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**ACOUSTIC DIAGNOSTIC OF  
ON LOAD TAP CHANGERS  
AND INVESTIGATION OF  
THE ARCING PHENOMENON**

**Ranjan Bhuyan**

**Supervisor:**

Dr. Ir. Peter H.F. Morshuis

**Daily Supervisor:**

Dr. Ir. Armando Rodrigo Mor

“Simplicity is the ultimate sophistication.”

- Leonardo da Vinci

“The best way to predict the future is to create it.”

Peter F. Drucker

# ABSTRACT

Power transformers are inseparable parts of the power system and the tap changer is an equally necessary part of the transformer. In order to keep the availability of power systems high, the reliability of the transformers must be improved. This can be done by improving the reliability of the tap changer, as tap changer failures are the cause for the majority of the power transformer failures.

This thesis focuses on the development of acoustic diagnostics of tap changers and the tap changer that is investigated for defects in this thesis is the selector switch type tap changer. The reason for choosing acoustic diagnostics is that this is a method which can be used online and can be used with the least disturbance to the normal operation of the power transformer.

Special emphasis has been laid on recreating the arcing conditions in the tap changer. Arcing inside the tap changer chamber is unavoidable but excessive arcing leads to a multitude of problems, so efforts have been made to acoustically detect the arcing phenomenon.

In order to have both flexibility and control over the experimental parameters, the experiments in the following chapters are conducted on three sets of test objects. Furthermore, the type of defects that pose the most imminent threat to the operation of the tap changer are focused upon and the most appropriate methods of signal acquisition and processing are determined for these experimental setups.

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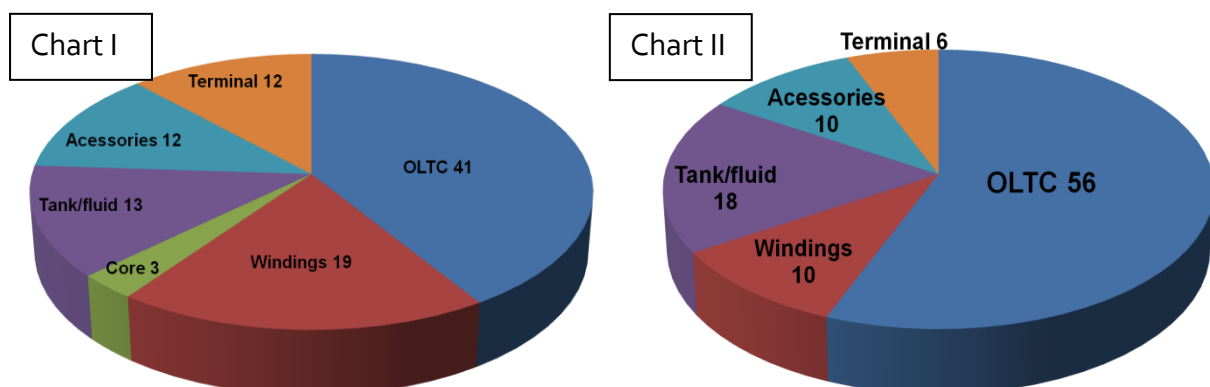
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# Chapter 1: Introduction

Power transformers are among the most critical equipment in the electrical power system, as they represent a sizeable and critical portion of the transmission and distribution system. The high criticality of the power transformer is partly due to the fact that it is a vital link ensuring operability of the power system and partly because of the large capital invested in this asset. The changes in the electricity market and the ever-increasing consumer demands push asset managers to operate transformers at their limits. The transformers age due to normal operation but also due to abnormal conditions like short circuit, lightning impulses and temporary overloading. These abnormal conditions accelerate the aging process and can lead to premature failure of the power transformer [4].

In order to keep the reliability of the power system high, the failures of the power transformers should be minimized and this can be achieved by various maintenance techniques. Traditionally, regular testing along with preventive maintenance and corrective maintenance strategies were used for power transformers. The problem with corrective maintenance in case of power transformers is that the cost and time required to repair or replace a power transformer is quite large. "The repair and replacement of a 345/138 kV transformer normally requires about 12 - 15 months. If a spare is available, the time needed for replacement of a failed unit is in the range of 8 - 12 weeks." [5].

The causes of failures in large power transformers from two studies are shown in Figure 1.1 below. Chart I. shows the Failure distribution of an international population of power transformers [6] whereas chart II. shows the failure distribution of the Dutch population of 50-150 kV power transformers [7]. It can be seen that the failure of the on load tap changer (OLTC) is a significant contributor to transformer failure in both the cases.



**Figure 1.1 : The contribution in percentage of transformer parts towards transformer failure**

The maintenance strategy used for tap changers is usually preventive maintenance. The maintenance schedule is either time based or based on the number of operations [8].

The maintenance period of the tap changer in the Netherlands is usually decided on the basis of the voltage stresses the tap changer faces. For star connected tap changers the maintenance is done not later than 5 years and for delta connected tap changers the maintenance is done not later than 3 years [1]. The disadvantage of this method is that high

costs are incurred during maintenance of the entire fleet of the transformers. Also preventive maintenance assumes a linear failure rate, but the transformer failures usually follow the bath tub curve hence failures near the end of life of the transformers increase [5].

## 1.1 Need for condition based maintenance

There has been a large investment in the generating capacity of power systems from the end of the second world war till the early 1970's and the transformer population that has been installed during that time is approaching its end of life [9]. The life time of the transformer, is usually specified by the manufacturer to be between 40 and 50 years and the end of life of a transformer is basically defined as loss of mechanical and insulation strength. The same condition applies to the OLTC.

With the changing structure of power systems and increasing deregulation, it has become essential to reduce the maintenance costs and equipment inventories. This has led to reductions in routine maintenance. Hence utilities shift from traditional time-based maintenance programs to condition-based maintenance. Now instead of conducting maintenance at a regular interval, it is carried out only if the condition of the equipment demands it. Hence, there is an increasing need for better nonintrusive diagnostic and monitoring tools to assess the internal condition of the transformers [5].

Acoustic diagnostics satisfies both these needs quite well, as acoustic measurements can be performed online and they provide a diagnosis of the internal condition of the tap changer.

## 1.2 Objective of the thesis

The objective of this thesis is to create a tool to diagnose the condition of an on load tap changer using the acoustic diagnostic methods. Before this tool for acoustic diagnostics can be realized, a number of issues need to be addressed:

- Deciding the type of defects in the tap changer that needs to be focused upon.
- Deciding the best methodology for signal acquisition.
- Choosing the appropriate measurement equipment and sensors of suitable frequency range.
- Determining of the most suitable processing method for acoustic signal.
- Obtaining a correlation between acquired results.
- And proposing a method for creation of the tool for defect analysis.

Only after the above issues are addressed, a diagnostic tool can be built. Hence to answer the above questions a number of experiments will be conducted along with extensive acoustic signal analysis and data processing.

## 1.3 Outline of this thesis

As described above, in order to achieve the objectives of this thesis the characteristics of the acoustic signal must be studied. Chapter 2 describes the basic principles of the electrical and mechanical operation of the tap changer, and the common defects found in the tap changer. There is also a section dedicated to acoustic signal processing and a summary of the prior research done on acoustic diagnostics.

Chapter 3 is about the experiments done in order to study the characteristics of the processes that occurs in the tap changer and on a small scale setup. For this study, two governing processes in the tap changer, contact movement and arcing were investigated.

Chapter 4 deals with acoustic measurements on a single phase tap changer. It describes the appropriate methods for analysis of the acoustic signals and the application of these methods of diagnosis for failure evaluation.

In chapter 5 the series of experiments are dedicated to a larger tap changer, the goal of these experiments is to see the reproducibility of the results obtained from the acoustic measurements of the single phase tap changer.

Finally chapter 6 contains some conclusions and observations derived from the experimental results, also some recommendations for future research are included in this chapter.

In the appendix section the LabVIEW code and the modules used for building the program for acoustic analysis has been provided.

# Chapter 2: On Load tap changers and acoustic diagnostics

## 2.1 Introduction

Voltage regulation is necessary for all networks, and this voltage regulation can be accomplished by changing the number of turns, either in the primary or the secondary side of the transformer. The only constraint is that this change in the number of turns should be accomplished without the interruption of current. This is where the tap changer comes into play. Although the underlying principle of every tap changer is the same, there are diverse methods by which this can be accomplished resulting in different on load tap changer (OLTC), technologies. The word “tap” has been referred to many times in this chapter and in the following chapters, tap as referred to here is the connection of a part of the winding to the contacts of the tap changer.

## 2.2 OLTC technologies

Based on the method of load current transfer, OLTC technologies can be classified into two main types, the selector switch type tap changer and the diverter switch type tap changer. Although the current is not interrupted during the process of current transfer from one part of the winding to another, arcing at the contacts is inevitable during the current transfer process. This classification is based on where and how the arcing takes places in the tap changer.

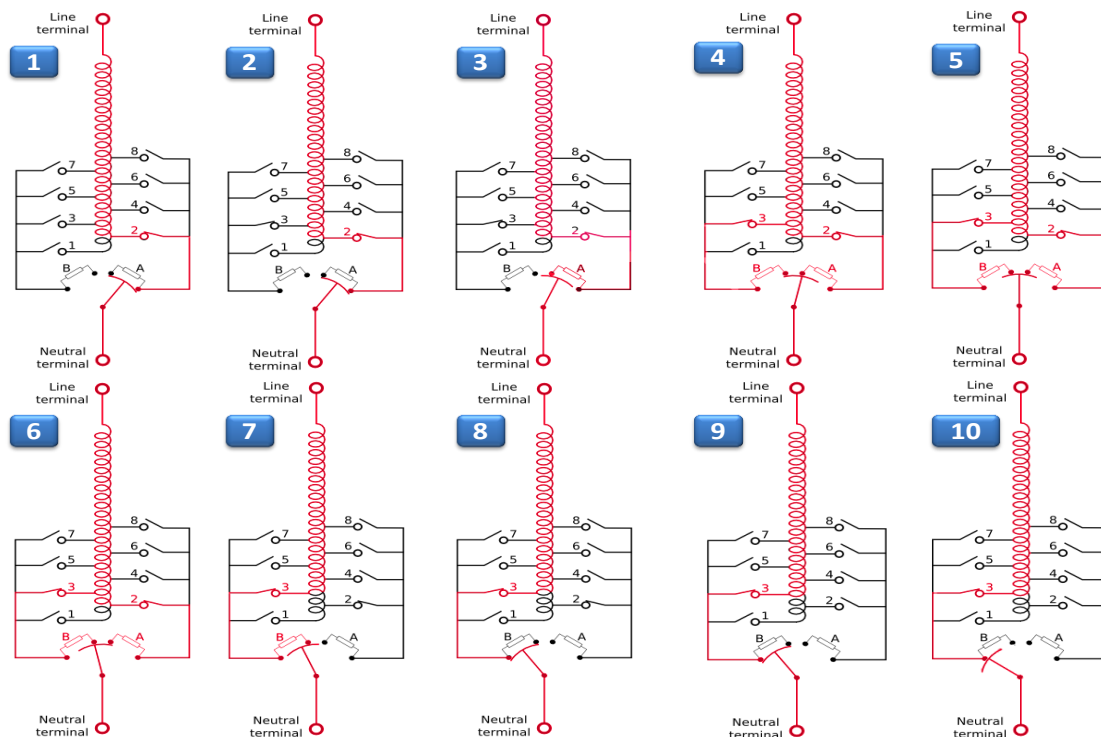
Another method of classification based on the design principle, is through the choice of the transition impedance. The transition impedance is needed to limiting the amount of circulating current flowing through the tap changer arms during the changeover process. The transition impedance can be either a resistance or a reactor. The network in the US mainly consists of reactance type impedances and the rest of the world uses resistor type impedance in the tap changers [10].

Further, the classification could also be made on the basis of the location of the tap changer, it can be either in-tank type or separate tank type. As the name suggests for the in-tank type changer the selector switch is inside the transformer tank and shares the oil with the transformer whereas the diverter oil is separated from the transformer. In the UK there are mostly separate tank tap-changers, but most of the tap changers in the world are of the in tank type. The in-tank type tap-changer offers greater flexibility in matching the tap-changing equipment to the transformer than the separate tank tap-changer [10].

## 2.2.1 The Diverter switch type OLTC

As in all tap changers there are stationary and moving contacts. In this type of tap changer operation, the arcing is diverted to a specific set of contacts, called the diverter switch. And another set of contacts called the tap selector makes the tap connection to the desired tap. During normal conditions current is flowing through one of the selector contacts (active) and the other selector contact (inactive) is not connected to windings. The transition resistances A and B are present in order to limit the circulating current in the diverter switch. The circulating current is formed when a part of the winding is shorted as shown by event 4 to event 6 in Figure 2.1 below. When a tap change sequence is initiated, the tap selector switch which is inactive makes a connection to the desired tap (Event 2). No current flows through this contact since it is a floating connection. Then the contacts of the diverter switch starts moving (Event 3) and current flows through resistance A. The diverter switch moves ahead bridging the two selector arms (Event 4 to Event 6) this is when the circulating current flows through the resistance A and resistance B. By event 8 the load current has completely been transferred to the other contact hence the contact which was previously connected to the transformer is now disengaged.

The advantage of these types of tap changers is that the arcing is limited to a certain set of contacts in the diverter switch which makes inspection and maintenance easier. On the other hand since only one set of contacts are arcing, this can cause accelerated deterioration of the contacts.



**Figure 2.1: Showing the sequence of operation or events that occur during a tap change operation in a diverter switch type tap changer.**

## 2.2.2 The selector switch type OLTC

The selector type on-load tap changer is a combination of the diverter switch and tap selector put together. The tap changer available for the experiments is selector switch type hence it shall be discussed in-depth. A selector switch consists of a fixed part and a moving part, the fixed part is the stator where the stationary contacts are mounted whereas the moving part inside the stator is called the rotor, both the stator and rotor are cylindrical in shape and the rotor rotates inside the stator.

A selector switch type tap changer may have two compartments, tap selector [1] or the fine selector switch and the changeover [1] or the coarse selector switch. The fine selector switch is usually accessible for maintenance from the top of the transformer whereas the coarse selector switch lies under the fine selector switch and as it is much deeper within the transformer, it is usually inaccessible for maintenance. The coarse selector unit shares the same oil as that of the transformer body, this can be seen in Figure 2.2. As it can be seen most of the times the coarse selector is open but in some cases it is also closed. Nevertheless it shares the same oil with the transformer. The fine selector switch on the other hand is completely sealed and contains its own Buchholz protection<sup>1</sup> and conservator<sup>2</sup> [11]. It has been designed in this way because the fine selector unit is the compartment where the arcing occurs and this oil has a large amount of carbon and dissolved gasses. If this oil contaminates the oil of the main transformer body:

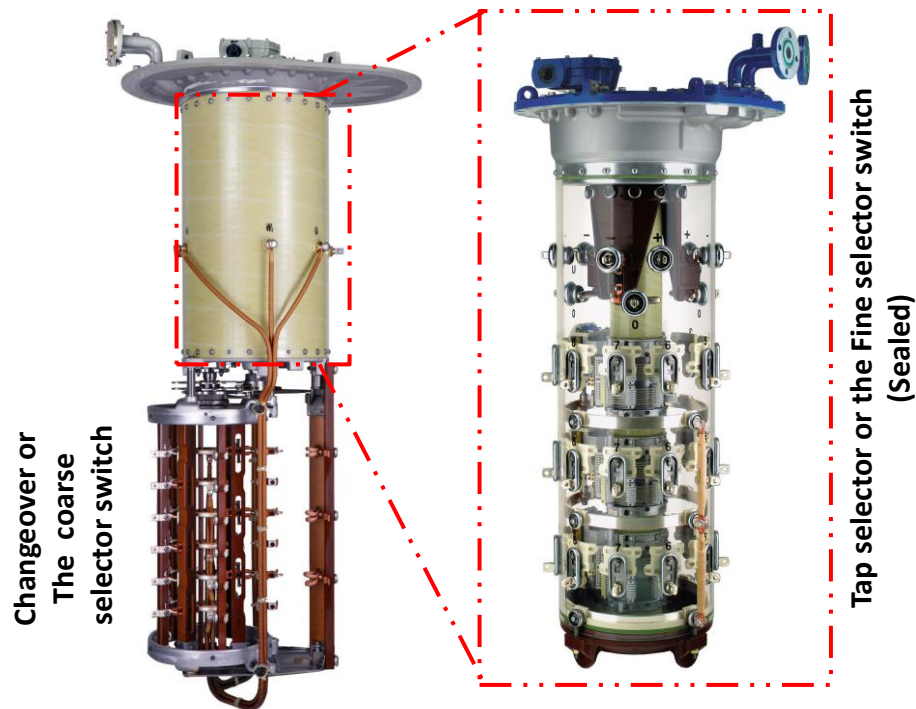
- Readings taken during dissolved gas analysis might indicate a condition of the transformer that is not an actual representative of its health.
- Excessive arcing may lead to formation of gasses that can trip the Buchholz.
- The carbon particles formed during arcing may increase the risk of flashovers in regions of high field concentration.

Although the probability of the tap changer oil leaking seems small, it is possible [12]. Along with the fixed contact the stator also contains a ring that serves as a connection to the other windings in case of a delta connected tap changer and as a neutral ring in case of a star connected tap changer as is shown below in Figure 2.2. The contacts of the stator are usually made of copper but have a 2-3mm layer of tungsten on it in order to prevent contact burning and damage during arcing. Hence they are also called arcing contacts.

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<sup>1</sup> The Buchholz protection works when there is a fault that causes an arc and a large amount of gasses is produced. This increase in pressure actuates a mercury switch inside the Buchholz relay and trips the transformer. The Buchholz relay is usually connected to the pipe connecting the conservator and the transformer.

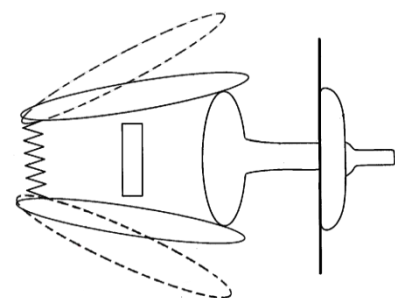
<sup>2</sup> This is an oil reservoir and an expansion vessel, the top part of the conservator contains air that is connected to the external atmosphere via a breather filled with a moisture absorbing agent, this prevents the oil in the conservator and hence the transformer from absorbing moisture.



**Figure 2.2 : Showing the cross section of a selector type tap changer, Shown in red is tap selector or the fine selector switch and the changeover or the coarse selector switch [13].**

The rotor is also cylindrical and has three sets of contacts for each phase and neutral contacts. The contacts of the rotor are in the shape of wheels and they roll on the stator contacts. The underlying design principle of the rounded rotor contacts is that they should always have tight contact with the stator contacts even while moving. This is achieved by using springs that hold the rollers tightly in place. The pressure of the spring keeps the rollers of the rotor contacts flexible allowing only one degree of freedom.

