time for the fourth transformer with a plus tap changer. As can be seen from Figure 4-31, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 5.

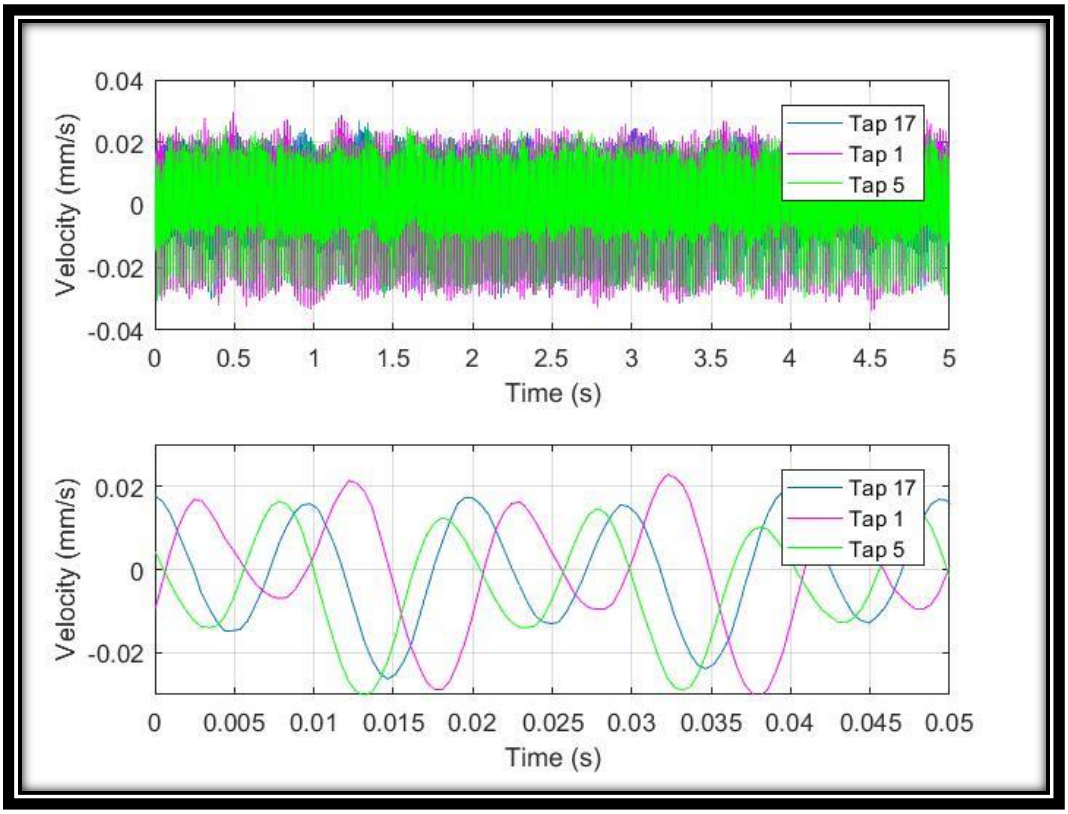

Figure 4-31: Plus 4 short circuit test radial (Z) vibration velocity vs time

Figure 4-32 shows the frequency spectrum of the short circuit test radial vibrations. As can be seen from Figure 4-32, the main frequency component of the radial winding vibrations is 100 Hz, that it does have integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component, the vibration amplitude of tap 17 is slightly greater than the vibration amplitude of tap 1 which is greater than the vibration amplitude of tap 5. This means that the fourth transformer with a plus tap changer conforms to the theory for the radial winding vibrations of transformers with plus tap changers with lower current carrying capacities as summarized in section 2.4.2.

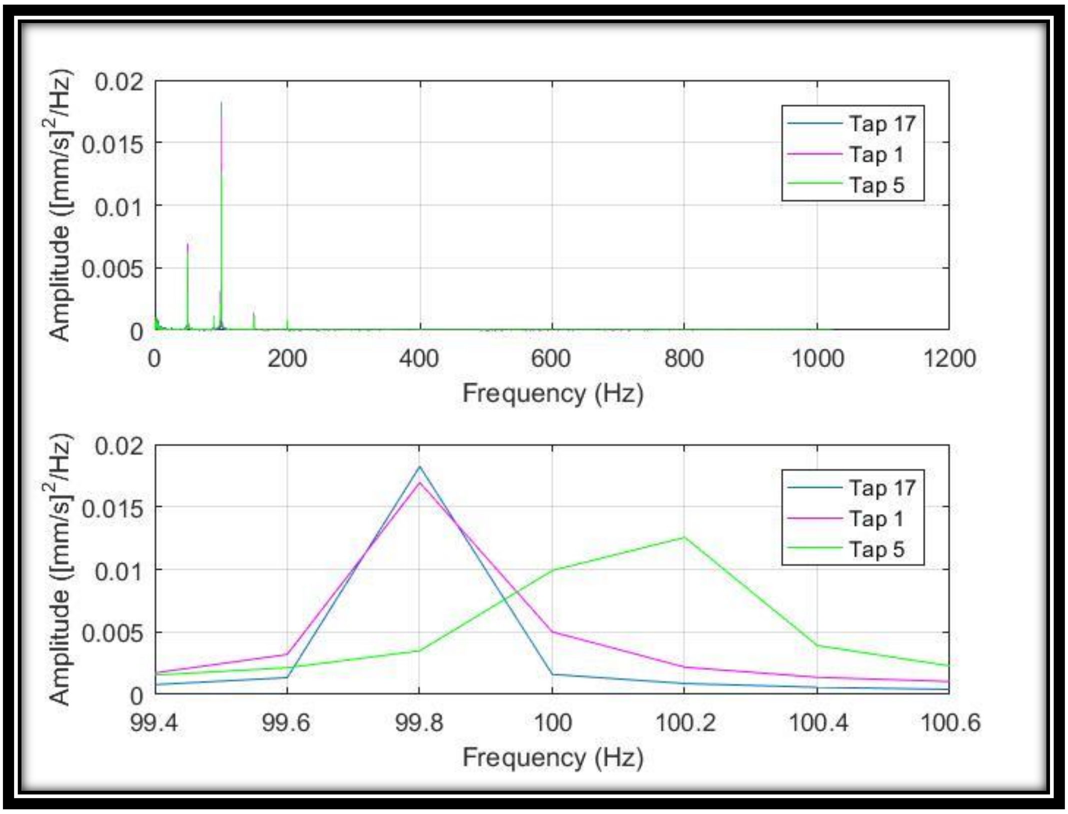

Figure 4-32: Plus 4 short circuit test radial (Z) vibration frequency spectrum

Figure 4-33 shows the short circuit test axial vibrations velocity versus time for the fourth transformer with a plus tap changer. As can be seen from Figure 4-33, the vibration velocity of tap 17 is greater than the vibration velocity of tap 1 which is greater than the vibration velocity of tap 5.