Each of the three sets of contacts have, a main roller or the middle roller  $R_M$ , and two transition contacts which are connected in series to two a low ohmic transition resistor. The two transition contacts are named right roller  $R_R$  and left roller  $R_L$  and the pair of contacts connected to the ring are called  $R_N$ . The placement of the  $R_R$  and  $R_L$  is such that they always bridge two stator contacts when the  $R_M$  is in between two stator contacts, this insures uninterrupted change over. The detailed construction of the rotor contacts is shown below in Figure 2.4. In some other designs the roller contacts can also be replaced by cylindrical contacts and the cylindrical contacts slide over the stationary contact. These mechanical contacts can align themselves and balance the forces in the contact fingers and provide connection even during wear of the stator contacts [14]. This research has been focused on the selector type on load tap changer with roller contacts.



**Figure 2.3 : Cylindrical contacts**

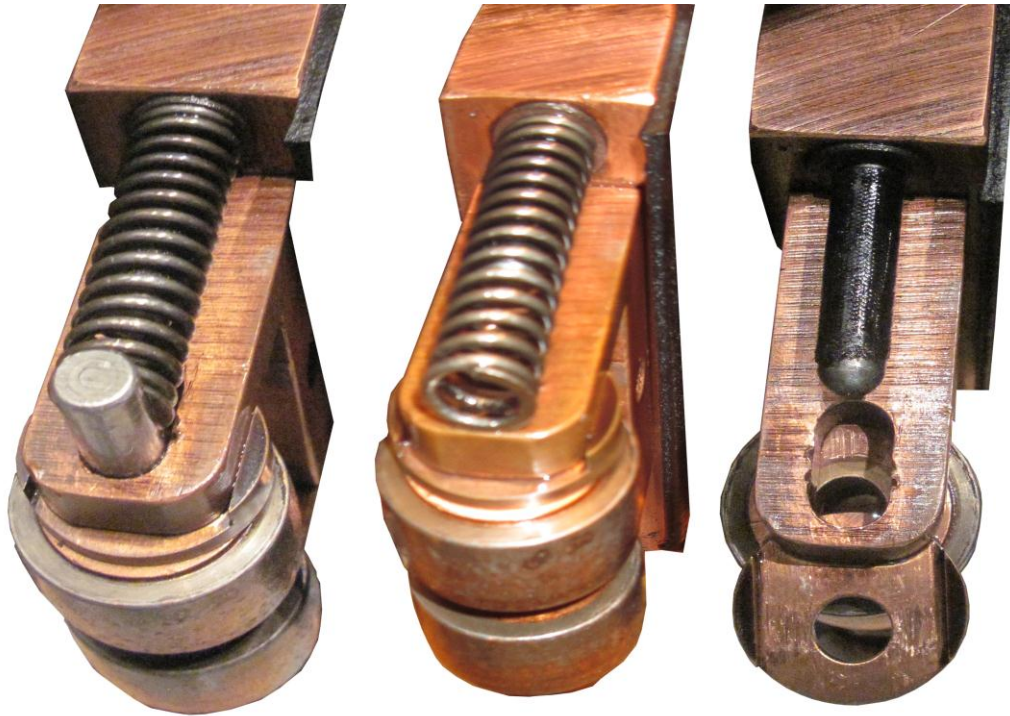


Figure 2.4 : Showing detailed construction of the roller contacts attached to the rotor.

### 2.2.2.1 Switching cycle of fine selector tap changer

A switching cycle of fine tap selector is said to be complete when the middle roller contacts  $R_M$  move from the center of one stator contact block (say A3) to the adjacent contact block (Say A4). This involves a number of small steps, throughout this thesis these steps have been referred to as events. An event can comprise of a single step or can be the combination of more than one step. The figure beside shows a single phase of a selector switch type OLTC with a coarse and fine selector switch.

Considering the nomenclature previously used for the roller contacts, a number of events can be defined for a single switching cycle, these events have been summarized in Table 1 below. Also shown alongside is the outcome in terms of electrical and acoustic signal. The contact block A3 as mentioned above has been given a general name as  $N^{\text{th}}$  contact and the contact block A4 has been called as  $N+1^{\text{th}}$  contact as shown in Table 1.

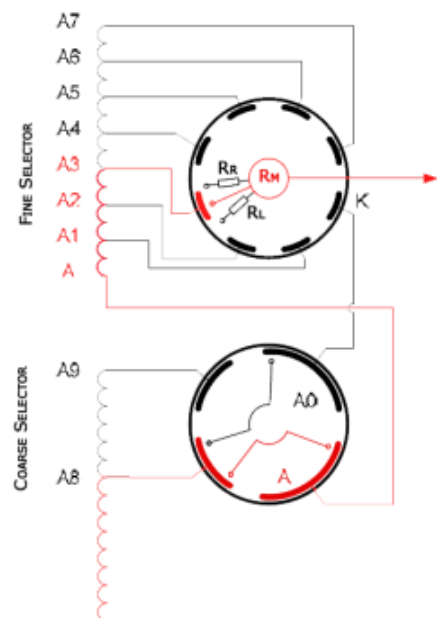


Figure 2.5: Showing the part of the winding the tap changer connects [3].

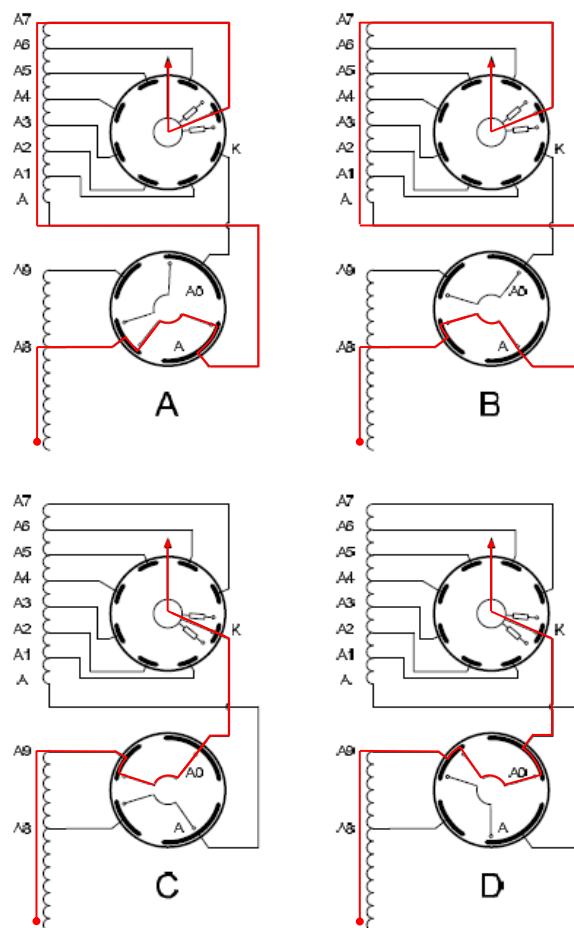
| Event Name | Physical outcome                                                   | Acoustic signal | Electrical change                                                                                                                                                                    | Pic |
|------------|--------------------------------------------------------------------|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 0          | This is the starting of the event                                  | None            | None                                                                                                                                                                                 |     |
| 1          | $R_R$ touches the contact N which is at the potential V            | Yes             | None                                                                                                                                                                                 |     |
| 2          | $R_M$ leaves the contact N                                         | Yes             | The entire load current is flowing through R1                                                                                                                                        |     |
| 3          | $R_L$ touches the $N+1^{th}$ contact at potential $V + \Delta V$ . | Yes             | The load current is shared between R1 and R2<br>Also since a potential difference of $\Delta V$ is shorted by the two arms of the tap changer a circulating current $\Delta I$ flows |     |
| 4          | $R_R$ leaves the Nth contact at potential V                        | Yes             | The entire load current is flowing through R1 and the circulating current is broken                                                                                                  |     |
| 5          | $R_M$ touches the $N+1^{th}$ contact                               | Yes             | The load current is diverted to the middle contact.                                                                                                                                  |     |
| 6          | The sequence of events end, $R_R$ leaves the $N+1^{th}$ contact    | None            | None                                                                                                                                                                                 |     |

Table 1: Showing the sequence of operation or events that occur during a tap change operation in a selector type tap changer during the operation of the fine selector switch.

### 2.2.2.2 Switching cycle of the coarse selector unit

The coarse change over selection switch is used when all the fine tap windings (as shown in Figure 2.5 above) from A0 to A7 have been selected. Now when the fine selector switch is at its last position, A7 a coarse tap contact has to be selected by the coarse tap changer before the fine tap changer can continue further. The switching sequence in the coarse roller switch is such that

there is no transfer of the load current in the coarse selector chamber. This is made possible by the following sequence of events shown in Figure 2.6. The fine tap selector in this case consists of 7 voltage steps and the voltage step of the coarse tap selector is always  $7+1 = 8$  voltage steps. When the fine tap selector reaches its end of all the available voltage steps (A) then the coarse tap selector moves by one step (B), it can be seen that the current is still being carried by contact A of the coarse tap selector. Now the fine tap selector moves to position k and the load current is diverted to the contacts Ao (C), this is a critical process as the current is switched in the fine selector unit. Also the voltage step is just 1 and not 8 steps as the fine selector contact



**Figure 2.6 : Showing the switching cycle of the coarse change over selection unit [3].**

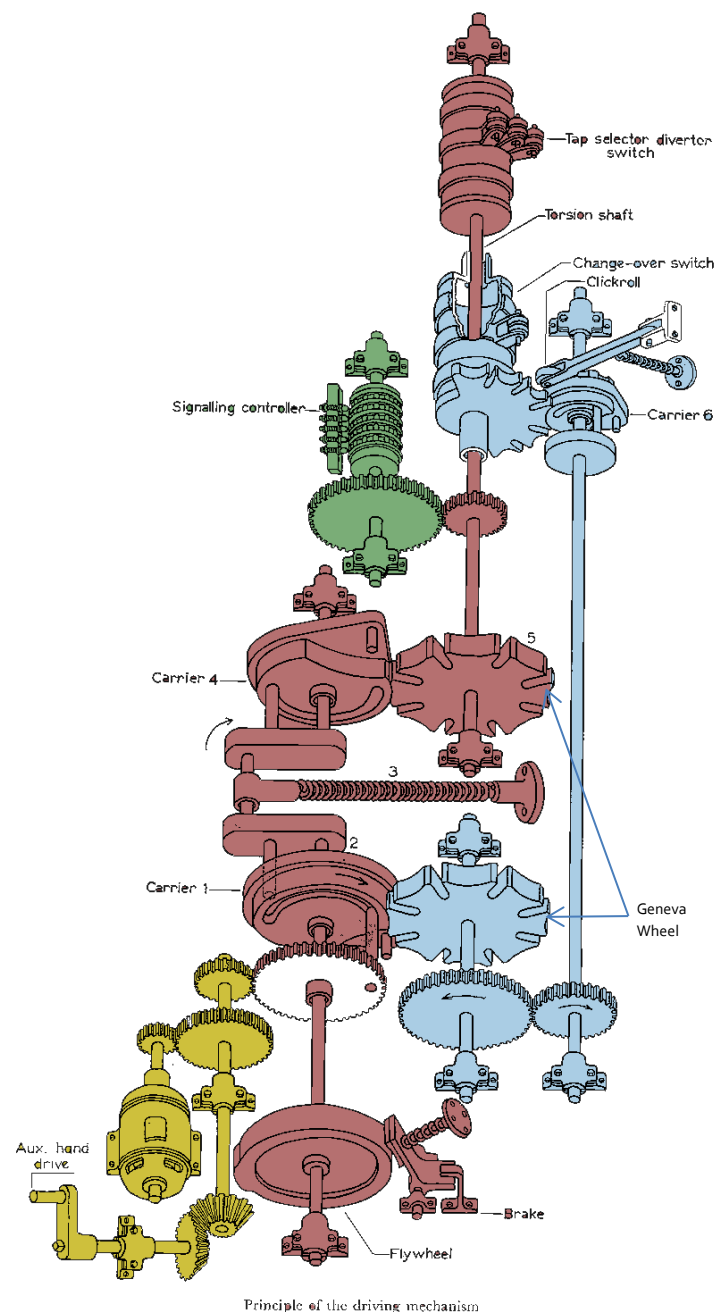
has moved to k which is position zero for the fine selector switch. Now the contact A moves into to the final position (D) to enable the fine selector tap changer to move ahead.

The tap change sequence shown above in the fine and coarse tap changer above is that of a single phase. A power transformer can have three separate single phase tap changers or just one tap changer having three phases. There are two test setups available for testing, one is a single phase tap changer having only a fine selector unit henceforth referred to as the single phase tap changer, the other is a three phase tap changer, complete with coarse selector unit, fine selector unit and the driving mechanism, hence forth called as the three phase tap changer. It is also important that the driving mechanism be reviewed in order completely understand the working of the tap changer.

## 2.2.3 Driving mechanism of the tap changer

The tap changer operates on the principle of stored energy such that once the tap change operation is initiated it is completed without the supply from the driving mechanism. This is achieved by charging a spring attached to the crankshaft (3). This crankshaft can be driven by motor or be driven manually. The springs are fully tensioned when the crankshaft has reached its high dead-center position, and as soon as this position is crossed the springs unload releasing their energy and driving the crankshaft with great speeds till the lower dead center position. To this crankshaft a carrier is attached which only rotates along with the crankshaft when the spring is unloading, about 180 degrees. The main advantage of using this mechanism is that the tap change operation cannot be affected by external conditions like loss of power to the drive and varying speed of rotation during manual operation.

As the spring is discharging the upper carrier (4) as shown in Figure 2.7, engages the Geneva wheel (5) and turns it by one step. This Geneva



**Figure 2.7: Showing the driving mechanism of the tap changer [1].**

wheel is connected to the rotor of the fine selector tap changer which in turn rotates the rotor by one tap step. To reduce shocks and ensure a smoother operation a flywheel is also attached. This flywheel also accommodates the braking unit.

By suitable gear transmission and carrier (6) the rotor of the coarse change over selector moves only after a certain number of tap change operations has been complete in the fine selector unit. There is usually a mechanical indication in to show the tap number for an operator who is operating the tap changer manually. The entire mechanism is then enclosed in cast iron housing. This housing can be easily opened for inspection without affecting the transformer. The shafts of the rotor are usually coupled to the drive mechanisms by a detachable coupling [1].

## 2.3 Defects in a tap changer

A tap changer is prone to develop defects due to a large number of operations over its long service life time. These defects can lead to a situation where the tap changer is no longer able to switch load currents without interruption. A damage to a tap changer can very well lead to a damage to the transformer and hence a considerable downtime [15]. These defects can be caused by many agents such as ageing, overloading, mal-operation and also maintenance errors. It is essential that these defects be discussed and classified and the most critical defects be studied first.

### 2.3.1 Surface Deterioration of Contacts

The deterioration of the contacts is mainly due to the ageing phenomenon and the load current. The load current can considerably accelerate the ageing phenomenon in a short time if the contact pressure between the rotor and stator are not proper and the contacts are arcing.

It might also sometimes happen that the ageing occurs even when the contacts are not carrying any load current. This occurs mainly in the coarse tap selector unit where

there is very infrequent contact movement. Shown in Figure 2.8 is a

part of a new contact. Based on the amount of damage to the contacts, the ageing phenomenon is divided into three phases, light, medium and advance aging [16].



**Figure 2.8 :showing a New Arcing contact.**

#### 2.3.1.1 Light Ageing

This is the earliest phase of contact deterioration, it is the phase in which there is the deposition of a thin oil film [17]. Left undisturbed over time a resistive layer due to insulation

oil decomposition may form over the contacts [16]. Since this contact area of the stator and rotor contacts are just a few spots even with a good contact [18] the contact area may further be reduced by this layer. A non-uniform current density is created along the point of contact and this leads to localized heating. Hot spots are formed, which further lead to oxidation of the oil film around the hotspot, as this oxidized layer is less conducting than the oil film and it further aggravates this situation. Although the formation of this layer cannot be avoided it is usually removed when the roller contacts of the rotor roll against the stator contacts.

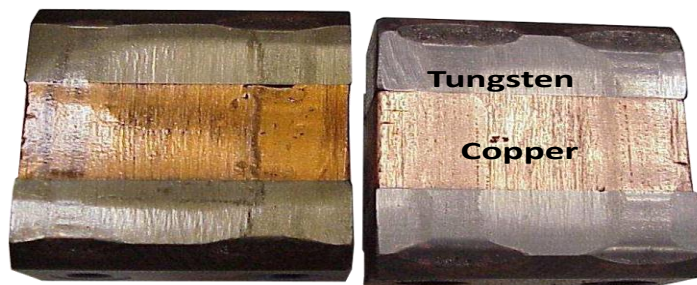


Figure 2.9 : Showing light aged contact with thin oil film on left hand side and good/clean contact on the right hand side [16].

### 2.3.1.2 Medium Ageing

This phase starts after the light ageing and the damages done to the contact are more permanent and cannot be removed by simple cleaning. The predominant process in this stage is called coking. As the oxidation film previously formed spreads, the contact voltage rises due to the increase in resistance. This increase in contact voltage leads to small discharges, similar to high voltage partial discharges. These discharges break this resistive layer and as the intensity of these discharges increases, the oil disassociates, liberating significant quantities of hydrogen gas [18]. These discharges also lead to the formation of tiny spots on the contacts and to the formation of carbon which gets deposited on this area. This process of deposition of pyrolytic carbon on the contact surface is called coking and the formation of craters in the contact surface is called pitting. Both these effects are long term effects and their appearance is an indication for maintenance of the tap changer. The long term ageing is accelerated by [3]:

- **Infrequent contact movement-** This occurs when the stator contacts are not used and are not wiped by the rotor, roller contacts. This situation usually occurs in the coarse selector switch which is hardly operated and also in fine tap selector switch which is operated only a few steps and not covering the entire tap range.
- **High temperatures**
- **High load** – Higher load currents increase the power losses in the resistive layer and hence lead to higher temperatures on the contact surface.

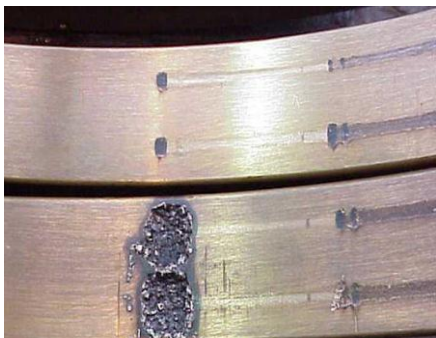
- **Low contact pressure** – A lower contact pressure of the roller contacts of the rotor will not be able to effectively wipe the stator contact leaving a larger layer of oil film and contaminants that will decompose pyrolytically.
- **Copper or brass contacts** – the growth rate of the surface film is accelerated when copper or brass contacts are used as compared to silver plated contacts.



**Figure 2.10:**  
Showing the damage to the coarse selector contacts due to the long term degradation effects [19].

### 2.3.1.3 Advanced ageing

Advanced ageing is the condition where extreme deterioration of the contacts has occurred and large pits appear on the contact surface, also a large amount of coking is seen on these surfaces. The occurrence of pitting is likely in both the stator as well as the roller contacts of the rotor.

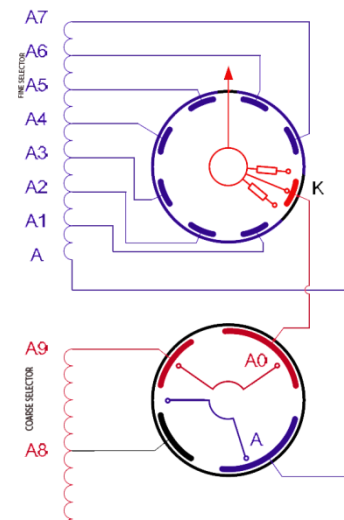


**Figure 2.11:** Left Showing extreme pitting on the stator contact surface, Right showing: Change-over selector stator roller contacts are damaged in the advanced stage of the long-term effect [3].



**Figure 2.12:** Showing heavy damage to the contacts due to coking [20].

The contact degradation mechanisms of medium ageing and advanced ageing are mainly due to flow of current through the contacts but there can also be another degradation mechanism that can occur in the changeover selector unit which is caused by floating windings. When the fine tap selector is at k and the coarse tap selector is switching, the fine tapped windings (shown in blue) are temporarily disconnected from the main winding and are floating. These floating windings are capacitively coupled to the transformer windings and when the switch A touches the contact A9 a small capacitive current discharge of the order of tens of milliamps recovery voltage of tens of kilovolts occurs, this discharge can damage the contacts[3].

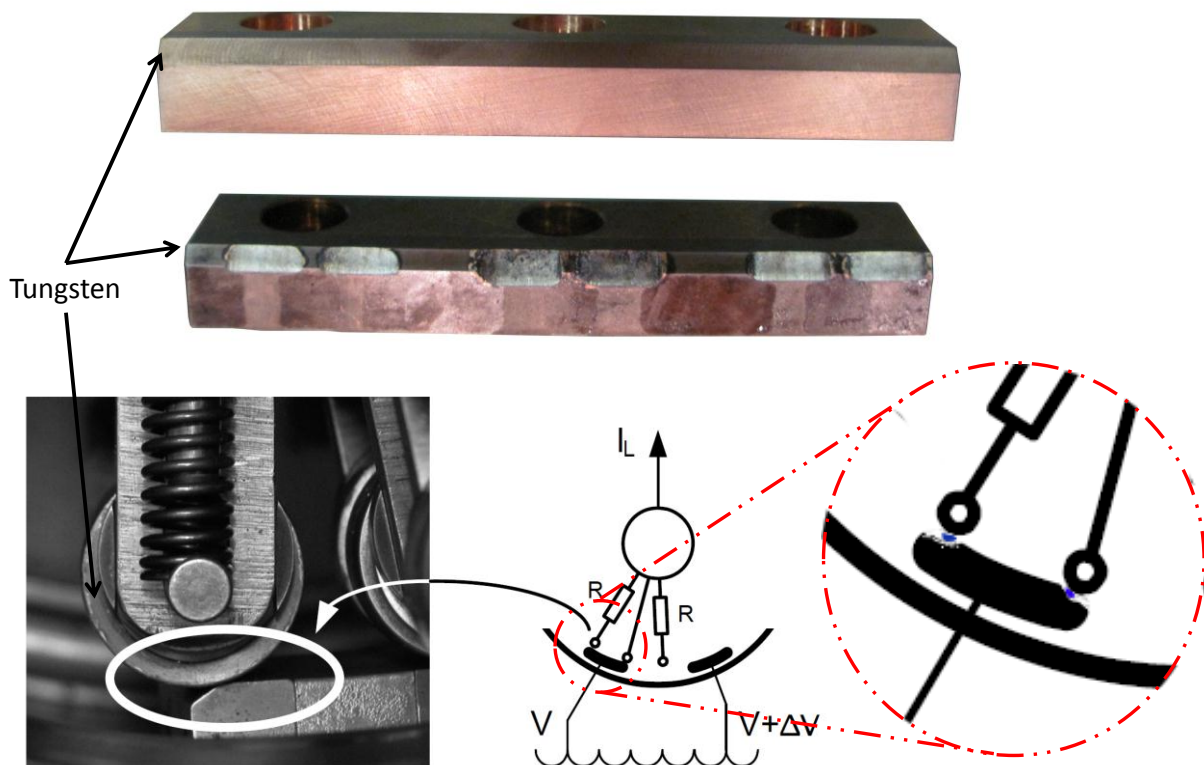


**Figure 2.13 : Showing Floating windings (in Blue) [3].**

### 2.3.2 Effects of arcing

The tap changer operates by transferring the current from the main contact to the transition contacts. During this transfer a current is interrupted to the contacts and hence arcing occurs. As previously discussed in Table 1 there is a short moment during which also a circulating current  $\Delta I$  flows through the transition resistor contacts in the tap changer along with the main current  $I$ . This circulating current  $\Delta I$  is formed when the transition contacts are bridging two contacts and this operation is necessary to ensure un-interrupted power flow during the tap change sequence and hence it is inevitable that an arcing will occur during event 3 and event 4 as shown in Table 1. The arc is normally quenched during the first current zero [3].

Arcing leads to pitting of the contacts, hence in order to avoid rapid contact deterioration a layer of tungsten is added to the copper contacts at the region where the arcing occurs in the stator contacts. But the deterioration of contacts occurs nevertheless, it is just that the speed at which the contacts deteriorate is reduced. Shown below in Figure 2.14 are the processes by which deterioration of the contact proceeds. As it can be seen, the tungsten contacts wear out first and when all the tungsten from the contact has been worn out the copper is exposed to the arc and as copper has a much lower melting point than the tungsten the contact degradation proceeds much faster. A similar tungsten layer is added to the roller contacts of the rotor.



**Figure 2.14: Top Showing a new contact and a contact that has been aged due to wear. Bottom : A roller contact at the moment it leaves the stator contact block. The contact block is wide enough for both roller contacts, but contact wear can endanger good contact timing [3].**

### 2.3.3 Mechanical damage to contacts & contact parts

The roller contacts are quite complex as they have to be flexible as well as provide good electrical contact to the system. There are several mechanism of mechanical failure that can occur to the roller contacts and its parts:

- I. As mentioned earlier the roller contacts are held at tension against the stator contact by the means of springs as can be seen from Figure 2.15 below. Over time, the springs may lose their elasticity and there will be a loose contact between the stator and the roller contacts.
- II. Another failure mechanism of the springs occurs when the sliders, meant for providing continuous electrical contact between the rollers and the holders, suffer from ageing and develop a resistive layer. The current then starts to flow via the holding pins through the springs into the holder, and this current also causes the spring to loose elasticity.

- III. The roller contacts are rolling on a shaft using brass cylindrical bearings. It might so happen that these bearings which are initially fused to the roller contacts come off and then the entire pressure of the rollers falls upon the copper part of the roller. As copper is a relatively soft metal as compared to brass it cracks under the pressure and it impairs the proper movement of the contacts.
- IV. Sometimes during extreme arcing the roller contacts become welded to the stator contacts, so the next tap change operation could lead to the breaking of the rotor shaft. This could lead to loss of synchronism between the arcing switch and the changeover selector
- V. The failure mechanisms mentioned above are the most common mechanical failure mechanisms that were found to exist <sup>3</sup>. There are many other mechanisms of failure which could occur like synchronisation problems, damaged transition resistor etc.

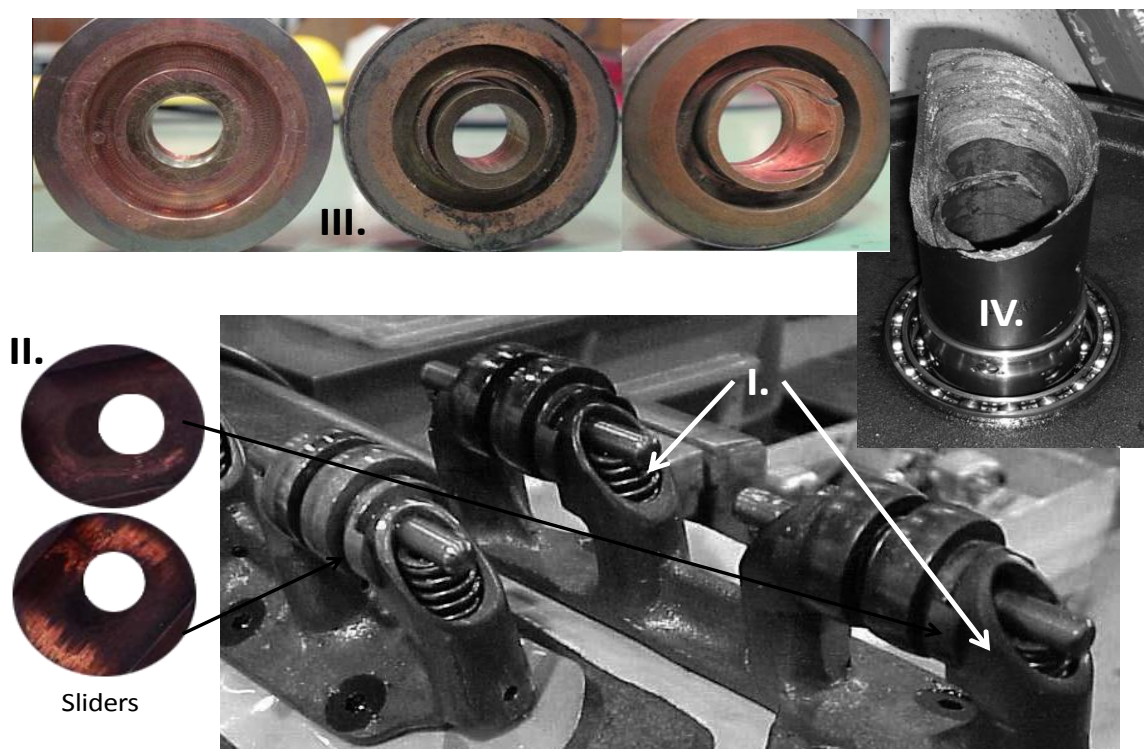


Figure 2.15: Showing the various mechanical damages ( I to IV ) as discussed above [3, 16].

### 2.3.4 Defects in the gear box

The problems that could arise from the drive unit and the gear box is that the gears might be worn out or broken, thus leading to problems in synchronism between the fine and the coarse selector unit. The spring providing energy to the crank shaft may lose its elasticity thus resulting in slower operation, which may further lead to damage to the

<sup>3</sup> The data regarding these failures were obtained from discussions with Smit Transformator Service, Which deals with transformer maintenance.

transition resistors [21]. A defective braking mechanism may cause the rotor to drive past the stator contact after completion of a tap change operation. The carrier or the Geneva gear may get damaged or worn out also leading to synchronism problems.

## 2.3.5 Maintenance induced failures

Preventive maintenance on tap changers is an activity which is regularly done in the time span of three to five years, on all tap changers. The maintenance of tap changers involves a number of steps and due to the mechanical complexity of the tap changer there can be a possibility of introducing a defect during maintenance. Previous studies [22] have shown that about 26 percent of tap changer failures occur due to incorrect maintenance or reassembly.

## 2.3.6 Classification of the defects based on criticality

OLTC defects can be from three main sources: mechanical, electrical or dielectric [23]. The defects described above, have been listed in the table below and a risk score of Failure Mode Effects and Criticality Analysis (FMECA) from one of the studies on tap changers is used [3]. As this research focuses on acoustic diagnostics, a column has been provided to indicate, if or not the mentioned defects can be measured acoustically.

| <i>Part</i>                        | <i>Cause of failure</i>                | <i>Detectable symptom</i>      | <i>Acoustic Detection</i> | <i>Total score</i> |
|------------------------------------|----------------------------------------|--------------------------------|---------------------------|--------------------|
| Arcing contacts                    | Contact wear                           | Arcing                         | Yes                       | 16                 |
| Change-over selector / tapselector | Contact degradation (long term effect) | Contact noise                  | Yes                       | 135                |
| Transition resistors               | Low switch speed, blocked half-way     | Transformer trip               | No                        | 80                 |
| Insulation oil                     | Switching arcs due to contamination    | Increased arcing               | Yes                       | 16                 |
| Drive axis arcing switch           | Rupture                                | Transformer trip               | No                        | 150                |
| Mounting of contacts               | Loose                                  | Arcing                         | Yes                       | 48                 |
| Springs                            | Weakening /Broken                      | Transformer trip               | Yes                       | 8                  |
| Brake                              | Blocked                                | Transformer trip               | Yes                       | 50                 |
| Gear/Geneva wheel                  | Wear                                   | Tap change not as per sequence | Yes                       | 50                 |
| Roller contacts Defects            | Pitted/ Weakening / Broken/ Loose      | Arcing                         | Yes                       | --                 |

**Table 2 : Showing the Failure Mode Effects and Criticality Analysis (FMECA) of certain defects [3].**

From the table above it can be observed that change-over selector / tap selector has one of the highest score in the probability of failure, after the rupture of the drive axis arcing switch. Therefore it was decided to study the acoustic characteristics of long term degraded contacts or the contacts that show symptoms of advanced ageing. Another point to note is that many defects can be detected by the arcing phenomenon, hence the investigation of the arcing phenomenon was kept as another priority.

The investigation of mechanical failures was not conducted because of the lack of damaged mechanical parts like Geneva gears and springs.

For studying the acoustic characteristics of long term degraded contacts accelerated ageing was tried out by passing a current of about 300 A through the contacts, while the tap changer was not filled with oil. It was hypothesized that the damage to the contacts by arcing would be accelerated if the quenching effect of oil was removed, but this approach failed as the tungsten electrodes seemed to withstand the 300 A without much damage.

Since a larger current source was not available, the contacts were damaged mechanically by creating pits on the contact that varied from a diameter of 0.5mm to about 3 mm. The diameter was kept to about 3 mm as this was the size of the largest pit that was measured in one of the damaged copper contacts. Also the roller wheels of the rotor were damaged in a similar fashion by creating grooves of about 2mm to 3mm.

The arcing phenomenon was reproduced using a variable flux welding transformer. The details of the arcing setup are mentioned in the next chapter. Figure 2.16 below shows the contact before and after mechanical damage. The undamaged contact is shown in (I) and termed as “Good” contact has been used hereafter in this thesis for this type of contact. Similarly the contacts that have been damaged mechanically as shown in (II) are termed as “Bad” contacts and this term is also used hereafter in this thesis to represent this type of contact.

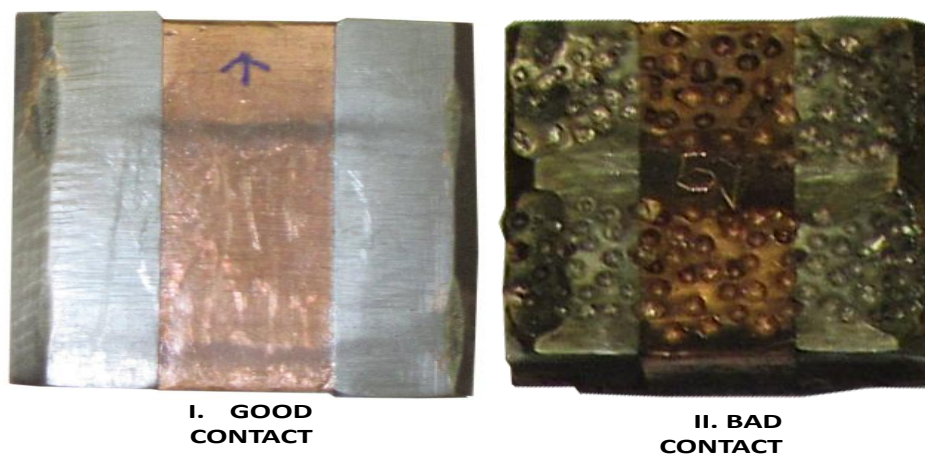


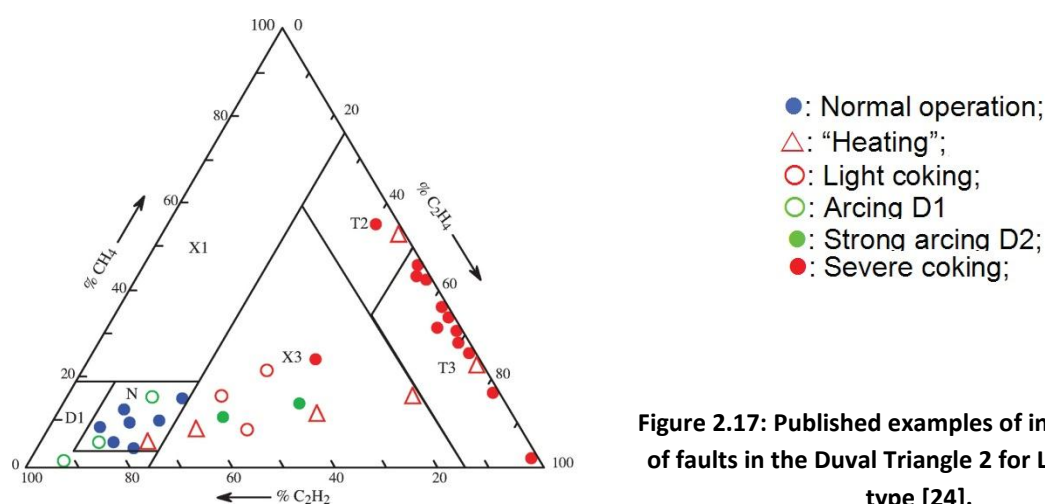
Figure 2.16 : Showing a undamaged contacts “Good” contact and a damaged or aged “Bad” Contact.

## 2.4 Methods available for OLTC diagnostics

The defects mentioned above need to be detected before they result in a catastrophic failure endangering both personal and environmental safety. The diagnostic methods are classified into two types, online and offline diagnostics. Discussed below are a few methods that are currently available for diagnosis of tap changers.