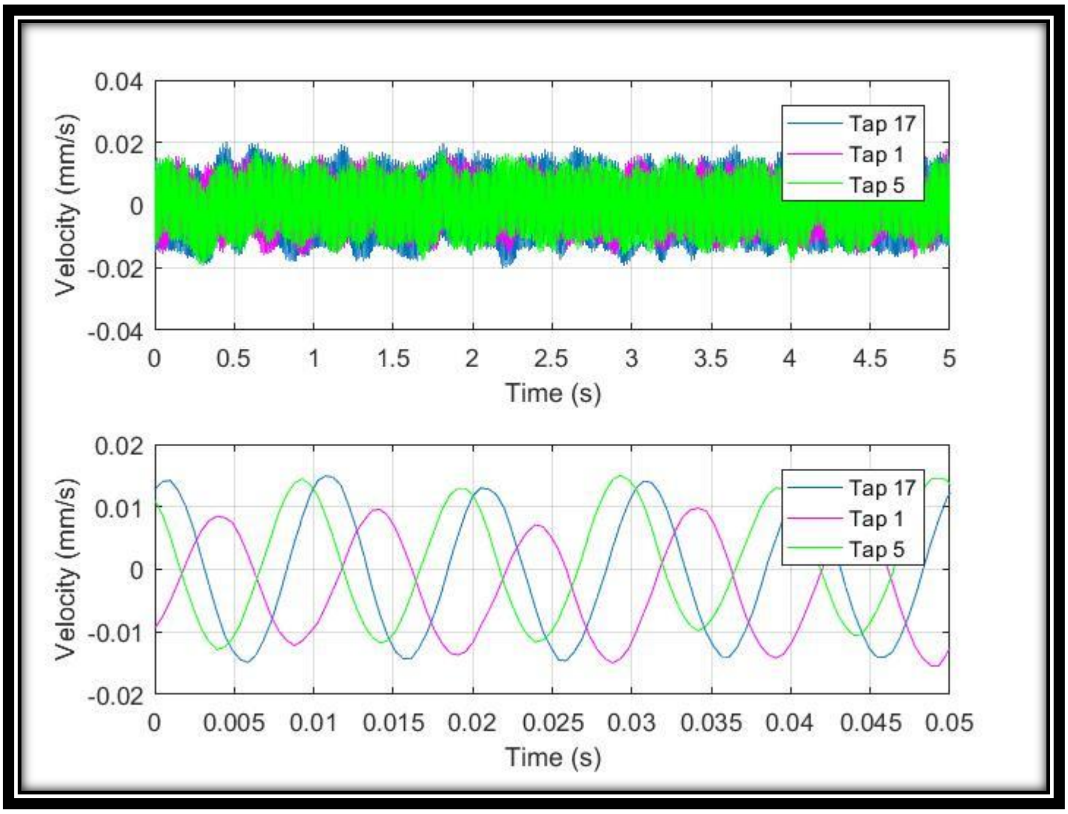

Figure 4-33: Plus 4 short circuit test axial (Y) vibration velocity vs time

Figure 4-34 shows the frequency spectrum of the short circuit test axial vibrations. As can be seen from Figure 4-34, the main frequency component of the axial winding vibrations is also 100 Hz, that it too has integral multiple harmonics but their amplitudes are insignificant compared to the main frequency component, and that at the main frequency component, the vibration amplitude of tap 17 is greater than the vibration amplitude of tap 1 which is greater than the vibration amplitude of tap 5. This means that the fourth transformer with a plus tap changer conforms to the theory for the axial winding vibrations of transformers with plus tap changers with lower current carrying capacities as summarized in section 2.4.2.

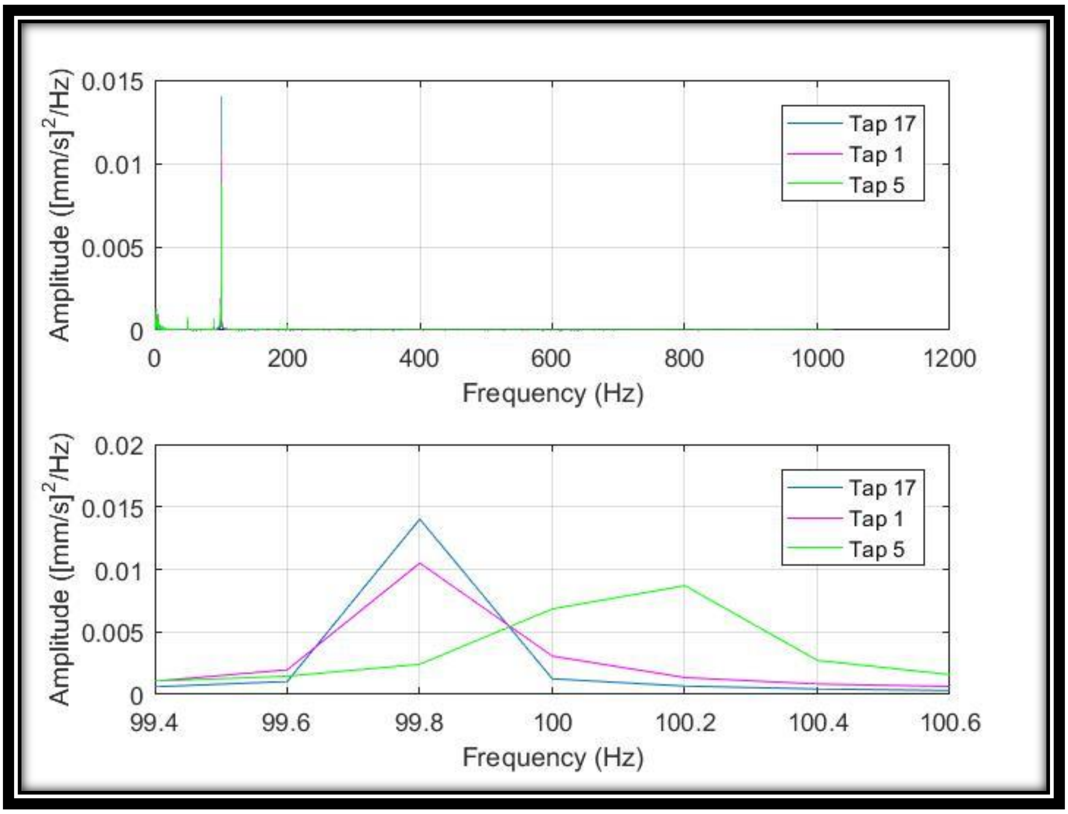

Figure 4-34: Plus 4 short circuit test axial (Y) vibration frequency spectrum

For the radial and axial vibrations of transformers with plus minus tap changers there is a point where the overall current carrying capacity is so low that the vibration amplitude of the nominal tap surpasses the vibration amplitude of the highest voltage tap, but that never happens to transformers with plus tap changers.

5. Discussion of results

The discussion is ordered as follows:

- Core vibrations of transformers with and without regulator windings.
- Linearity of the radial and axial vibrations of each tap to the normalized square of the load current of that tap for both transformers with plus minus and plus tap changers.
- Radial and axial winding vibrations of transformers with plus minus tap changers.
- Radial and axial winding vibrations of transformers with plus tap changers.

The theory for the core vibrations of transformers with and without regulator windings as summarized in section 2.4 states that:

The core vibrations (X, Y and Z components) of all transformers should be positively, linearly related to the normalized square of the excitation voltage.