This is an online diagnostic and can be used without having to power down the transformer for testing. In this method an oil sample is taken from the tap changer and the gasses dissolved in the oil are analyzed, this method works on the basis of decomposition of oil onto different gasses depending on temperature of the defective area. For analyzing the data obtained from the gas samples the Duval triangle method is used. In this method, concentrations (in ppm) of the different gasses evolved like ethylene, acetylene etc. are expressed as a percentage of the total concentration of gasses and plotted in a triangular coordinate system on a triangular chart. This triangular chart is divided into fault zones and the fault can be predicted depending on where the obtained plot point lies. The fine selector switch of the load tap changer is designed to arc under normal circumstances, hence the Duval triangle is modified as shown in Figure 2.17 below [24].

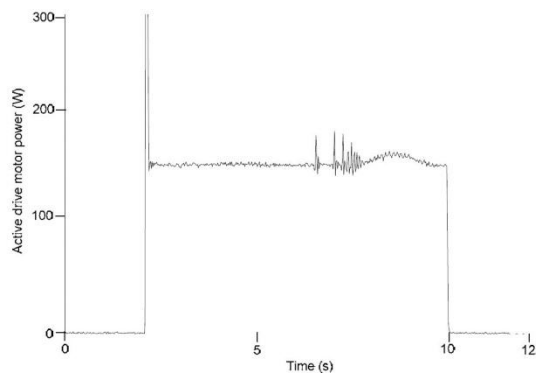
The number of particles in the sample of oil can be found out by particle count and formation of larger particles indicates advanced deterioration. Also the metal test which determines both the particulate metals and the metals dissolved in oil provides an important insight to the degree of contact degradation [20].



**Figure 2.17: Published examples of inspected cases of faults in the Duval Triangle 2 for LTCs of the oil type [24].**

## 2.4.2 Motor power measurement

This is also an online measurement method and defects in the drive mechanism in the gear box can be detected by the measurement of the active power consumption of the drive motor [25]. The motor power measurement can be a good measurement to determine if there are any variations in the torque required to charge the springs connected to the crankshaft. Also, a variation in power due to broken gear parts can be detected using this method.



**Figure 2.18: The motor power of a tap changer drive motor shows the inrush current followed by a stable operation. Power variations can be caused by moving the selector contacts or by loading the springs [3].**

### 2.4.3 Temperature difference measurement

As previously discussed, medium and advanced ageing leads to the formation of a layer of carbon on the contact surface and the losses might be hundreds of watts at nominal current [3]. If the tap changers are mounted externally then the difference in temperature between the transformer chamber and the tap changer compartment is easier to observe through sensors or through thermography. But if the tap changer is inside the transformer body the difference in temperature is difficult to observe as there is heat exchange between the transformer oil and the tap changer. This method is also an online method.

### 2.4.4 Static resistance measurement

This is an offline measurement in which resistance of the contact is used as a tool to determine the condition of the contact. The resistance measurements are taken when the tap changer is not operating and fixed on a contact, hence the name, static resistance measurement. Since the measurements are taken when the measurement current through the windings of the transformer completely stabilizes, this method takes a lot of time.

### 2.4.5 Dynamic resistance measurements

This is a similar diagnostic method as the static resistance measurement, with the only difference being that the dynamic resistance measurements are conducted when the tap changer is moving. Doing this helps in measurement of long term effects on the changeover selector contacts. Since the contacts are not in the same contact position long enough to allow the stabilization of the current through the transformer winding as in the case of static resistance measurements, the dynamic resistance measurements can be considered less accurate than static resistance measurements. Nevertheless it provides more information about the type and location of the defect inside the OLTC [3].

## 2.5 Introduction to acoustic monitoring

Acoustic emission (AE) is nothing but sound waves that are generated when objects vibrate or are under some form of stress. When this stress energy is released most likely at the surface of the object, a displacement wave is generated and this is the acoustic wave. This displacement thus results in high frequency elastic waves which can be captured by means of sensors and converted to electric data and thus analyzed and stored. Thus, acoustic monitoring can be described as the process of “listening” to these signals.

Acoustic testing is considered as Non Destructive Testing (NDT) as energy is not supplied to the test object, and acoustic monitoring is a dynamic process hence it can monitor changes as they happen and thus provides us with an important tool for online diagnostics.

### 2.5.1 Method of acoustic monitoring

The detection process of these acoustic signals is fairly straight forward and is performed by converting the acoustic waves into charge. This is done by attaching the piezoelectric accelerometers to the surface of the test object; the signal thus obtained is amplified through a low-noise preamplifier. The amplification can be either inside the sensor (also known as Integrated Electronic piezoelectric IEPE sensors), or through an external amplifier. The signal is then converted from analog to digital through a Digital to Analog Converter (DAC), and sent to the computer for further processing. A schematic presenting the various configurations is shown in Figure 2.19.

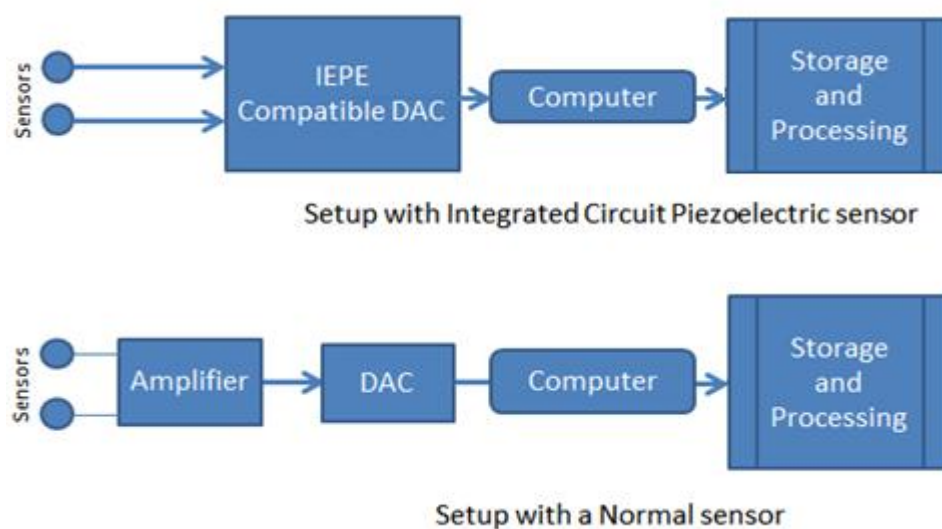


Figure 2.19 :Schematic showing the acquisition of acoustic signals.

## 2.5.2 Vibro-Acoustic sensors: Piezoelectric accelerometers

The sensors used for acoustic monitoring are mostly accelerometers. The mechanism of working of an accelerometer is based on an active material, which can be either piezoelectric or piezoresistive. The active material used in our case is piezoelectric, because a piezoelectric sensor is more sensitive than its counterpart the piezoresistive sensor. Also the frequency bandwidth and temperature stability is higher in case of piezoelectric materials. Piezoelectric materials are commonly made from a ceramic such as lead zirconate titanate (PZT).

In a piezoelectric sensor, one side of the piezoelectric material is connected firmly to the sensor base and on the other face of the piezoelectric material rests a “seismic mass”. Now depending on how the seismic mass is held in place, the sensors are classified into shear and compression sensors.

When an accelerometer is exposed to vibration a force is generated by the seismic mass as it is moveable, this force acts on the piezoelectric material to produce a charge. Now as we know force is mass times acceleration, and the seismic mass remains constant therefore:

$$\text{Charge} \propto \text{Force} \propto \text{Acceleration}$$

This charge can be collected from the piezoelectric material and measured.

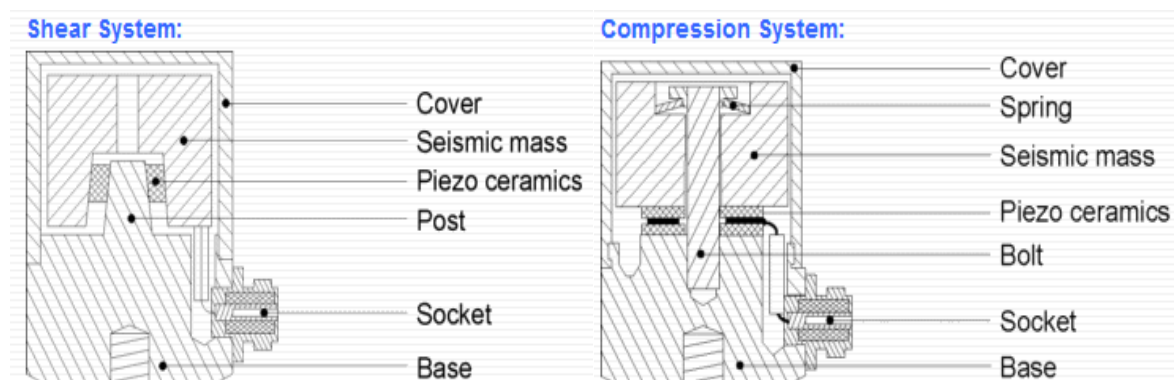


Figure 2.20: Showing the two sensor types [13].

## 2.5.3 Integrated Circuit Piezoelectric Accelerometers (IEPE)

Some accelerometers have a build-in electronic circuit that converts the charge to a voltage signal. The electronics also act as a preamplifier, thus eliminating the need for an

external preamplifier and the voltage signal can be transferred to a much longer distance. The only drawback is that an energy source is required to operate the internal electronics. Sometimes the constant supply current  $I_{\text{const}}$  and the output voltage signal from the IEPE transducer is transmitted over the same coaxial cable.

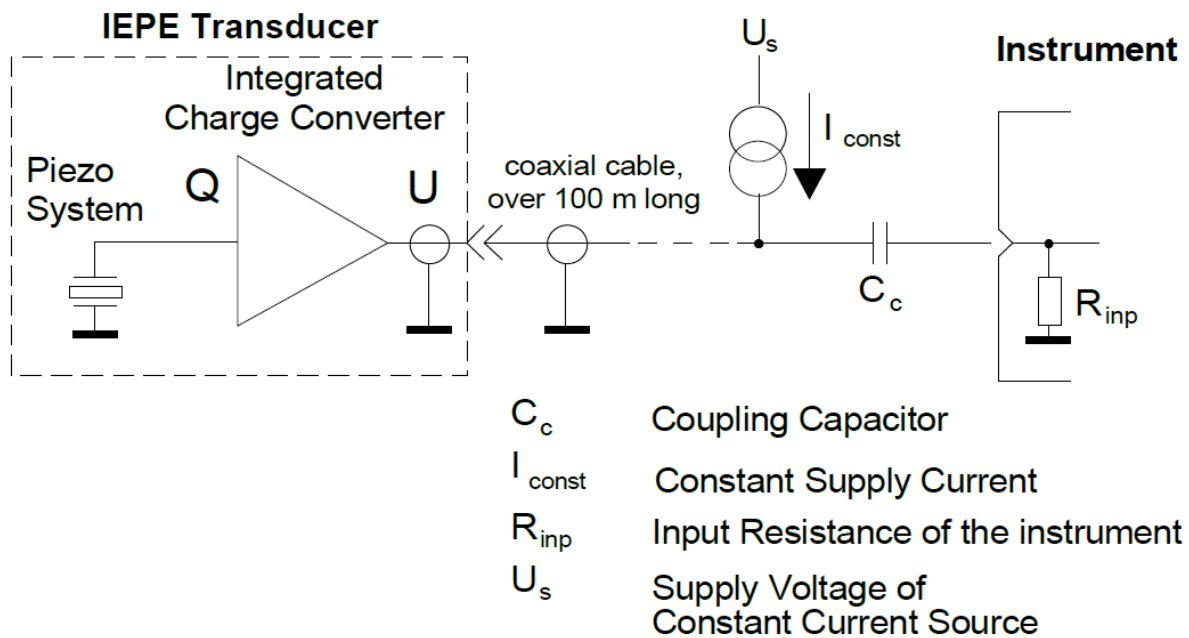


Figure 2.21 : Showing Integrated Circuit Piezoelectric Accelerometers (IEPE) Schematic [26].

### 2.5.3.1 Performance parameters of accelerometers

Mentioned below are a few parameters that are used to characterize the accelerometers. These parameters are usually mentioned in the datasheet of the measurement sensor.

- **Sensitivity:** The ratio of the change in acceleration (input) to the change in the output signal. A piezoelectric accelerometer can have a charge output or a voltage output. Now the sensitivity of an accelerometer is the amount of volts or charge given by the accelerometer for a given acceleration in  $\text{m/s}^2$ , it is typically expressed in units of  $\text{mV/g}$ .

**Example:** Voltage Sensitivity ( $\pm 10\%$ ) -10  $\text{mV/g}$  (1,02  $\text{mV}/[\text{m/s}^2]$ )

- **Measurement range** is the maximum level of acceleration that can be converted to an output signal by the sensor's electronics, the level of acceleration supported by the sensor's electronics and is normally specified in  $\pm g$ .
- **Frequency Response:** An accelerometer is bounded by two frequency limits, the low frequency limit and the upper frequency limit. The low frequency limit usually depends on the preamplifier and the RC constant formed by the accelerometer circuit [27]. The upper frequency however depends on the resonant frequency of the accelerometer. In order to achieve a wider operating frequency range the resonance frequency should be increased. This is usually done by reducing the seismic mass.

However, the lower the seismic mass, the lower is the sensitivity. An accelerometer with high resonance frequency (for example a shock accelerometer) will be less sensitive, whereas a seismic accelerometer with high sensitivity will have a low resonance frequency [27].

**Example** Frequency Range: ( $\pm 5\%$ )-2 to 10 000 Hz, Mounted Resonant Frequency- 35 kHz

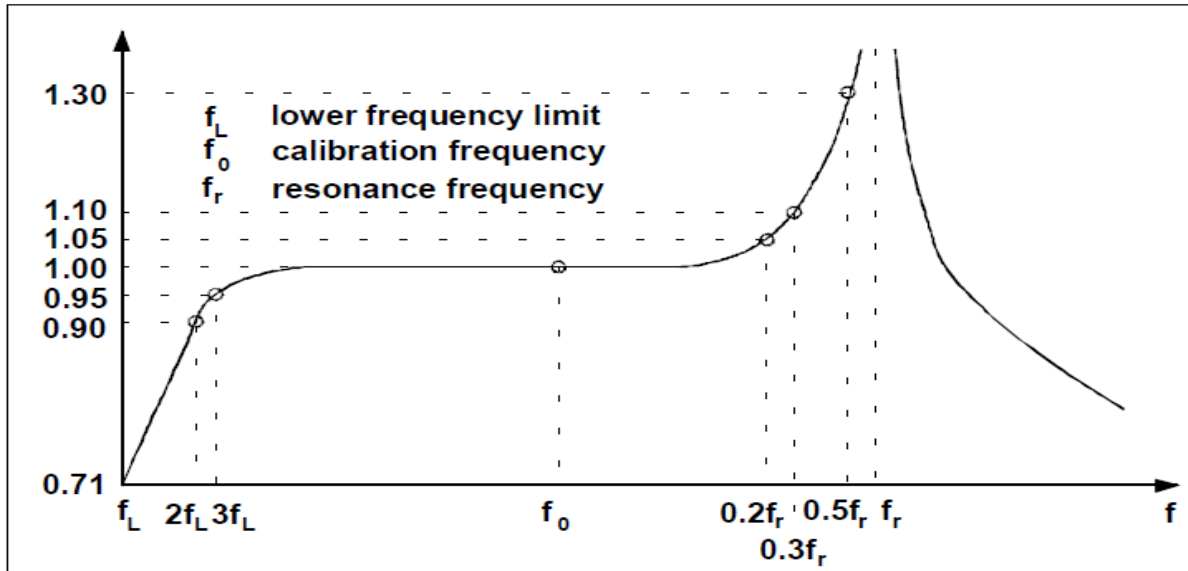


Figure 2.22: Typical frequency response curve of an accelerometer ( acoustic sensor ) [13].

## 2.5.4 Data Acquisition Device

A data acquisition device is an electronic device that converts analog signals to a digital form. It uses an analog-to-digital converter to convert the signals to a digital form, it also has features that allow it to be directly connected to a computer so that the digital signal can be obtained for further processing.

### 2.5.4.1 Performance parameters of data acquisition devices

There are many parameters which define the performance of a data acquisition device, DAC. Here we consider only the important parameters:

- **Resolution** is defined in number of bits for example, a 3-bit ADC divides the range of the signal being measured into  $2^3$  or eight divisions. A binary or digital code between 000 and 111 represents each division; this gives the name 3 bit. The ADC translates each measurement of the analog signal to one of the digital divisions. Figure 2.23 below shows a 5 kHz sine wave digital image obtained by a 3-bit ADC. As we see, the digital signal does not represent the original signal adequately because the converter has too few digital divisions to represent the varying voltages of the

analog signal. However, increasing the resolution to 16 bits to increase the ADC number of divisions from eight ( $2^3$ ) to 65,536 ( $2^{16}$ ) allowing the 16-bit ADC to obtain an extremely accurate representation of the analog signal [28].

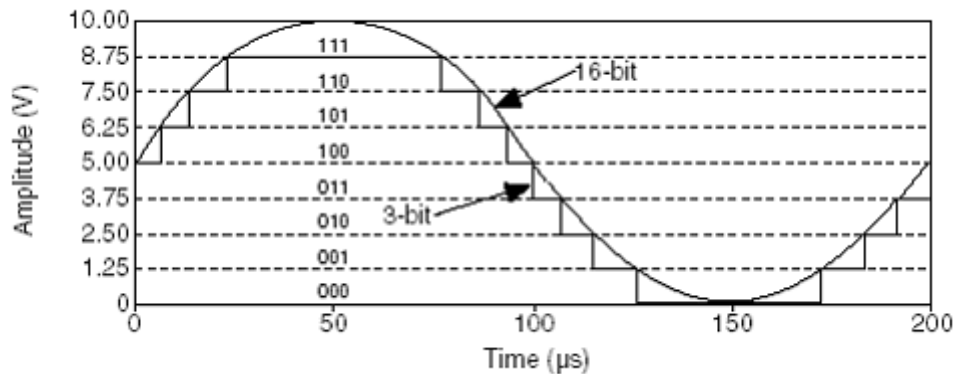


Figure 2.23 : Digital image of a 5 kHz sine wave obtained by a 3 bit ADC and the same signal with a 16 bit ADC [28].

- **Sample Rate:** Sampling rate is the rate at which data is sampled. Nyquist theorem states that, the sample rate of a digitizer needs to be at least twice the highest frequency component in the signal that is being measured. But having a sample rate two times the highest frequency is not enough and in order to properly reproduce the signal a real-time sample rate should be at least three to four times the digitizer's bandwidth.
- **Maximum Voltage Range:** It is the maximum voltage that can be measured at the input of the DAC.
- **Bandwidth:** Bandwidth of a circuit or measuring device is its ability to permit a signal without significant attenuation over a range of frequencies. In an amplitude v/s frequency plot, bandwidth is measured as two points of the frequency plot where the signal amplitude falls to -3 dB below the maximum amplitude. The -3 dB points are referred to as the half-power points.