The results of the transformer core vibrations as shown and discussed in the practical measurements and literature review completely proves this theory. Furthermore, the main frequency component of the core vibrations of transformers with and without regulator windings is 100 Hz, and both types also have integral multiple harmonics. This means that the core vibrations of transformers with and without regulator windings have the exact same characteristics and they are as summarized in Table 2-2 in the literature review and Table 6-1 in the conclusion.

The theory for the linearity of the radial and axial winding vibrations of each tap to the normalized square of the load current of that tap for transformers with plus minus and plus tap changers as summarized in section 2.4 states that:

For transformers with plus and plus minus tap changers the radial and axial winding vibrations of a specific tap should be positively, linearly related to the normalized square of the load current of that specific tap.

The results of the leakage reactance curve test completely proved this theory even though it was only performed on the third transformer with a plus minus tap changer. The reason why it was not necessary to do this test on a transformer with a plus tap changer as well, is because a transformer with a plus tap changer is basically the same as a transformer with a plus minus tap changer of which the HV and regulator windings are connected in an enhancing connection orientation. Transformers with plus tap changers will usually just have a few more turns connected in an enhancing connection orientation.

The two theories for the radial winding vibrations of transformers with plus minus tap changers as summarized in section 2.4 states that:

For higher current carrying capacity transformers with plus minus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected.

For lower current carrying capacity transformers with plus minus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected.

Figure 5-1 compares the results of the radial winding vibrations at the main frequency component of the three transformers with plus minus tap changers. From section 4.1 and the specifications of the transformers it is known that each consecutive transformer with a plus minus (and plus) tap changer has a lower overall current carrying capacity, thus by plotting the results as shown in Figure 5-1, the effect that the overall current carrying capacity have on the radial vibrations is indicated clearly.

Furthermore, in section 2.4 it was stated that, in terms of the radial winding vibrations of transformers with plus minus and plus tap changers, as the overall current carrying capacity of the transformers lowers, the weight of the number of regulator turns included and the connection orientation thereof decreases, and the weight of the tap specific currents flowing through the HV windings increases. In other words, as the overall current carrying capacity lowers, the contribution of the regulator windings to the radial winding vibrations reduces whereas the contribution of the HV windings (which carries the tap specific currents) to the radial winding vibrations increases. This phenomenon is also applicable to the axial winding vibrations of transformers with plus minus and plus tap changers, but in the case of the axial winding vibrations, the connection orientation of the HV and regulator windings has zero influence, no matter what the overall current carrying capacity of the transformer is.

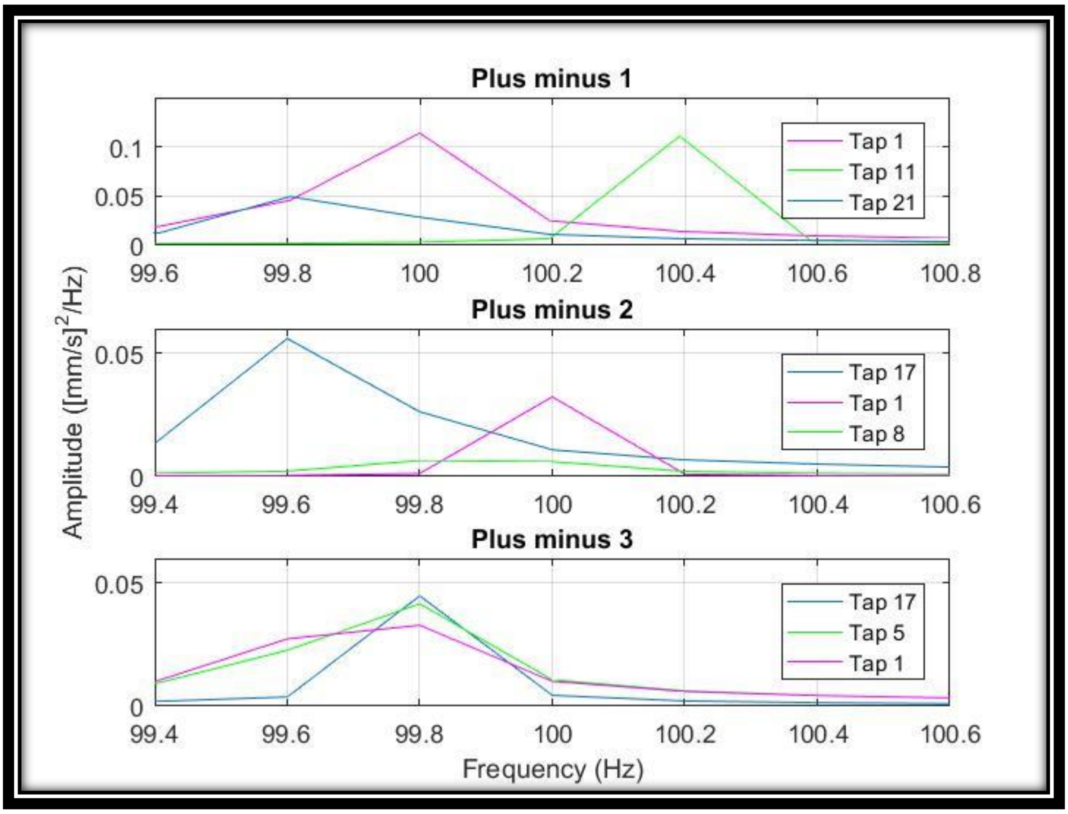

Figure 5-1: Transformers with plus minus tap changers short circuit test radial (Z) vibration comparison

By considering the radial winding vibrations at the main frequency component of the three transformers with plus minus tap changers as shown in Figure 5-1, the phenomenon as described previously is illustrated at the hands of practical measurements one last time. For the first transformer with a plus minus tap changer, the overall current carrying capacity is high enough so that the number of regulator turns included and the connection orientation thereof ensures that the radial winding vibrations, when the highest voltage tap, thus lowest current tap, is tested at its rated current, is greater than the radial winding vibrations when the lowest voltage tap, thus highest current tap, is tested at its rated current. From this it is clear that the results of the first transformer with a plus minus tap changer proves the theory for the radial winding vibrations of transformers with plus minus tap changers with higher current carrying capacities.

Furthermore, although the aforementioned theory does not include the radial winding vibrations of the nominal voltage and current tap, it too can be used to indicate the effects of the overall current carrying capacity. Once again, consider the first transformer with a plus minus tap changer. Its overall current carrying capacity is high enough so that the enhancing connection orientation and the number of regulator taps included when the highest voltage tap is tested at its rated current, ensures that its radial winding vibrations is greater than that of the nominal tap, which in turn is greater than that of the lowest voltage tap when it is tested at its rated current due to the opposing connection orientation and the number of regulator windings included.

From the radial winding vibration results of the second and third transformers with plus minus tap changers it is clear that both of them proves the theory for the radial winding vibrations of transformers with plus minus tap changers with lower current carrying capacities. Although this is the case, it is still possible to make a distinction between the second and third transformers with plus minus tap changers due to the fact that for the third transformer with a plus minus tap changer, the radial winding vibrations of the nominal tap surpassed that of the highest voltage tap. This means that the overall current carrying capacity of the third transformer is low enough so that its radial winding vibrations resembles the radial winding vibrations of a transformer without regulator windings (the higher the current flowing through the HV winding, the higher the radial winding vibrations will be).

By considering the axial winding vibrations of the second and third transformers with plus minus tap changers as shown in Figure 5-2, it is clear that both of them proves the theory for the axial winding vibrations of transformers with plus minus tap changers as summarized in section 2.4 which states:

For all transformers with plus minus tap changers, the amplitude of the axial winding vibrations when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the axial winding vibrations when the highest voltage, thus lowest current tap is selected, given that there are not much more enhancing taps than opposing tap.

Although the axial winding vibrations of the first transformer with a plus minus tap changer was not measured, it is believed that its axial winding vibrations will also prove the theory as stated above. Furthermore, in order to make a distinction between transformers with different current carrying capacities, whether they are considered as transformers with higher or lower overall current capacities, the axial winding vibrations of the nominal tap in relation to that of the highest and lowest voltage taps should once again be considered. In other words, from the axial winding vibrations of the second and third transformers with a plus minus tap changers it should be clear that the third transformer with a plus minus tap changer has a lower overall current carrying capacity than the second due to the fact that the nominal tap axial winding vibrations of the third transformer with a plus minus tap changer has surpassed that of the highest voltage tap.

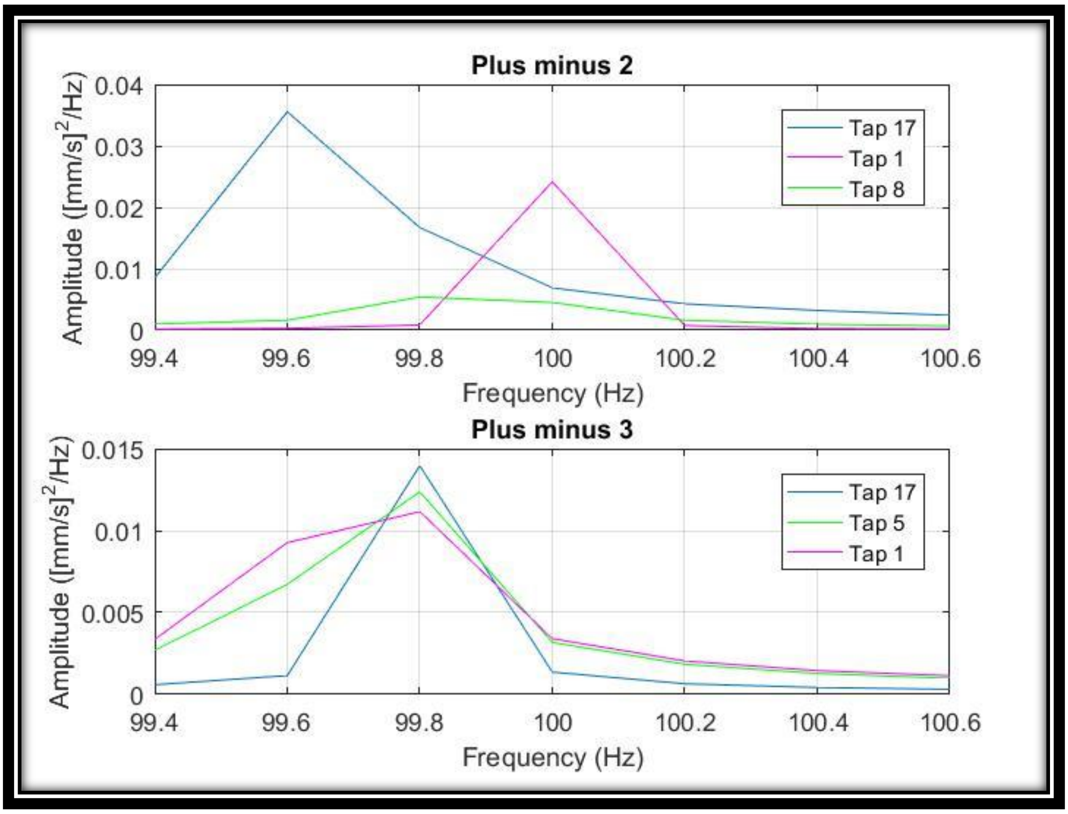

Figure 5-2: Transformers with plus minus tap changers short circuit test axial (Y) vibration comparison

Before moving on to transformers with plus tap changers, consider Table 5-1 which summarizes the apparent power ratings, tapping ranges and the winding and conductor types for the HV and LV windings of the transformers with plus minus tap changers. The winding and conductor types for the regulator windings are not included in this table seeing that all regulator windings make use of loop layer windings and strip conductors as previously stated.

Table 5-1: Transformers with plus minus tap changers specifications

Trfr	APR (MVA)	Tapping range	Windings			
			HV		LV	
			Winding type	Conductor type	Winding type	Conductor type
1	180	161 + 10(-10) × 1%	Disk	Twin paper	Helical	CTCE
2	45	88 + 7(-9) × 1.5%	Disk	Twin paper	Helical	Strip
3	20	33 + 4(-12) × 1.25%	Disk	Strip	Disk	CTCE

From the two theories for the radial winding vibration amplitudes for transformers with plus minus tap changers, it is clear that the current carrying capacity is the main factor which determines whether the radial winding vibrations when the highest voltage tap, thus lowest current tap is selected is greater than the radial winding vibrations when the lowest voltage, thus highest current tap is selected and vice versa. Furthermore, in section 2.4 it was also stated that the LV and HV winding and conductor types for transformers with plus minus tap changers do not have an influence on the radial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap.

By once again considering the radial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap for the first two transformers with plus minus tap changers, it is clear that the radial winding vibration amplitudes for the highest and lowest voltage taps just switched positions. Now, by considering the apparent power ratings, which as stated previously, for the transformers that are included in this study, the lower the apparent power rating the lower the overall current carrying capacity of the transformer, and the winding and conductor types of the first two transformers with plus minus tap changers, the cause of the radial winding vibrations amplitudes for the highest and lowest voltage taps switching positions must be the drop in the current carrying capacity seeing that the LV and HV winding and conductor types for the first and second transformers with plus minus tap changers is almost exactly the same. This proves that the LV and HV winding and conductor types do not influence the radial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap.

From Table 5-1 it can also be seen that the number of regulator taps included when the first transformer delivers its maximum or reduced voltage is slightly more than the number of regulator taps included when the second transformer delivers its maximum or reduced voltage. Although this is the case, the number of regulator taps included should not influence on the radial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap seeing that the tapping range for the second transformer, although it has less taps to include, is larger than that of the first transformer seeing that each tap step for the second transformer is 1.5% whereas it is 1% for the first transformer.

The two theories for the radial winding vibrations of transformers with plus tap changers as summarized in section 2.4 states that:

For higher current carrying capacity transformers with plus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected.

For lower current carrying capacity transformers with plus tap changers, the amplitude of the radial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the radial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected.

As can be seen from Figure 5-3 and Figure 5-4, the results of the fourth transformer with a plus tap changer is not included in the comparison of the winding vibrations of the transformers with plus tap changers. The reasons for this are as follows. Firstly, the order of the highest, nominal and lowest voltage tap radial and axial winding vibrations for the third and fourth transformers with plus tap changers is exactly the same, there is just a difference in the amplitude of the signals. And secondly, by trying to compare too many results on a single figure, the legibility of the results lowers.