## 2.6 Research in acoustic diagnostics

The table below summarizes the research that has been conducted towards acoustic diagnostics on transformer tap changers. The left side of the table gives the title of the research paper and the column on the right contains portions of the abstract to describe the research that has been done.

|                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                               |
|---------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Characterization of vibration signal using continuous wavelet transform for condition assessment of on-load tap-changers</b> | The authors work towards "the development of an OLTC vibration signal characterization technique using the continuous wavelet transform (CWT). The CWT, due to its capability of multi-scale localization in the time domain, is an effective tool in extracting the essential features from the original signals." [29]                      |
| <b>Condition monitoring of power transformer on-load tap-changers. Part 2: Detection of ageing from vibration signatures</b>    | "The paper describes a technique for on-line automatic condition assessment of an on-load tap-changer (OLTC) using a self-organizing map (SOM). With a condition indicator giving the correct indication of the current condition status, an estimate can be made of the remaining life of the equipment." [30]                               |
| <b>Mechanical Fault Diagnostics of On Load Tap Changer Within Power Transformers Based on Hidden Markov Model</b>               | "This paper investigated a novel strategy based on a Hidden Markov Model (HMM) for mechanical fault diagnosis of OLTCs. With partition, normalization, and vector quantization of the power spectral density of the obtained vibration signals, a feature vector extraction methodology was presented for the discrete power spectrums." [31] |
| <b>A New Approach for Condition Assessment of On-Load Tap-Changers using Discrete Wavelet Transform</b>                         | In this paper" A non-invasive monitoring method was developed using discrete wavelet transform (DWT) for condition assessment of on-load tap-changers using vibration analysis signals." [32]                                                                                                                                                 |
| <b>Vibration Monitoring of On-Load Tap Changers Using a Genetic Algorithm</b>                                                   | "The vibration signals emitted during the tap changes are usually recorded and post-processed using spectral analysis and some pattern classifier technique. To reduce the complexity of the classifier, a new technique based on Genetic Algorithm is proposed in this paper." [33]                                                          |
| <b>Condition Analysis and Assessment of On Load Tap Changer Acoustic Monitoring Principles and Techniques</b>                   | In this study the author characterizes the signals using a Wigner-Ville Spectrum Analysis and Discrete Wavelet Transforms. [34]                                                                                                                                                                                                               |

|                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>Methodology for Vibration Signal Processing of an On-load Tap Changer</b></p> | <p>“The purpose of this paper is to present a methodology implemented to find the OLTC diagnostic indicators (Number of vibration bursts, Vibration burst amplitude, Time between vibration bursts, Main frequency bands in the burst, energy of the vibration bursts). To obtain these indicators pre-processing and processing of the vibration signal is needed. In the pre-processing stage the signal is synchronized, normalized and then Hilbert transform is applied to obtain the envelope. In the signal processing stage a technique in time-frequency domain, Discrete Wavelet Transform, is used and then a threshold based on preserved energy is applied in order to determine the characteristic bursts of the vibration signal both the OLTC in good condition and with faults.” [35]</p> |
| <p><b>On-line tap changer diagnosis based on acoustic techniques</b></p>            | <p>In this paper, The sequence of tap-change process in the diverter switch is studied to understand the operation of the investigated tap changer. The studies were done in different tapping positions during off-load condition. The investigations took place during normal operation and under failure conditions of the tap changer, in order to verify the performance of the acoustic method. [36]</p>                                                                                                                                                                                                                                                                                                                                                                                             |
| <p><b>Vibro-Acoustic Testing Applied on Tap Changers and Circuit Breakers</b></p>   | <p>In this paper the author uses Vibro-Acoustic signal Envelope Extraction, and time of impact of contacts as a parameter to determine contact condition. [37]</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |

In this research, the major focus areas will be on observing the acoustic phenomenon in a small scale representation of the tap changer, on which specific parameters can be controlled to observe changes in the acoustic output. Also a special emphasis will be laid on determining the characteristics of arcing phenomenon and towards the development of a simple algorithm to analyse this acoustic phenomenon. Another major research question, will be to determine if any useful diagnostic data can be obtained from the measurement and analysis of higher frequencies ( > 2 kHz ) in the acoustic signal, as many papers above suggest a measurement range of less than 2 kHz.

## 2.7 Summary

There are numerous designs of on load tap changers but the operating principle can be divided into two main types, the selector switch type tap changer and the diverter switch type tap changer. In this chapter, the selector type tap changer has been discussed in detail because this is the type of tap changer this research focusses upon.

The selector type tap changer usually has two switching units, the changeover switch which is referred to as the coarse selector switch and the selector switch or the fine selector switch. The names, coarse and fine selectors have been chosen based on their functionality, in order to make understanding easier.

A part of the chapter was dedicated to the description of the commonly occurring defects in the tap changer. The priority of selection of the defects is based on a FMECA model. Two defects were chosen to be of paramount importance, advanced aged contacts and the arcing phenomenon.

Also discussed are the diagnostic methods currently available for tap changer diagnostics. Some of the available methods that can be used online are dissolved gas analysis, motor power analysis and temperature difference measurement. Although these are field tested methods, they cannot provide information about location of the defects and the condition of a particular defect. Other methods such as dynamic resistance measurements and static resistance measurements can predict the location of the defect but these are offline methods. Acoustic diagnostics can help in this regard, as it is both online and can help predict the location and condition of a particular of the defect.

Finally, an overview of the research done by various researchers in the field of acoustic diagnostic of tap changers has been mentioned. In the following chapter an attempt will be made to study the characteristics of acoustics signals.

# Chapter3: Study of acoustic signal characteristics

## 3.1 Introduction

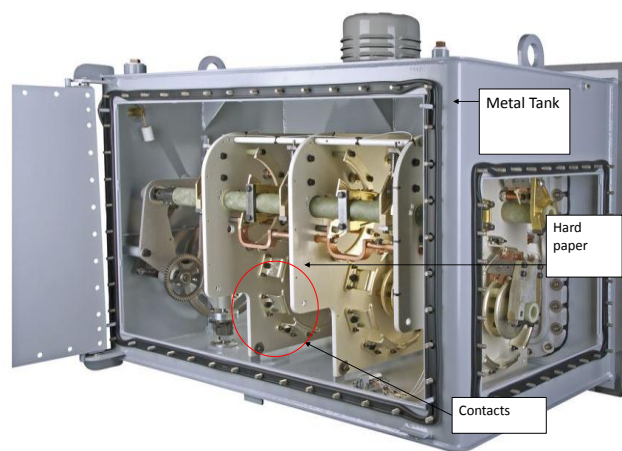
Before the initial measurements on the tap changer it was decided that it would be beneficial to separately study the characteristics of the processes that occurred in the tap changer and on a small scale setup where changes to the setup could be made very conveniently. For this the study of two processes were chosen, namely contact movement and arcing, as these are the governing processes in the tap changer. In the experiments below both the processes are analyzed in, time as well as in the frequency domain and the observations from these experiments will form the stepping stone for the next set of experiments in chapter 4.

## 3.2 Finding the characteristics of contact movement.

To study the acoustic characteristics of contact movement, it was necessary to replicate the conditions present in a tap changer to obtain the acoustic waveform in a way that is as close as possible to the acoustic waveform obtained from an actual tap changer. Seen in Figure 3.1 below is a tap changer and typically in almost all tap changers the acoustic signal is emitted from a moving contact, passes through a layer of hard paper and the whole setup is enclosed inside a metal container. The medium of transmission for the acoustic signal is mainly the high voltage mineral oil inside the chamber.

In the experiment described in the following sections the characteristics of the acoustic signal obtained from the movement of a contact will be analyzed and compared with other sets of acoustic signals obtained from the same setup.

These tests are also important to observe the characteristics of the measurement setup and acquisition devices.



**Figure 3.1 : Showing the internal arrangement of a tap changer[2].**

### 3.2.1.1 Laboratory Set-up and Procedure to study the characteristics of contact movement.

In the laboratory, a model of the tap changer shown in Figure 3.2 is obtained in the following way:

- The movement of the contacts in the tap changer is replicated by a power contactor having a contact area of  $25\text{mm}^2$ . Normally the power contactor has three or four moving contacts but for this experiment only one of the contacts has been used and the other contacts are removed. This has been done so that the sound is obtained from only one contact. The contact material is copper with a coating of tungsten on the contact surface. This is to a certain extent similar to the contact arrangement in a tap changer.
- The power contactor is then surrounded by a layer of hard paper to simulate the effect of an insulator surrounding a tap changer.
- Then the whole unit is placed inside a metal tank of dimensions: 400 mm height and 300 mm in length and breadth and filled with 27 liters of mineral oil.

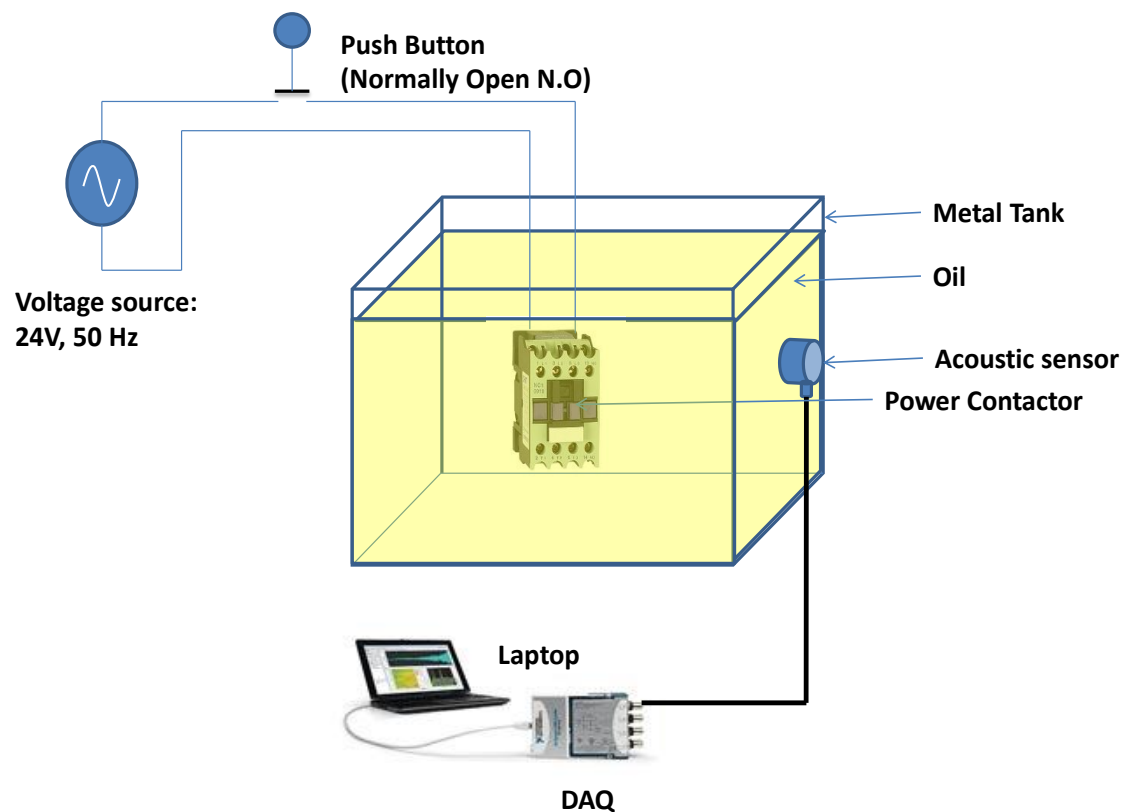


Figure 3.2 : Schematic diagram of the setup for finding the characteristics of contact movement.

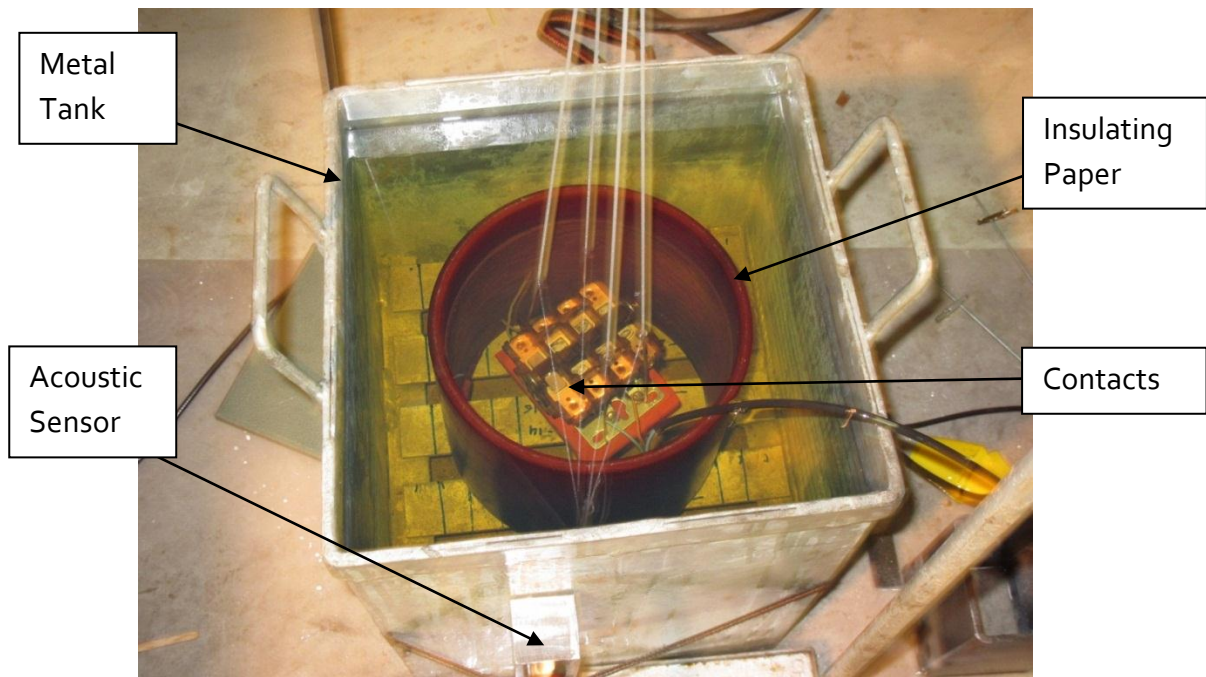


Figure 3.3: Image Showing the arrangement of the test setup.

Specifications of measuring devices:

| <i>Acoustic sensor</i>    |                                |
|---------------------------|--------------------------------|
| Sensor Name               | HS-100 Series Vibration Sensor |
| Sensitivity               | 100 mV/g $\pm 10\%$            |
| Frequency Response        | 0.8 Hz to 15 kHz $\pm 3$ dB    |
| Measurement Range         | $\pm 80$ g                     |
| <i>DAQ</i>                |                                |
| Equipment Name            | NI USB-9233 with 9162 Carrier  |
| Bus                       | USB                            |
| Input Resolution (bits)   | 24                             |
| Dynamic Range (dB)        | 120                            |
| Sampling Rate per Channel | 50kS/s                         |
| Analog Inputs             | 4                              |
| Input Range               | $\pm 5.4$ V peak               |
| Type                      | IEPE                           |

### 3.2.1.2 Working principle of the test setup

The power contactor is supplied through a 24V AC power supply and is connected in series with a push button switch. When the push button is pressed the contactor is actuated and the metal contacts close producing a sound. This sound (acoustic signal) travels through the oil to the acoustic sensor. This acoustic wave is converted into an analog electrical signal by the acoustic sensor and sent to the DAQ. The DAQ converts the analog signal to a digital signal and is acquired using NI LabVIEW SignalExpress on a laptop and stored. This DAQ does not support digital or analog triggers [38] so a software trigger using NI LabVIEW SignalExpress is used to obtain the waveform on a certain amplitude crossing.

## 3.2.2 Analysis procedure

As an initial approach to the analysis it was important to determine if the signal obtained from the measurement setup is reproducible. To check this, a cross correlation function was used to compare the shape of the signals.

### 3.2.2.1 The cross correlation function

Cross correlation is a well-known method for comparing signals. It is used for audio and image signal processing. The cross correlation CC of the sequences  $x_i$  and  $y_i$  is defined by the following equation [39]:

$$cc = \frac{\sum x_i \cdot y_i - \sum x_i \cdot \sum y_i / n}{\sqrt{\left[\sum x_i^2 - (\sum x_i)^2 / n\right] \cdot \left[\sum y_i^2 - (\sum y_i)^2 / n\right]}}$$

Equation 1: Showing the Cross correlation function.

Where  $x_i$  and  $y_i$  are the amplitudes of the signal X and Y respectively and n in this case is the number of samples. The cross correlation factor indicates the difference in shape of the signals. The values of cross correlation factor lies between -1 and +1, the cross correlation factor is:

- +1 if the shape of both signals is exactly the same.
- - 1 if the shapes of both the signals are the opposite of each other.
- 0 if the shape of both the signals has no correlation.

The above formula normalizes the signal so signals of different amplitudes can be compared. As the cross correlation function does a point to point comparison of the signal, it is important that the signals obtained are of the same time length and that the signals are aligned along a common point. In our case the common point was chosen to be the peak of the signal. The algorithm for obtaining the cross correlation function is described in Figure 3.4 below.