As can be seen from Figure 5-3, both the first and second transformers with plus tap changers prove the theory for the radial winding vibrations of transformers with plus tap changers with higher overall current carrying capacities. Futthermore, the third transformer with a plus tap changer proves the theory for the radial winding vibrations of transformers with plus tap changers with lower overall current carrying capacities. With this being said, it can be noted that the second transformer with a plus tap changer is very close to being labelled as a transformer with a plus tap changer with a lower overall current carrying capacity in terms of the radial winding vibrations due to the fact that the amplitude of tap 17's radial winding vibrations is only slightly lower than that of tap 1.

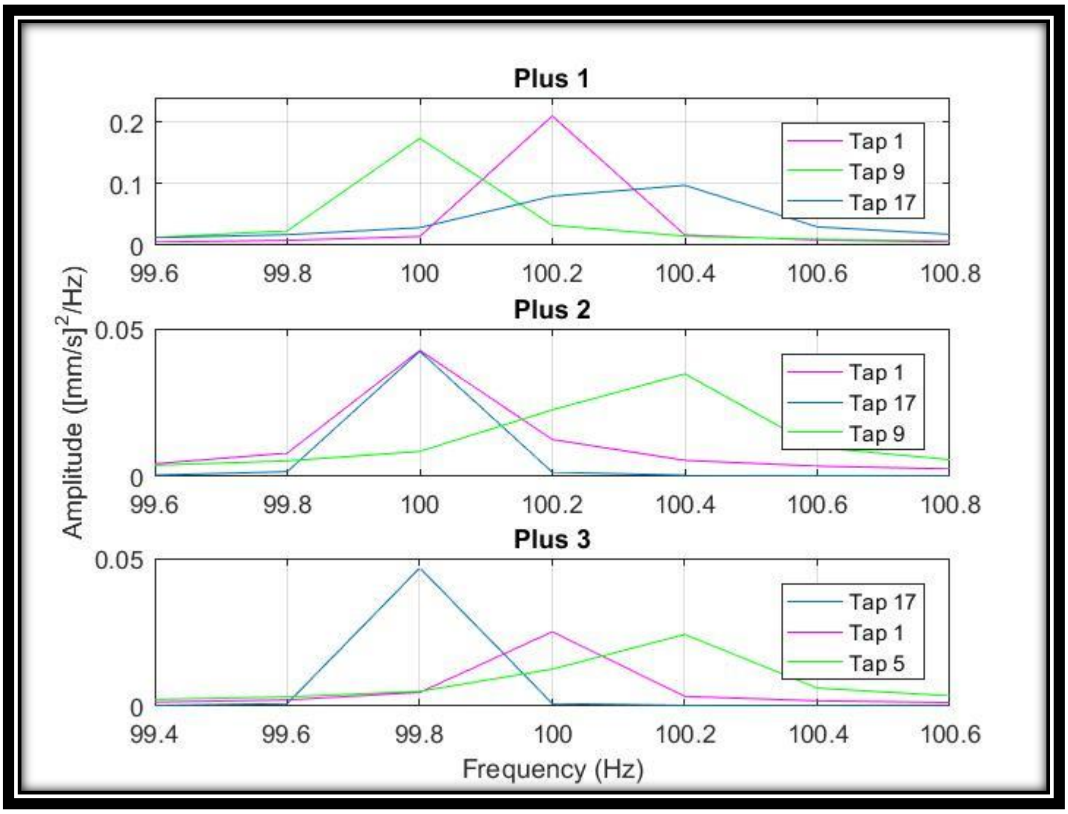

Figure 5-3: Transformers with plus tap changers short circuit test radial (Z) vibration comparison

The two theories for the axial winding vibrations of transformers with plus tap changers as summarized in section 2.4 states that:

For higher current carrying capacity transformers with plus tap changers, the amplitude of the axial winding vibration at the main frequency component when the highest voltage, thus lowest current tap is selected, should be greater than the amplitude of the axial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected.

For lower current carrying capacity transformers with plus tap changers, the amplitude of the axial winding vibrations at the main frequency component when the lowest voltage, thus highest current tap is selected, should be greater than the amplitude of the axial winding vibrations at the main frequency component when the highest voltage, thus lowest current tap is selected.

As can be seen from Figure 5-4, the first transformer with a plus tap changer proves the theory for the axial winding vibrations of transformers with plus tap changers with higher overall current carrying capacities and the second and third transformers with plus tap changers proves the theory for the axial winding vibrations of transformers with plus tap changers with lower overall current carrying capacities.

From the results of the radial and axial winding vibrations it can be noted that, in terms of the radial winding vibrations the second transformer with a plus tap changer conforms to the theory for transformers with higher overall current carrying capacities and in terms of the axial winding vibrations it conforms to the theory for transformers with lower overall current carrying capacities. What this means is that the second transformer with a plus tap changer cannot simply be labelled as a transformer with a higher or lower overall current carrying capacity like the other transformers that are included in this study. This does not mean that the theories that are summarized in section 2.4 is incorrect, it just shows that there are some border cases.

Furthermore, in the same way that the amplitude of the nominal tap in relation to the amplitudes of the highest and lowest voltage taps was used to make distinctions between the transformers with plus minus tap changers with different current carrying capacities in terms of the radial and axial winding vibrations, it can also be used to make distinctions between the transformers with plus tap changers with different current carrying capacities in terms of the radial and axial winding vibrations. The only difference is that for the transformers with plus tap changers with lower overall current carrying capacities, the radial and the axial winding vibrations of the nominal tap never surpasses that of the highest voltage tap.