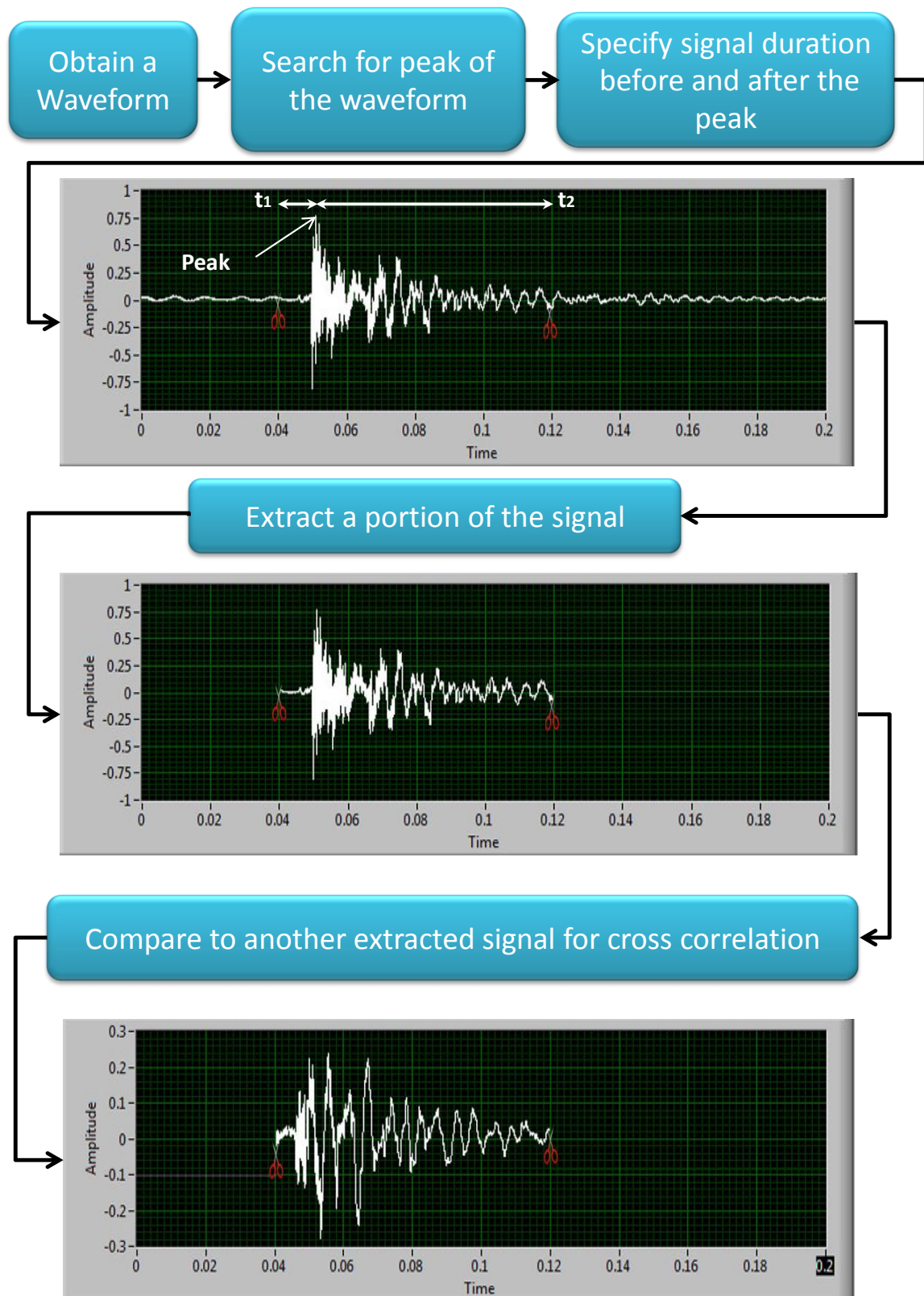


Figure 3.4 : Algorithm for signal operation in order to obtain the Cross Correlation Function

### 3.2.2.2 Explanation of the algorithm

This algorithm works by comparing the shape of the waveforms using the cross correlation function. For making this comparison the two waveforms need to be of the same length and aligned along a specific point, the algorithm does this by searching the peak of the signal and finding the time where the peak occurs.

Then a portion of the signals is extracted and the shape of the signal is compared to another signal that has been processed by a similar process using the cross correlation function.

### 3.2.3 Results for the analysis of characteristics of contact movement

A set of values were obtained for the cross correlation factor of different signals which are tabulated below:

| <i><b>Trial no</b></i>          | <b>1</b> | <b>2</b> | <b>3</b> | <b>4</b> | <b>5</b> |
|---------------------------------|----------|----------|----------|----------|----------|
| <b>Cross correlation factor</b> | 0.8905   | 0.90085  | 0.877667 | 0.915303 | 0.903    |

From the above table it is seen that the cross correlation factor is relatively high so it can be said that the signature of an acoustic waveform obtained from the closing of contacts remains relatively constant if all other parameters like the sensor position, power contactor position, volume of oil are kept constant. The experiments below determine the effect of change of these parameters to the cross correlation factor.

## 3.3 Investigating the effect of sensor position

Another phenomenon that was studied was the effect on the cross correlation factor due to the position of the sensor and the contactor. For this first the position of the power contactor was changed, horizontally in the X-Y plane. When the power contactor was moved around the tank the only difference that was seen was in the amplitude of the signal without a large change in the cross correlation factor. Then, the sensor position was changed in the Z plane and two sets of readings, trial 1 and trial 2 were taken.

- Trial 1: Sensor at the bottom of the tank (A, shown in Figure 3.5 below).
- Trial 2: Sensor at the top of the tank (B, shown in Figure 3.5 below).
- Trial 3: Comparison of signals obtained from trial 1 and trial 2.

Below is a chart showing the cross correlation for the three trials. The points shown in purple are the cross correlation factors obtained when two signals that were obtained during Trial 2 were compared. Similarly points shown in orange are the cross correlation factors obtained when two signals from trial 1 are compared and the points shown in green show the cross correlation factor obtained when a signal from trial 1 and another signal from trial 2 were compared.

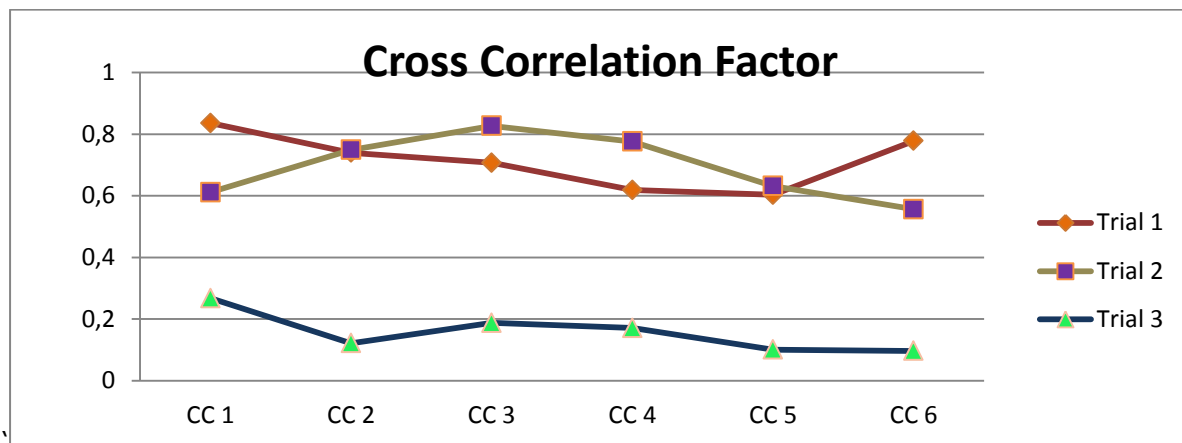


Figure 3.5 Chart showing the comparison of cross correlation factors

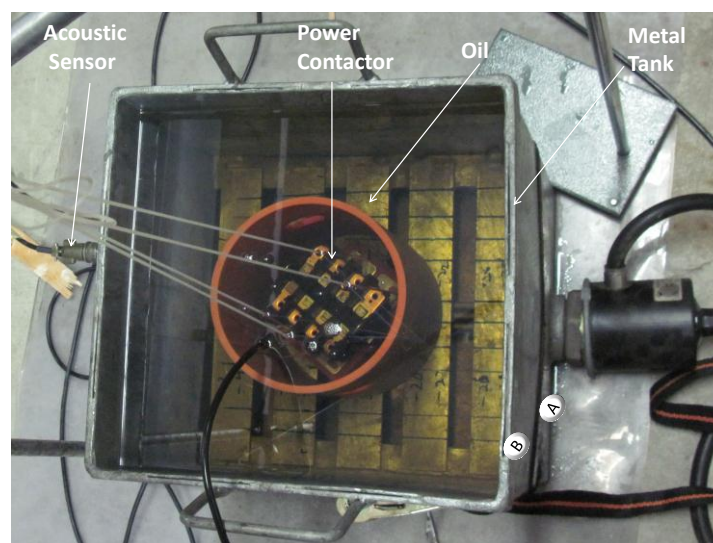


Figure 3.6 showing the setup to test the effect of sensor position

### 3.3.1 Observations and analysis

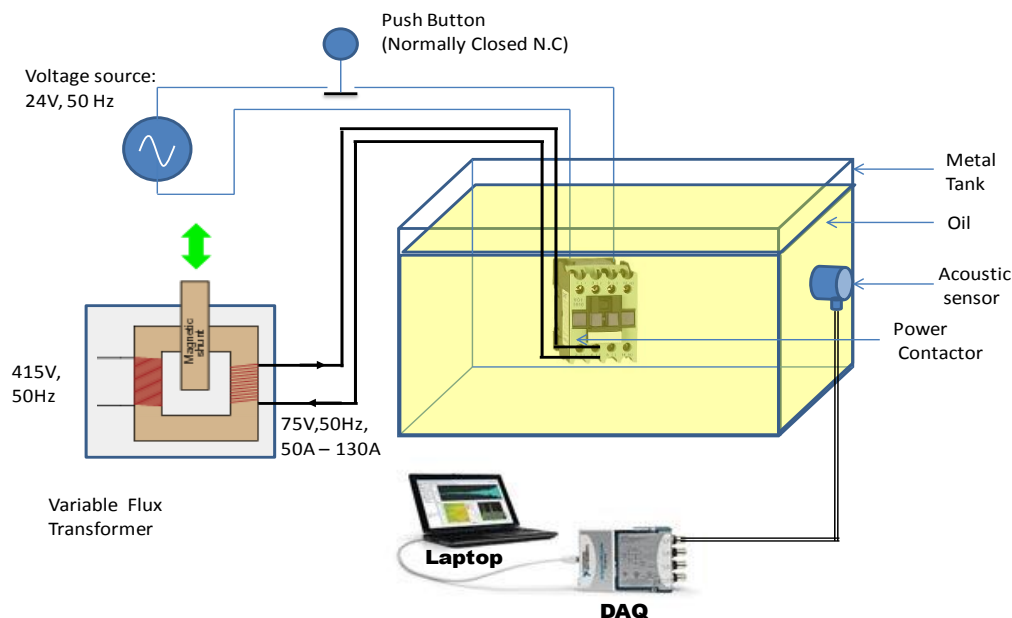
As it is seen from Figure 3.6 above, there is a high cross correlation factor when the signals obtained from the same position (A or B) were compared, but when the signals obtained from two different positions are compared (one signal from position A compared to another signal from position B), the cross correlation factor goes down significantly.

## 3.4 Arc Characteristics

As discussed in chapter 2 arcing is an undesirable but unavoidable phenomenon inside the tap changer, hence an experimental test set up was created that could produce an arc under oil for a short time. The arc was produced by a variable flux AC transformer so the current can be continuously increased or decreased. One of the advantages of using this transformer is that both the voltage and the current needed to sustain the arc are present. Another advantage of creating an arc using this method is that the arc current is 50 Hz AC, similar to what is present in a real tap changer. The effect of the transformer inductance and transients during the arcing process in the tap changer, and its effect on arcing, has been neglected mainly because we are dealing with the acoustic measurements of the arc and not the direct current or voltage measurement of the arc.

### 3.4.1 Laboratory set-up and measurement procedure

In order to study the acoustic characteristics of the arcing phenomena the set up shown in Figure 3.2 is modified. As mentioned earlier, the power contactor used in the experiment contains only one set of contacts, these contacts are connected to a variable flux transformer which is capable of providing an AC current of about 130 amps. The push



**Figure 3.7 Schematics showing setup for arcing.**

button in this case is a normally closed pushbutton so the power contactor is actuated (on) during normal conditions and its contacts are closed (shorted), but when the push button is pushed the current to the power contactor is interrupted and its contacts open. When the

contacts of the power contactors open, a current of about 120A is interrupted at the point of contact opening and an arc is created on the contacts. This arc sustains itself for a short time (<10 milliseconds) before the cooling action of the oil quenches the arc.

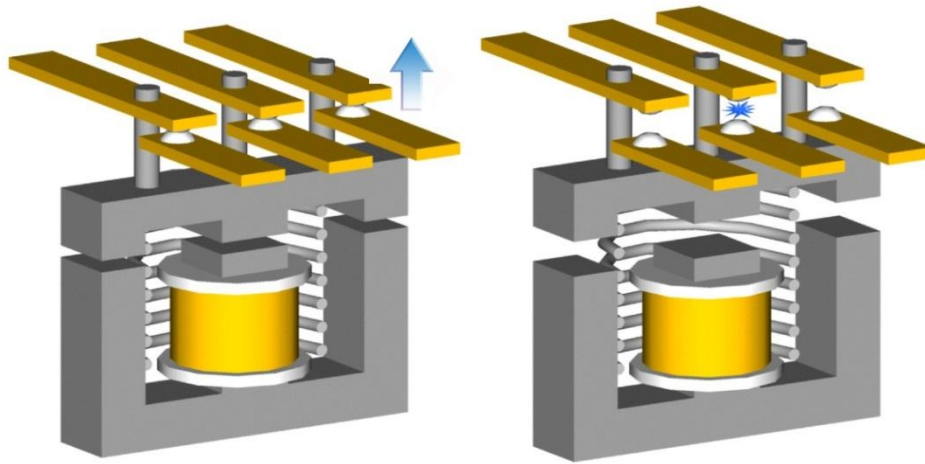


Figure 3.8 Simulation of arcing in a Power contactor [13].



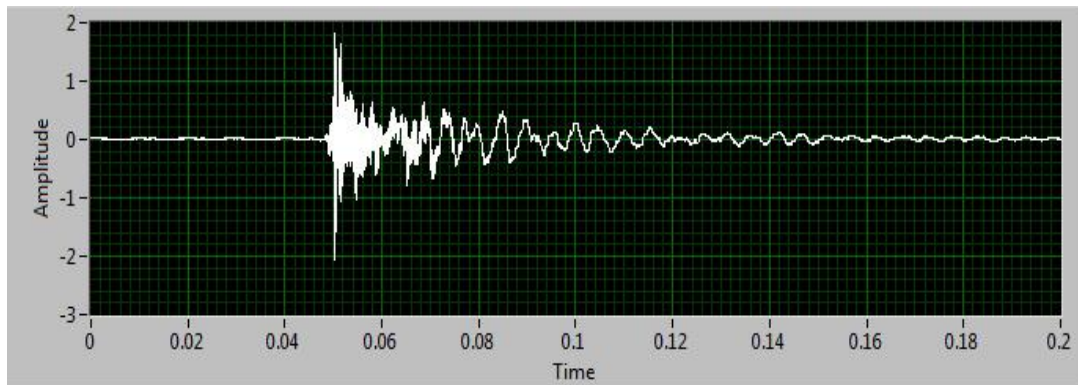
Figure 3.9 : Arc as seen in the laboratory setup for arcing.

### 3.4.2 Analysis procedure

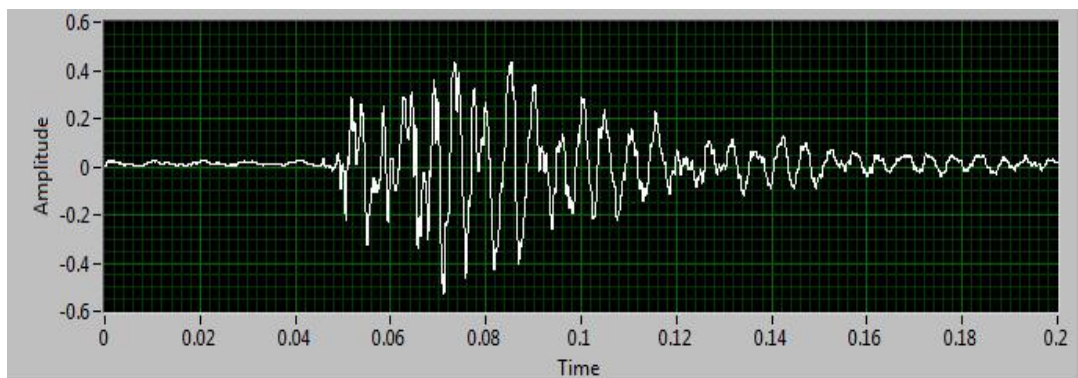
The processing and analysis of the signals is done in the same way as in section 3.2.2 and the cross correlation function for a set of signals is obtained. The values of the cross correlation function for the signal with arc are tabulated below:

| <i><b>Trial no</b></i>          | <b>1</b> | <b>2</b> | <b>3</b> | <b>4</b> | <b>5</b> |
|---------------------------------|----------|----------|----------|----------|----------|
| <b>Cross correlation factor</b> | 0.109633 | 0.33650  | 0.359057 | 0.3024   | 0.30428  |

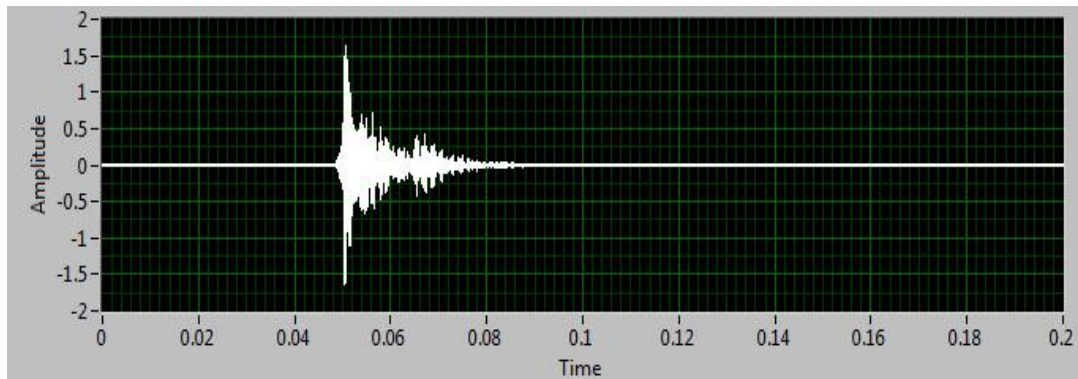
As seen above, the cross correlation factor changes from an average of 0.9 (in case of acoustic signal produced only by contact motion) to an average of 0.3 in case of arcing contacts. In order to understand this phenomenon a comparative study of the two signals was done and it was observed that in the arcing contacts there was an increase in the high frequency components (in this case 2kHz to 10kHz) in the signal. To study this phenomenon, the high and the low frequency components in the signal needed to be separated. For doing this a software filter (Butterworth filter of order 8) is applied to the signal. Shown below is the change in the shape of the signal on application of a low pass filter (upper cut off frequency of 2kHz) and a high pass filter (lower cut off frequency of 2kHz).



**No Filter**



**Low Pass Filter 0-2 kHz**



High Pass Filter 2 kHz –  $\infty$

Figure 3.10 Snapshots of waveform on the application of a filter.

### 3.4.3 Observations and analysis

The table below shows the average cross correlation and the change in cross correlation as the filters are applied.

| Filter                   | None    | Low pass | High pass |
|--------------------------|---------|----------|-----------|
| Cross correlation factor | 0.37803 | 0.71854  | 0.119129  |

The cross correlation factor between two signals that have been filtered by a 2 kHz low pass filter is much higher than that compared the cross correlation factor of the unfiltered signal and it is also evident is that the signal that has been filtered by the high pass filter has a very low cross correlation factor. Although cross correlation factor is a good tool for comparing the shapes of the signals it is not a very convenient tool to analyze the high frequency signals because the shape of the high frequency signals obtained from the same source may differ from one signal to another. To compare signals obtained from the same source over a number of trials, such a parameter was needed that would stay relatively constant over a number of trials. As another exercise, an envelope of the high frequency signal was taken and then the cross correlation factor was obtained from this envelope, on doing this the cross correlation factor goes up to an average of about 0.7 but since most of the frequency content in the signal is lost on taking the envelope, this method was shelved and it was decided that the frequency content of the signals be analyzed rather than the shape of the waveform.

### 3.4.4 Study of contact sound characteristics in the frequency domain

In order to determine how the energy distribution of the signal changes with time a spectral map with color map display was used. A spectral map is a three-dimensional display and a color map displays spectral map as an intensity graph. The X axis represents the time and the Y axis represents the frequency, different colors on the plot represent the signal power distribution. This color map plotting uses the build in color map functionality in LabVIEW. The parameters used for developing this color map are:

- The step size specifies the time between two spectra, the smaller the step size, the finer the color map display.
- Window type: it specifies the type of window used for spectral calculation, e.g. Gaussian etc.
- Window length specifies the length of the window to apply to the color map. Window length must be a power of two and greater than or equal to 128.

| <i>PLOT</i>    | <i>Step Size</i> | <i>Window Type</i> | <i>Window Length</i> |
|----------------|------------------|--------------------|----------------------|
| Frequency time | 10 $\mu$         | None               | 128                  |

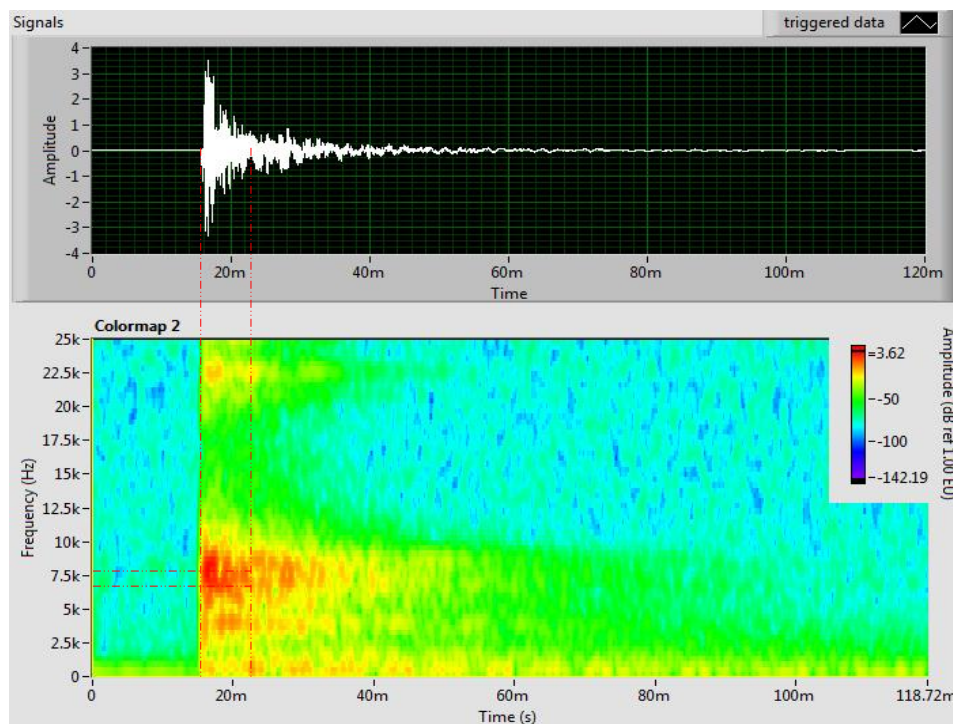
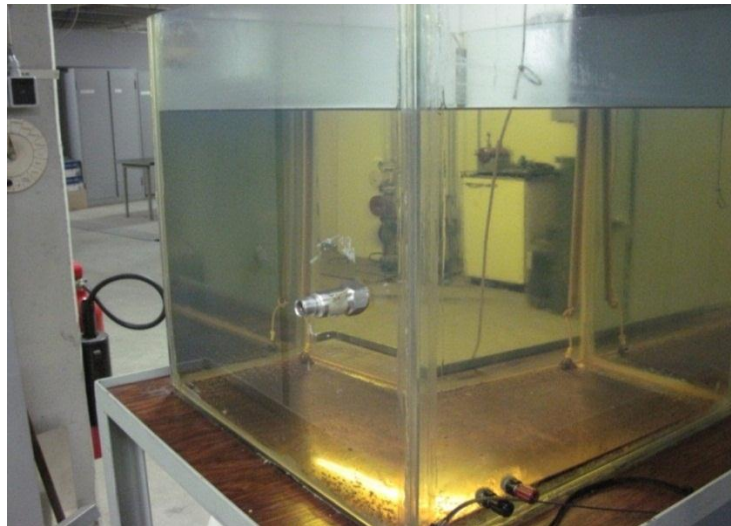


Figure 3.11 Color map representation of the waveform

In the color map above it is observed that on considering a band, shown in dotted red lines, for frequency and time length (corresponding to a 70 percent or greater decay in signal amplitude), the energy content of the signal does not change much with time. This energy content can be seen in Figure 3.11 above as a concentration in red inside the intersection of the two bands. It is also observed that there is a high concentration of energy at 22.5 kHz and this phenomenon is seen to repeat in all the readings. One of the reasons for this was believed to be the resonance of the system due to the combination of the volume of the oil and the metal tank, so in order to verify the validity of this hypothesis another experiment was conducted.

### 3.5 Experiments to study the effect of oil volume and tank material

For this experiment a tank made of glass was chosen with a larger quantity of oil, and the tests with the arcing contacts were repeated in the same procedure. Shown below is the setup in the glass tank. It was expected that if resonance was the cause of the high concentration of energy at 7.5 kHz and 22.5 kHz on the color map display than using a larger volume of oil (100 liters) with a tank of a different material, would shift these concentration of energy at 7.5 kHz and 22.5 kHz on the color map display to a different frequency.



**Figure 3.12 Showing the glass tank used for the experiment .**

On analyzing the obtained signal it was found that the color map is exactly the same as the one obtained in the metal tank. So the possibility that resonance is causing the peaks (shown in red in Figure 3.11) can be dismissed.

As the sensor used in the experiments had an optimum frequency response from 0.8 Hz to 15 kHz  $\pm 3$  dB but in the color map frequency contents much higher than 15 kHz are

observed it was decided to switch to a different sensor with a higher bandwidth to study the arcing phenomenon.

## 3.6 Experiment with 15 kHz to 60 kHz sensor

The Sensor now used is an IEPE sensor, D9241A from Physical Acoustic Cooperation (PAC). This is a high sensitivity sensor with low noise differential output. Since this is not an IEPE sensor it needs a power supply and a charge preamplifier. The specifications of the measuring instruments are mentioned below. Now instead of acquiring the signal on a DAQ the signal was acquired on a scope. This was done for two reasons:

- The sample rate of the available DAQ was limited up to 50 ksa/s, so according to the Nyquist sampling theorem "The sampling frequency should be at least twice the highest frequency contained in the signal. Or in mathematical terms:  $f_s = 2 * f_c$  where  $f_s$  is the sampling frequency, and  $f_c$  is the highest frequency contained in the signal [13]. Therefore having a sampling rate of 50KS/s limits the frequency range for the measurements to about 25 kHz whereas the sensor (D9241A) is capable of acquiring up to 60 kHz frequencies.
- Another reason is that it is not possible to synchronize two channels of the DAQ being used over a common software trigger [38]. Thus, also a hardware trigger will be required in future experiments and as mentioned earlier it is not possible to hardware trigger the DAQ.

| <i>Sensor Characteristics</i>       |                            |
|-------------------------------------|----------------------------|
| Sensor Model                        | D9241A                     |
| Shock Limit (g)                     | 500                        |
| Case Material                       | Stainless Steel            |
| Face Material                       | Ceramic                    |
| Peak Sensitivity dB                 | 85 [-70]                   |
| Operating Freq. Range (kHz)*        | 15 to 60                   |
| Resonant Frequency (kHz)            | 30                         |
| <i>Oscilloscope Characteristics</i> |                            |
| Model                               | Leroy Wave runner : LT584L |
| Bandwidth                           | 1GHz                       |
| Channels                            | Four                       |
| Sample Rate/Ch.                     | 2GS/s                      |
| Maximum Sample Rate                 | 4GS/s                      |
| <i>Amplifier and Power Supplies</i> |                            |
| Charge Per amplifier                | PAC 1220A                  |
| Voltage support                     | AIA                        |

\*This is the Frequency Range that the Sensor has the highest sensitivity. However, the Sensor can operate in other frequencies around this range.

### 3.6.1 Laboratory Set-up and Procedure

The schematic in Figure 3.13 shows the connection using the new sensor (D9241A), the setup was kept the same as in section 3.4.1 except the measurement setup shown in dotted lines. The tests in the metal tank and glass tank are repeated again and the acquired waveforms are compared using color maps.

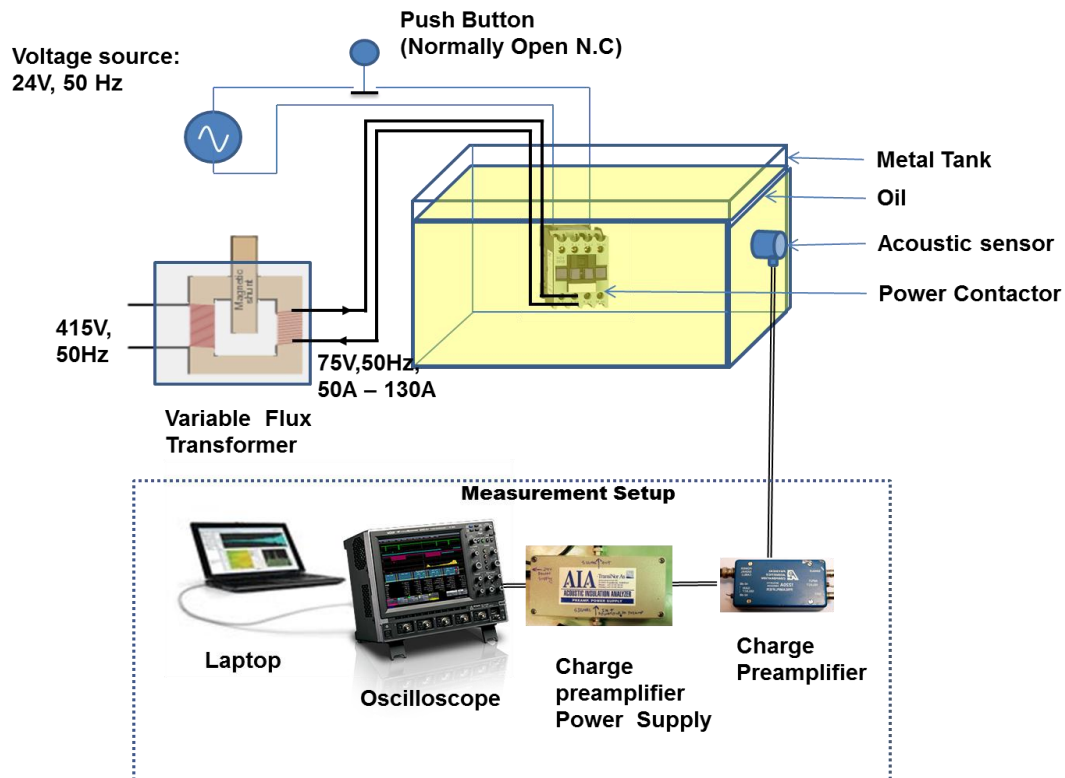
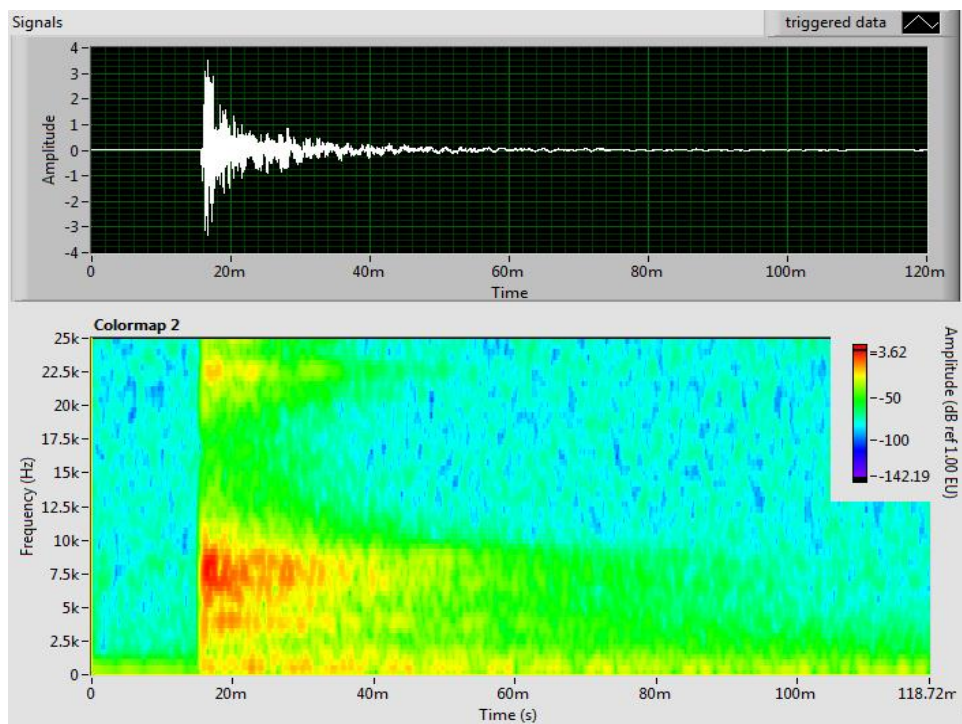


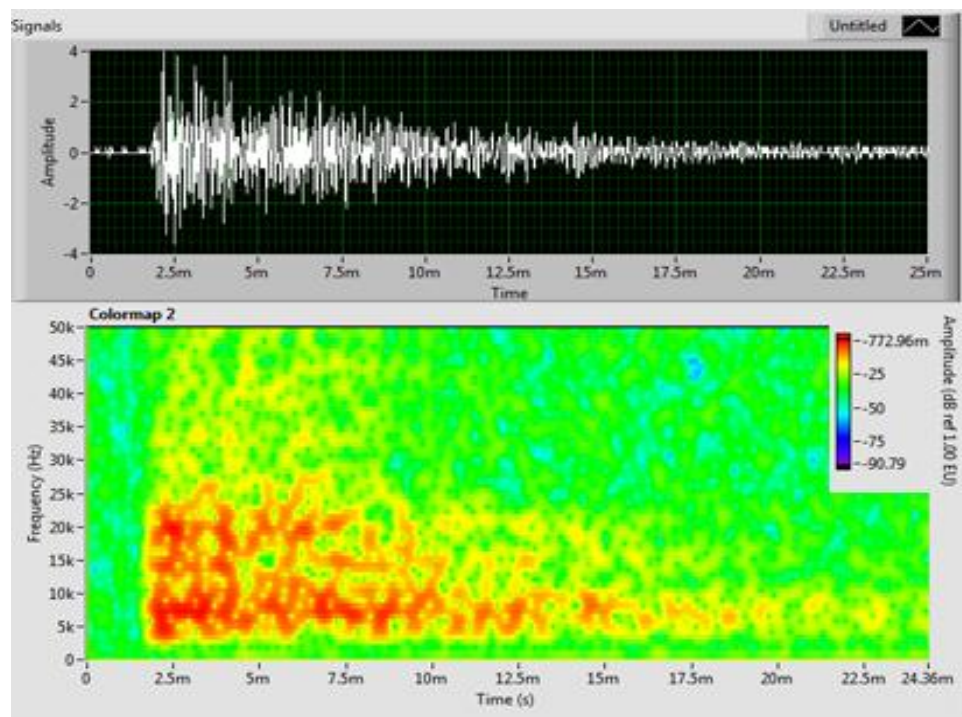
Figure 3.13 : Schematic setup for measurement with the new (10-60kHz) sensor

### 3.6.2 Experiments and Results

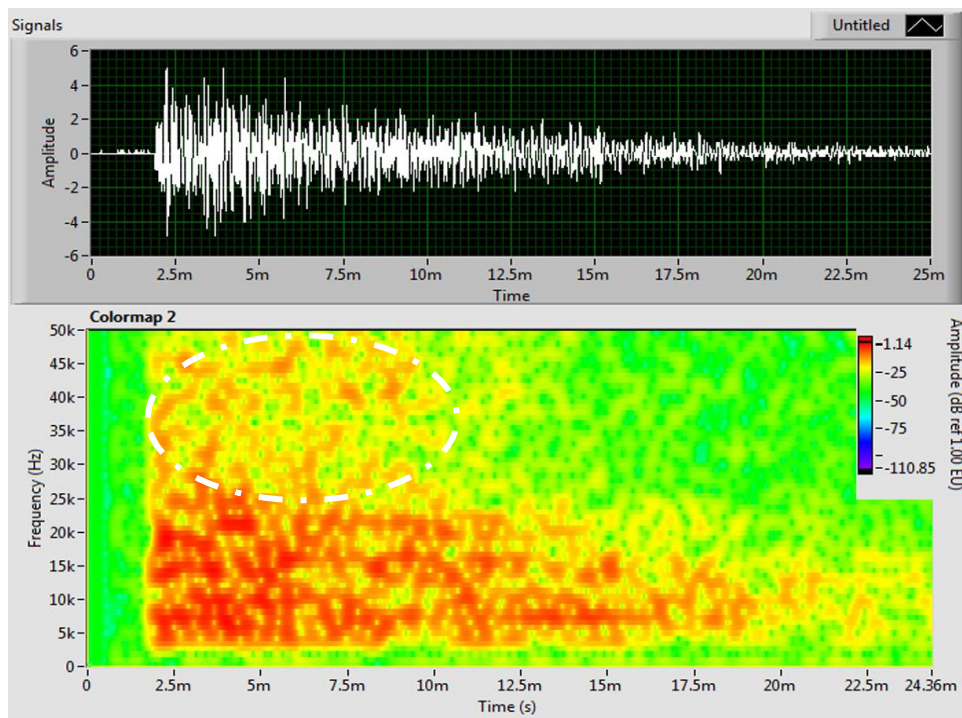
Shown below are the spectral maps with color map display first for a signal obtained by the normal contact movement and afterwards with a current of 120A flowing through the contacts and creating the arc.