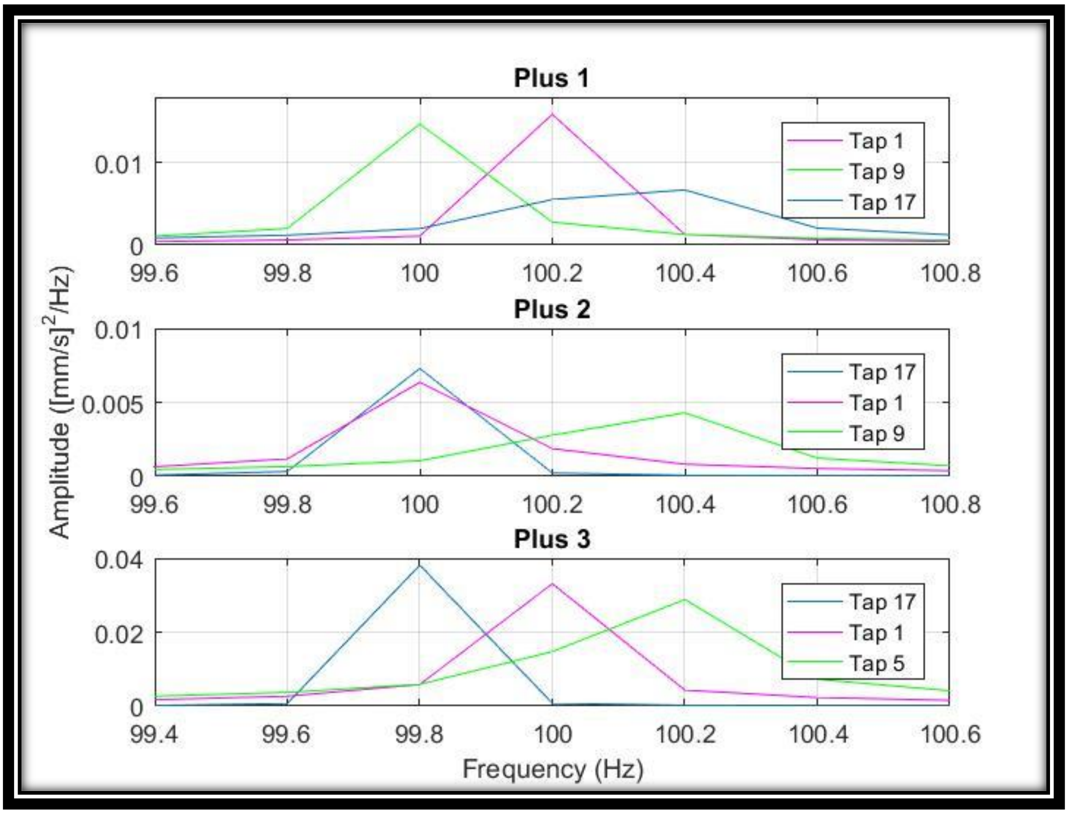

Figure 5-4: Transformers with plus tap changer short circuit test axial (Y) vibration comparison

Before moving on to the conclusion and recommendations, consider Table 5-2 which summarizes the apparent power ratings, tapping ranges and the winding and conductor types of the first three transformers with plus tap changers.

Table 5-2: Transformers with plus tap changers specifications

Trfr	APR (MVA)	Tapping range	Windings			
			HV		LV	
			Winding type	Conductor type	Winding type	Conductor type
1	80	132 + 8(-8) × 1.25%	Disk	Twin paper	Disk	Strip
2	60	132 + 8(-8) × 1.25%	Disk	Strip	Disk	Strip
3	40	132 +4(-12) × 1.25%	Disk	Twin paper	Disk	Strip

From the two theories for the radial winding vibration amplitudes as well as the two theories for the axial winding vibration amplitudes for transformers with plus tap changers, it is clear that the current carrying capacity is the main factor which determines whether the radial and axial winding vibrations when the highest voltage, thus lowest current tap is selected is greater than the radial winding vibrations when the lowest voltage, thus highest current tap is selected and vice versa. Furthermore, in section 2.4 it was also stated that the LV and HV winding and conductor types for transformers with plus tap changers do not have an influence on the radial or axial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap.

By considering the winding and conductor types of the first three transformers with plus tap changers, it is clear that they are very similar, thus any changes in the radial or axial winding vibrations of the highest voltage, thus lowest current taps relative to that of the lowest voltage, thus highest current taps must be as a result of the current carrying capacities of the transformers.

6. Conclusion and recommendations

6.1. Conclusion

In terms of the core vibrations, the following has been proven:

- The core vibrations (X, Y and Z components) of transformers with plus and plus minus tap changers are positively linearly related to the square of the excitation voltage.
- In proving this it was also proven that the regulator windings do not influence the core vibrations in any way, which means that the characteristics of the core vibrations for transformers with and without regulator windings are exactly the same.
- Overall the amplitude of the core vibrations in the Z direction is greater than the amplitude of the core vibrations in the Y direction which is greater than the amplitude of the core vibrations in the X direction. This is definitely a result of the propagation path of the signals.
- The X, Y and Z core vibration components do have integral multiple harmonics, but due to the fact that for some of the transformers that were investigated in this study, some of the approximated natural frequencies of the cores coincided with the integral multiple harmonics, the amplitudes of these integral multiple harmonics were bigger than that of the main frequency component (200 and 300 Hz components of the first transformer with a plus tap changer).
- Although it was proven in this and in previous studies that only the main frequency component of the core vibrations (100 Hz) is linearly related to the normalized square of the excitation voltage, a closer look was taken at the integral multiple harmonics of the core vibrations and the following was concluded. When the excitation voltage is increased to above the rated voltage of the transformer, so in other words when the excitation voltage is at a 110%, the amplitude of the 110% component at the integral multiple harmonics increased much more than the 100% and less components. This means that if the transformers were not excited at a 110% of the excitation voltage, the integral multiple harmonics of some of the transformers would have had smaller amplitudes than the main frequency component.

With all of this in mind, here are the characteristics of the core vibrations for transformers with regulator windings, which are exactly the same as the characteristics of the core vibrations of transformers without regulator windings.

Table 6-1: Transformer core vibration characteristics

Core vibrations	
Phenomenon	Magnetostriction
Dependency	Excitation/source voltage
Directions	X, Y and Z
Main frequency	100 Hz
Harmonics	Integral multiple harmonics

In terms of the winding vibrations, the following has been proven:

- For transformers with plus and plus minus tap changers the radial and axial winding vibrations of a specific tap are positively linearly related to the normalized square of the load current of that specific tap.
- For higher current carrying capacity transformers with plus minus tap changers, the radial winding vibration amplitudes at the main frequency component when the highest voltage, thus lowest current tap is selected, is greater than the radial winding vibrations amplitudes at the main frequency component when the lowest voltage, thus highest current tap is selected.
- For lower current carrying capacity transformers with plus minus tap changers, the radial winding vibration amplitudes at the main frequency component when the lowest voltage, thus highest current tap is selected, is greater than the radial winding vibrations amplitudes at the main frequency component when the highest voltage, thus lowest current tap is selected.
- For transformers with plus minus tap changers, the LV and HV winding and conductor types do not have an influence on the radial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap
- For all transformers with plus minus tap changers, the axial winding vibrations when the lowest voltage, thus highest current tap is selected, is greater than the axial winding vibrations when the highest voltage, thus lowest current tap is selected, given that there are not much more enhancing taps than opposing tap.
- For higher current carrying capacity transformers with plus tap changers, the radial winding vibration amplitudes at the main frequency component when the highest voltage, thus lowest current tap is selected, is greater than the radial winding vibrations amplitudes at the main frequency component when the lowest voltage, thus highest current tap is selected.
- For lower current carrying capacity transformers with plus tap changers, the radial winding vibration amplitudes at the main frequency component when the lowest voltage, thus highest

current tap is selected, is greater than the radial winding vibrations amplitudes at the main frequency component when the highest voltage, thus lowest current tap is selected.

- For higher current carrying capacity transformers with plus tap changers, the axial winding vibration amplitudes at the main frequency component when the highest voltage, thus lowest current tap is selected, is greater than the axial winding vibration amplitudes at the main frequency component when the lowest voltage, thus highest current tap is selected.
- For lower current carrying capacity transformers with plus tap changers, the axial winding vibration amplitudes at the main frequency component when the lowest voltage, thus highest current tap is selected, is greater than the axial winding vibration amplitudes at the main frequency component when the highest voltage, thus lowest current tap is selected.
- For transformers with plus tap changers, the LV and HV winding and conductor types do not have an influence on the radial or axial winding vibrations of the highest voltage, thus lowest current tap relative to that of the highest current, thus lowest voltage tap.
- Overall the amplitude of the radial (Z) winding vibrations is greater than the amplitude of the axial (Y) winding vibrations which is greater than the amplitude of the radial (X) winding vibrations. This too is definitely a result of the propagation path of the signals.
- Both the axial and radial winding vibrations does have integral multiple harmonics, but its amplitudes are negligible compared to the main frequency component.
- It has also been proven that all four factors as mentioned in section 2.4 influences the radial winding vibrations of transformers with plus minus and plus tap changers and only the last three influences the axial winding vibrations of transformers with plus minus and plus tap changers.

With all of this in mind, here are the characteristics of the winding vibrations for transformers with regulator windings, which are very similar to the characteristics of the winding vibrations of transformers without regulator windings, the only difference being the dependencies.

Table 6-2: Transformers winding vibration characteristics (including effects of regulator windings)

Winding vibrations	
Phenomenon	Electrodynamic forces
Dependency	Connection orientation of regulator and HV windings Number of regulator taps included Tap specific currents Overall current carrying capacity of transformer Load current
Directions	Axial (Y) and radial (X/Z)
Main frequency	100 Hz
Harmonics	Integral multiple harmonics

Furthermore, in terms of both the core and winding vibrations, it appears that the winding vibrations contribution to the overall tank vibration is greater than that of the core.

The objectives of this project were:

- Characterize the core and winding vibrations of transformers with regulator windings.
- Advise on an online vibration monitoring procedure for transformers with regulator windings.
- Provide practical transformer vibration information.

The characteristics of the core and winding vibrations of transformers with regulator windings have been determined in this study and are as summarized in Table 6-1 and Table 6-2. As far as providing practical transformer vibration information, all of the transformers that are investigated in this study are practical transformers which were designed to be incorporated into the national electrical energy network etc.. In terms of the online vibration monitoring procedure for transformers with regulator windings, the OLCM of (Shengchang, et al., 2006) will have to be used and all of the dependencies as listed in tables 6.1 and 6.2 would have to be taken into consideration when taking the measurements. What this basically means is that the tap position has to be monitored and a vibration amplitude versus the normalized square of the load current curve will have to be set up for each tap position.

6.2. Recommendations

If the invasiveness of the vibration measuring equipment and the vibration measuring tests was not such a big determining factor, in order to increase the accuracy and credibility of the vibration measurements that were taken in this project, the following could have been changed:

- Number of accelerometers used to record the vibration measurements.
- Sensitivities of the accelerometers used to record the vibration measurements.
- A different accelerometer attachment method could have been used which would not limit the sampling frequency that much.
- The sampling time could have been longer to ensure that the frequency resolution of the results are higher.
- The leakage reactance characteristics could have been determined up for all the tap positions.

In order to test the theories for the core and winding vibrations of transformers with regulator windings even further, the tank vibrations of practical transformers that are fully loaded could also be measured. In order to do this the OLCM of (Shengchang, et al., 2006) would have to be used and the tap position would also have to be taken into account as previously said.

Furthermore, a more in depth study can be done to determine which winding type (helical, disk, layer(x) loop layer etc.) and conductor type (strip, CTCE, twin paper etc.) has the lowest radial and axial winding vibrations, or in other words, which winding and conductor types are best at resisting the radial and axial electrodynamic forces imposed on it.

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8. Appendix A: Measuring equipment and data logger specifications

8.1. Laser Doppler vibrometer (PDV100)

The most important characteristics of the PDV100 are summarized below.

- General:
  - Power supply:
    - Supply voltage: 11 – 14 V_{DC}.
    - Power consumption: 15 W (max).
  - Mains connection:
    - Mains voltage: 100 – 240 V_{AC} $\pm$ 10%, 50/60 Hz.
    - Output voltage: 12 V_{DC}.
    - Power consumption: 20 W (max).
  - Ambient conditions:
    - Operating temperature: 5 – 40°C.
    - Relative humidity: 80% (max).
- Metrological:
  - Signal output analogue out:
    - Output swing: $\pm$ 4 V.
    - Frequency range: 0.5 Hz – 22 kHz.
    - Resolution (D/A converter): 24 bit.
    - Calibration accuracy: $\pm$ 1% (20 Hz – 22 kHz).
    - Measurement ranges:

Table 8-1: PDV100 analogue out measurement ranges

Measurement range full scale (peak) $\frac{mm}{s}$	Scaling factor (Analogue output) $\frac{\frac{mm}{s}}{V}$	Resolution $\frac{\frac{\mu m}{s}}{\sqrt{Hz}}$	Maximum acceleration $\frac{m}{s^2}$
20	5	< 0.02	2760
100	25	< 0.02	13800
500	125	< 0.1	69000

- Low pass filter:
  - Filter type: Digital, FIR type.
  - Cutoff frequencies (-0.1 dB): 1, 5 and 22 kHz.
  - Frequency roll-off: >120 dB/dec.
  - Stop band attenuation: > 100 dB.

Table 8-2: PDV100 low pass filter characteristics

Filter setting (kHz)	Pass band $\pm$ 0.1 dB	Stop band (attenuation > 40 dB)
1	0.5 Hz – 1 kHz	> 4.3 kHz
5	0.5 Hz – 5 kHz	> 8.4 kHz
22	0.5 Hz – 22 kHz	> 25 kHz

- High pass filter:
  - Filter type: Analogue, 3rd order Butterworth.
  - Cutoff frequency (-3 dB): 100 Hz $\pm$ 10%.
  - Frequency roll-off: -60 dB/dec.
- Optics:
  - Laser:
    - Laser type: Helium neon.
    - Wavelength: 633 nm.
    - Cavity length: 138 mm.

8.2. Tri-axial accelerometer (Dytran tri-axial accelerometer)

The most important characteristics of the Dytran tri-axial acceleromter are summarized below.

- Performance:
  - Sensitivity: 10 mV/g.
  - Range: $\pm$ 500 g.
  - Frequency response: 0.3 to 10 000 Hz.
  - Resonant frequency: > 40 kHz.
- Environmental:
  - Maximum vibration: $\pm$ 600 g.
  - Maximum shock: $\pm$ 5000 g.
  - Operating temperature: -51.1 to 121.1°C.
  - Seal: Hermetic.

8.3. Data logger (CoCo-80)

The most important characteristics of the CoCo-80 data logger are summarized below.

- Inputs:
    - Channels: 4 BNC connectors (Built-in IEPE current source, single-ended or differential).
    - Analog to digital converter (ADC): 24 bit.
    - Range: $\pm$ 10 V.
    - Sampling rate: 102.4 kHz.
- Power:
    - AC adapter: 110 – 240 V_{AC}.
    - Max power consumption: 14 W.
    - Battery operation time: 10 hours.

9. Appendix B: Complete transformer specifications

9.1. Plus minus 1

The bullets below summarize the basic information of the first transformer with a plus minus tap changer and Table 9-1 summarizes its tap specifications.

- 180 MVA, 161/15 kV.
- Plus minus tap changer (161 + 10(-10) × 1%).
- YNd.
- HV – disk type twin paper / LV – helical CTCE / regulator – loop layer strip

Table 9-1: Plus minus 1 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	177.10	586.80	11.81
	2	175.49	592.19	11.70
	3	173.88	597.67	11.59
	4	172.27	603.26	11.48
	5	170.66	608.95	11.38
	6	169.05	614.75	11.27
	7	167.44	620.66	11.16
	8	165.83	626.68	11.06
	9	164.22	632.83	10.95
	10	162.61	639.09	10.84
	11	161.00	645.48	10.73
	12	159.39	652.00	10.63
	13	157.78	658.66	10.52
	14	156.17	665.45	10.41
	15	154.56	672.38	10.30
	16	152.95	679.46	10.20
	17	151.34	686.69	10.09
	18	149.73	694.07	9.98
	19	148.12	701.61	9.87
	20	146.51	709.32	9.77
	21	144.90	717.21	9.66

LV	All taps	15	6928.20	NA

9.2. Plus minus 2

The bullets below summarize the basic information of the second transformer with a plus minus tap changer and Table 9-2 summarizes its tap specifications.

- 45 MVA, 88/11 kV.
- Plus minus tap changer (88 + 7(-9) × 1.5%).
- YNyn.
- HV – disk type twin paper / LV – helical strip / regulator – loop layer strip

Table 9-2: Plus minus 2 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	97.24	267.18	8.84
	2	95.92	270.86	8.72
	3	94.60	274.64	8.60
	4	93.28	278.52	8.48
	5	91.96	282.52	8.36
	6	90.64	286.64	8.24
	7	89.32	290.87	8.12
	8	88	295.24	8
	9	86.68	299.73	7.88
	10	85.36	304.37	7.76
	11	84.04	309.15	7.64
	12	82.72	314.08	7.52
	13	81.40	319.17	7.4
	14	80.08	324.44	7.28
	15	78.76	329.87	7.16
	16	77.44	335.50	7.04
	17	76.12	341.31	6.92
LV	All taps	11	2361.89	NA

9.3. Plus minus 3

The bullets below summarize the basic information of the third transformer with a plus minus tap changer and Table 9-3 summarizes its tap specifications.

- 20 MVA, 33/11.5 kV.
- Plus minus tap changer (33 + 4(-12) × 1.25%).
- Dyn.
- HV – disk type strip / LV – disk CTCE / regulator – loop layer strip

Table 9-3: Plus minus 3 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	34.65	333.25	3.01
	2	34.2375	337.26	2.98
	3	33.825	341.37	2.94
	4	33.4125	345.59	2.91
	5	33	349.91	2.87
	6	32.5875	354.34	2.83
	7	32.175	358.88	2.8
	8	31.7625	363.54	2.76
	9	31.35	368.33	2.72
	10	30.9375	373.24	2.69
	11	30.525	378.28	2.65
	12	30.1125	383.46	2.62
	13	29.7	388.79	2.58
	14	29.2875	394.26	2.55
	15	28.875	399.9	2.51
	16	28.4625	405.69	2.48
	17	28.05	411.66	2.44
LV	All taps	11.5	1004.09	NA

9.4. Plus 1

The bullets below summarize the basic information of the first transformer with a plus tap changer and Table 9-4 summarizes its tap specifications.

- 80 MVA, 132/33 kV.
- Plus tap changer (132 + 8(-8) × 1.25%).
- YNd.
- HV – disk type twin paper / LV – disk strip / regulator – loop layer strip

Table 9-4: Plus 1 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	145.2	318.1	4.4
	2	143.55	321.76	4.35
	3	141.9	325.5	4.3
	4	140.25	329.3	4.25
	5	138.6	333.25	4.2
	6	136.95	337.26	4.15
	7	135.3	341.37	4.1
	8	133.65	345.59	4.05
	9	132	349.91	4
	10	130.35	354.34	3.95
	11	128.7	358.88	3.9
	12	127.05	363.54	3.85
	13	125.5	368.33	3.8
	14	123.75	373.24	3.75
	15	122.1	378.28	3.7
	16	120.45	383.46	3.65
	17	118.8	388.79	3.6
LV	All taps	33	1399.64	NA

9.5. Plus 2

The bullets below summarize the basic information of the second transformer with a plus tap changer and Table 9-5 summarizes its tap specifications.

- 60 MVA, 132/33 kV.
- Plus tap changer (132 + 8(-8) × 1.25%).
- YNd
- HV – disk type strip / LV – disk strip / regulator – loop layer strip

Table 9-5: Plus 2 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	145.2	238.57	4.4
	2	143.55	241.32	4.35
	3	141.9	244.12	4.3
	4	140.25	246.99	4.25
	5	138.6	249.94	4.2
	6	136.95	252.95	4.15
	7	135.3	256.03	4.1
	8	133.65	259.19	4.05
	9	132	262.43	4
	10	130.35	265.75	3.95
	11	128.7	269.16	3.9
	12	127.05	272.66	3.85
	13	125.5	276.24	3.8
	14	123.75	279.93	3.75
	15	122.1	283.71	3.7
	16	120.45	287.60	3.65
	17	118.8	291.59	3.6
LV	All taps	33	1049.73	NA

9.6. Plus 3

The bullets below summarize the basic information of the third transformer with a plus tap changer and Table 9-6 summarizes its tap specifications.

- 40 MVA, 132/33 kV.
- Plus tap changer (132 + 4(-12) × 1.25%).
- YNd.
- HV – disk type twin paper / LV – disk strip / regulator – loop layer strip

Table 9-6: Plus 3 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	138.6	166.62	4.2
	2	136.95	168.63	4.15
	3	135.3	170.69	4.1
	4	133.65	172.79	4.05
	5	132	174.95	4
	6	130.35	177.17	3.95
	7	128.7	179.44	3.9
	8	127.05	181.77	3.85
	9	125.4	184.16	3.8
	10	123.75	186.62	3.75
	11	122.1	189.14	3.7
	12	120.45	191.73	3.65
	13	118.8	194.39	3.6
	14	117.15	197.13	3.55
	15	115.5	199.95	3.5
	16	113.85	202.85	3.45
	17	112.2	205.83	3.4
LV	All taps	33	699.82	NA

9.7. Plus 4

The bullets below summarize the basic information of the fourth transformer with a plus tap changer and Table 9-7 summarizes its tap specifications.

- 5 MVA, 22/11 kV.
- Plus tap changer (22 + 4(-12) × 1.25%).
- Dyn.
- HV – layer(8) strip / LV – layer(4) strip / regulator – loop layer strip

Table 9-7: Plus 4 tap specifications

Winding	Tap	Voltage (kV)	Rated Current (A)	Ratio
HV	1	23.1	124.97	2.1
	2	22.825	126.47	2.075
	3	22.55	128.02	2.05
	4	22.275	129.59	2.025
	5	22	131.22	2
	6	21.725	132.88	1.975
	7	21.45	134.58	1.95
	8	21.175	136.33	1.925
	9	20.9	138.12	1.9
	10	20.625	139.96	1.875
	11	20.35	141.86	1.85
	12	20.075	143.80	1.825
	13	19.8	145.80	1.8
	14	19.525	147.85	1.775
	15	19.25	149.96	1.75
	16	18.975	152.13	1.725
	17	18.7	154.37	1.7
LV	All taps	11	262.43	NA