Normal Contact Movement without arc and HS-100 Series Vibration Sensor



Normal Contact Movement without arc and D9241A Sensor



### Contact Movement With an arc (of 120A) with D9241A Sensor

**Figure 3.14 Comparison of the signals and color maps obtained from normal contact movement and arcing contacts.**

On comparing the signals on Figure 3.14 it is observed that all three signals have average amplitude of about 2v. On comparing the color map displays of the signals measured from the D9241A sensor (with arc) with the color map of the signal obtained from normal contact movement (without arc), an increase in the amplitude of the higher frequency components of the waveform is observed (as shown in white) in case of the color maps obtained from the signals measured from the D9241A sensor.

Also comparing the above two color maps with the color map obtained from the HS-100 Series Vibration Sensor in case of Normal Contact Movement (without arc) it can be seen that the frequency spectrum is quite different and the bandwidth of measurement is limited to 25 kHz.

## 3.7 Summary

The experiments in this chapter were conducted to determine the characteristics of the acoustic signal from a small test object that replicated the behavior of a tap changer and to provide for a basis of measurements in chapter 4.

In the above experiments the characteristics of the acoustic signal obtained from impact of two copper-tungsten contacts were determined and observations were done to determine, if there were any features that repeated consistently with the signals.

In the first experiment, to determine the characteristics of the shape of the acoustic wave, the cross correlation factor which indicates the difference in shape of the signals was used. It was observed that the waveforms have a high cross correlation factor hence the shape of the signals remain the similar over a number of trials.

The next experiment in section 3.3 was conducted to determine if changing the position of the sensor had an effect on the waveform shape, and a difference was observed in cross correlation factor, so in future sets of experiments the position of the sensor was kept constant till all sets of readings were completed.

To study the arc characteristics the cross correlation factor was used as a tool but it was seen that the cross correlation factor dropped when the tests were repeated with the contacts arcing, one of the reasons attributing to this drop was speculated to be the high frequency (>2kHz) components present in the waveform and to support this hypothesis digital filters were applied to process the signal before calculating the cross correlation factor and an increase in the cross correlation coefficient was observed on comparing the low frequency components of the signal, but the cross correlation coefficient decreased significantly on comparing the high frequency components, present in the signal.

It was also observed that a high frequency band of about 22.5 kHz is dominant in all the signals and resonance of the system was suspected to be a cause but on conducting the experiment on a different setup the same phenomenon was seen to be repeating so it was confirmed that high frequency components are present.

Hence this observation led to the choice of a higher bandwidth sensor (D9241A) for the measurements. Further, a difference was observed in the spectral color maps showing an increase in the amplitude of the higher frequency components in case of arcing contacts. Therefore, for the measurements reported in the next chapters the D9241A was used.

# Chapter 4: Experiments on a single phase tap changer

## 4.1 Introduction

This chapter deals with measurements on a single phase tap changer. For outlining the experiments on this single phase tap changer the observations that were made in chapter 3 are used. The first part of the chapter deals with determining the best method for the analysis of the signals in the frequency domain. The second part of the chapter deals with the analysis of the data obtained from the various defects and analysis of the arcing phenomenon in the tap changer. Some studies mention the frequency bandwidth of the acoustic signals obtained from various defects [35], these experiments were also done with an intention of verifying these findings.

## 4.2 The single phase tap changer

The single phase tap changer used in these experiments was a part of another setup used for "On-load Tap Changer Diagnosis on High-Voltage Power Transformers using Dynamic Resistance Measurements" [3]. The setup was modified to fit the requirements of acoustic measurements. Shown below in Figure 4.1 and Figure 4.2 are the stator and rotor of the tap changer. In the single phase tap changer that is available, there are nine contacts "C" mounted on the stator "S" and a neutral ring "N". The rotor "R" goes inside the stator "S" and is held in the center by the top cover "Tc" and bottom cover "Bc" and the transition resistance is highlighted as " $\Omega$ ".

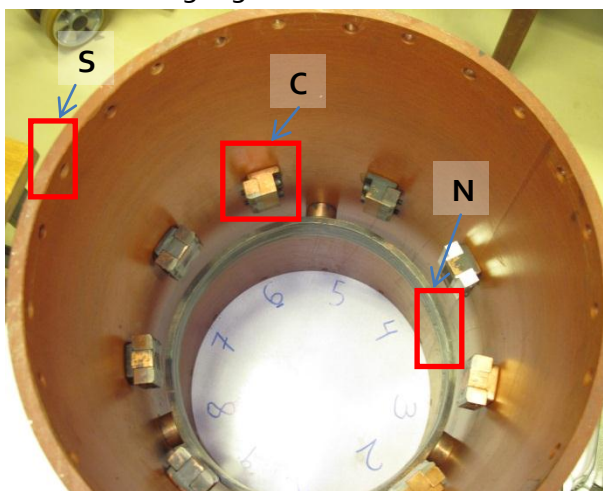


Figure 4.1: Rotor of the single phase tap changer.

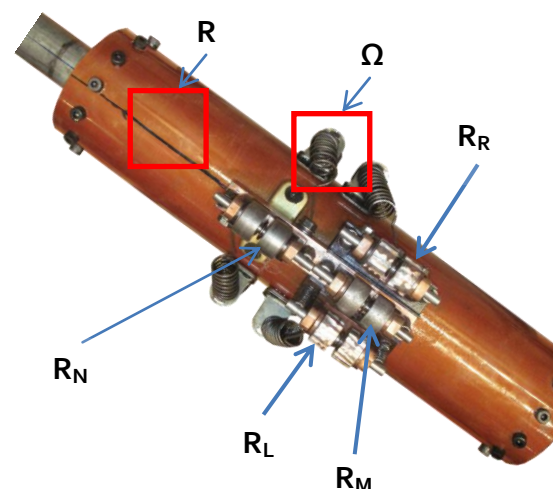
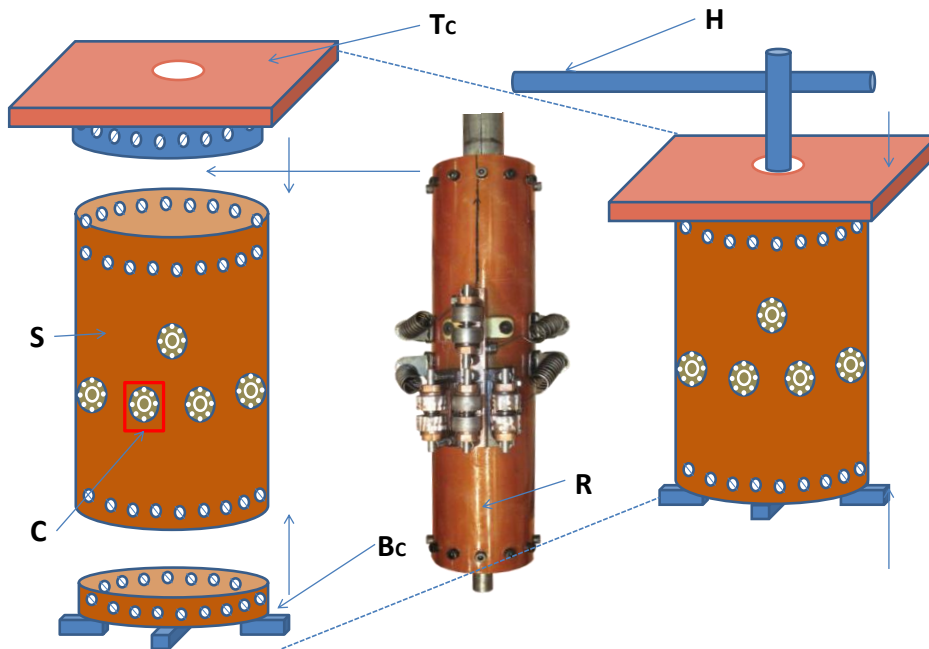


Figure 4.2 :Stator of the single phase tap changer.

The roller contacts, R left ( $R_L$ ), R middle ( $R_M$ ), R right ( $R_R$ ) make tight contact with the stator contacts "C" and the neutral roller contact, R neutral ( $R_N$ ), makes contact with the neutral ring "N". Shown below in Figure 4.3 is the assembly of the test setup. The modification made to the original setup is the inclusion of a large top cover "Tc". This enables the tap changer to rest on the Tc instead of resting on the bottom Cover "Bc", this change brings our setup closer to a normal tap changer where the tap changer is hanging from the top of the transformer [1].



**Figure 4.3: Schematic showing the assembly of the single phase tap changer.**

Also added to the setup is a long handle "H" that enables us to turn the rotor in order to replicate the tap changer movement. The process of turning the rotor with the handle is manual as attempts to make it an automatic process and rotating it with a motor and spring proved very difficult to build. Due to the manual movement, the timing of rotor movement varies with each motion, to overcome this problem a circuit was designed and build to accurately measure the timing of transition of the roller contacts and this is discussed in detail in the section below of dynamic resistance measurements.

Shown in Figure 4.4 and Figure 4.5 below, are images of the setup brought together. The assembled tap changer is put in a drum "D" and filled with oil, and as described above Tc rests on the "RIM" of the drum "D".

Attached to the drum is the sensor SE1 (D9241A) as it was decided in chapter 3 to use the higher frequency sensor (15kHz to 60kHz).

#### 4.2.1.1 Dynamic resistance measurements

As mentioned earlier this setup is hand operated. Hence, in order to get the exact position of the rotor contacts, (a typical sequence of events during one tap movement of a fine selector switch is described in section 2.2.2.1 of chapter 2) dynamic resistance measurements (DRM) need to be conducted. Having a reference of events occurring in the tap changer, an acoustic signal can be superimposed on the time reference to pinpoint exactly which event caused the acoustic signal.



Figure 4.4: Showing the stator and top cover.



Figure 4.5: Showing the connections and sensors.

The process of dynamic resistance measurement is, the measurement of the change in current across a shunt  $R_{sh}$  which manifests as a change in voltage [40]. In this setup all the contacts through which current is fed into the single phase tap changer have been shorted, and the return path for the current is through the neutral ring. The sequence of events has been split into four parts and the sequence repeats itself after 4. The sequence of events, 1 to 4 shown in blue, in Figure 4.6 shows how the current path changes through the contacts and how the DRM graph is obtained. For each event the formula for the voltage across the shunt  $V_{sh}$  is mentioned, it is seen that the formula for  $V_{sh}$  changes as the tap changer moves from one tap to another. When the value of  $V_{sh}$  is plotted against time a DRM graph is obtained and from this plot the time period of events 1 to 4 can be determined. Shown below in Figure 4.7 is the DRM graph obtained from an actual three phase, spring actuated tap changer and it can be seen that the entire process of  $R_m$  leaving tap  $n$  and touching tap  $N+1$  takes about 70 milliseconds.

Although this is a very accurate method it cannot be directly applied to a real transformer as there is the presence of the transformer windings connected to the tap changer which will cause large transients in the readings when the current in the tap changer is interrupted because of the largely inductive load of the transformer winding [3].

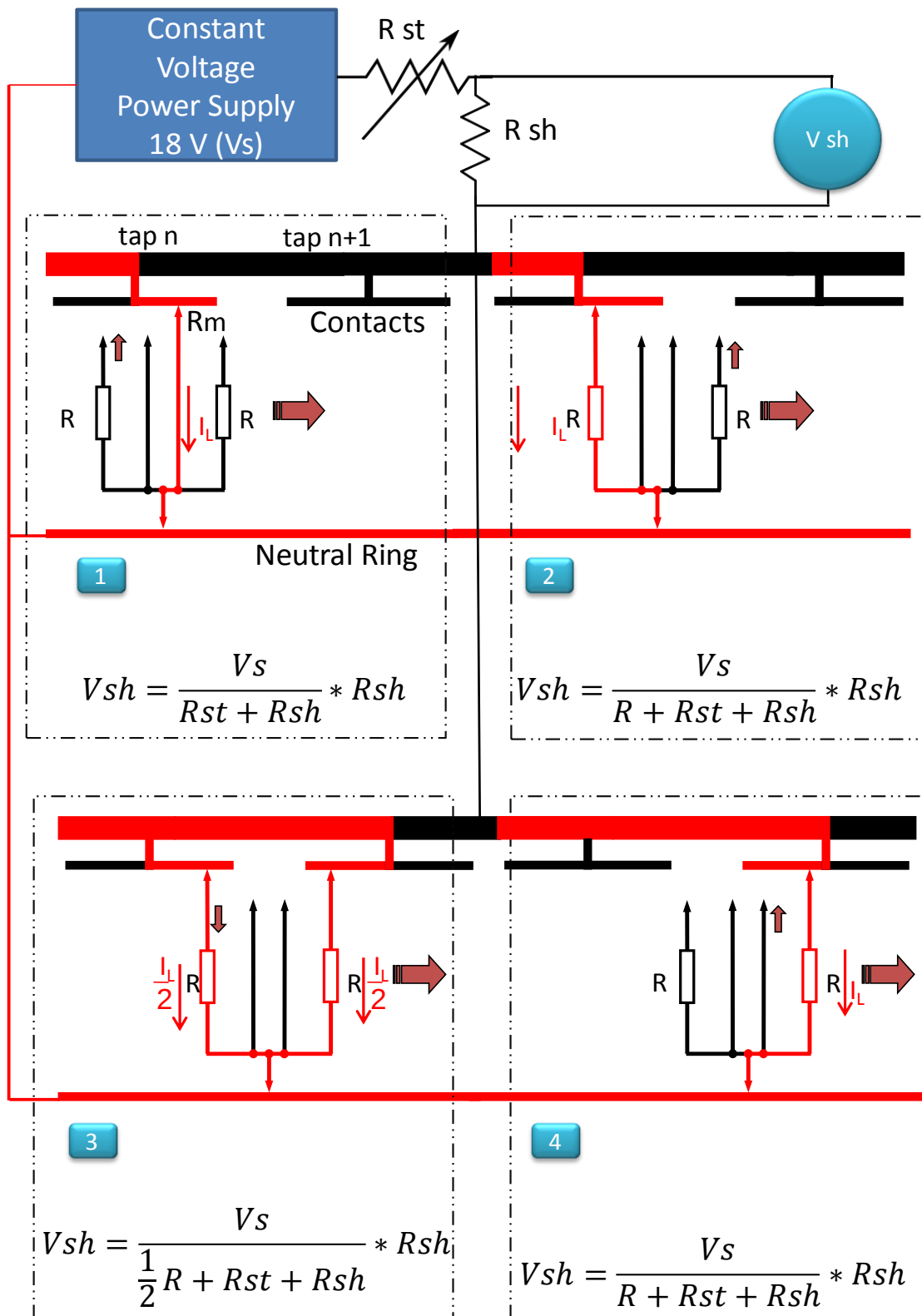


Figure 4.6: Sequence of events for the dynamic resistance measurements [40].



Figure 4.7 : DRM graph obtained from an actual 3 phase, motor and spring actuated tap changer.

## 4.2.2 Laboratory set-up and procedure for DRM & Acoustic measurements

The setup described below in Figure 4.8 is similar to the one described in chapter 3. Here the metal tank is replaced by a metal drum filled with oil which holds the single phase tap changer. For our measurements the D9241A sensor from PAC was used along with the measurement setup as shown below. The connections of the DRM unit are made to the single phase tap changer as shown below and the DRM graph was obtained on one of the channels of the scope. The acquisition is triggered by the change in the DRM graph and in this way a combined plot of the DRM graph and acoustic signal due to the movement of contacts in the tap changer is obtained. For these sets of experiments the set of “good contacts” as described in chapter 2 section 2.3.6 were used.

Shown in Figure 4.9 is the sequence of events. This sequence of events has been described in detail in chapter 2 section 2.2.2.1, so here only the acoustic waveform in green and the DRM waveform in blue are disused with respect to the events:

In order to define the motion of a single tap change it is considered that the rotor is moving anticlockwise. The motion is being observed from the top (top view), and the direction of observation (front view) is from the rotor towards the stator. The contact numbering is  $N$ ,  $N+1$ , and  $N+2$  etc. in the anticlockwise direction.

- Event 1 when the left roller contact  $R_L$  “strikes” the contact  $N$ .
- Event 2 when the middle roller contacts  $R_M$  leave  $N$ .
- Event 3 when the right roller  $R_R$  “strikes” the contact  $N+1$ .
- Event 4 when the Right roller contacts  $R_R$  leave  $N$ .
- Event 5 when the middle roller contact  $R_M$  “strikes” contact  $N+1$ .

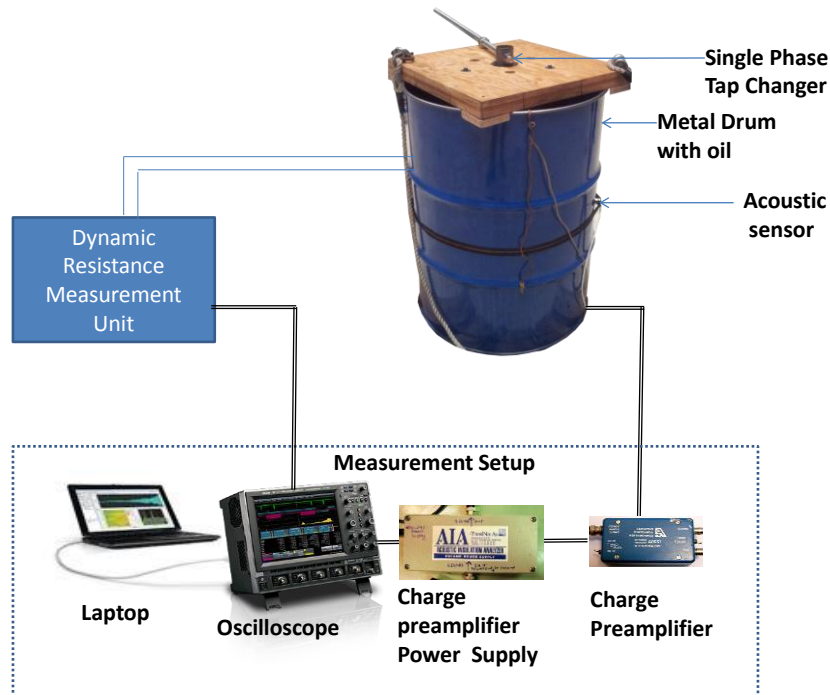


Figure 4.8 : Schematic showing the setup for the DRM and Acoustic signal measurement.

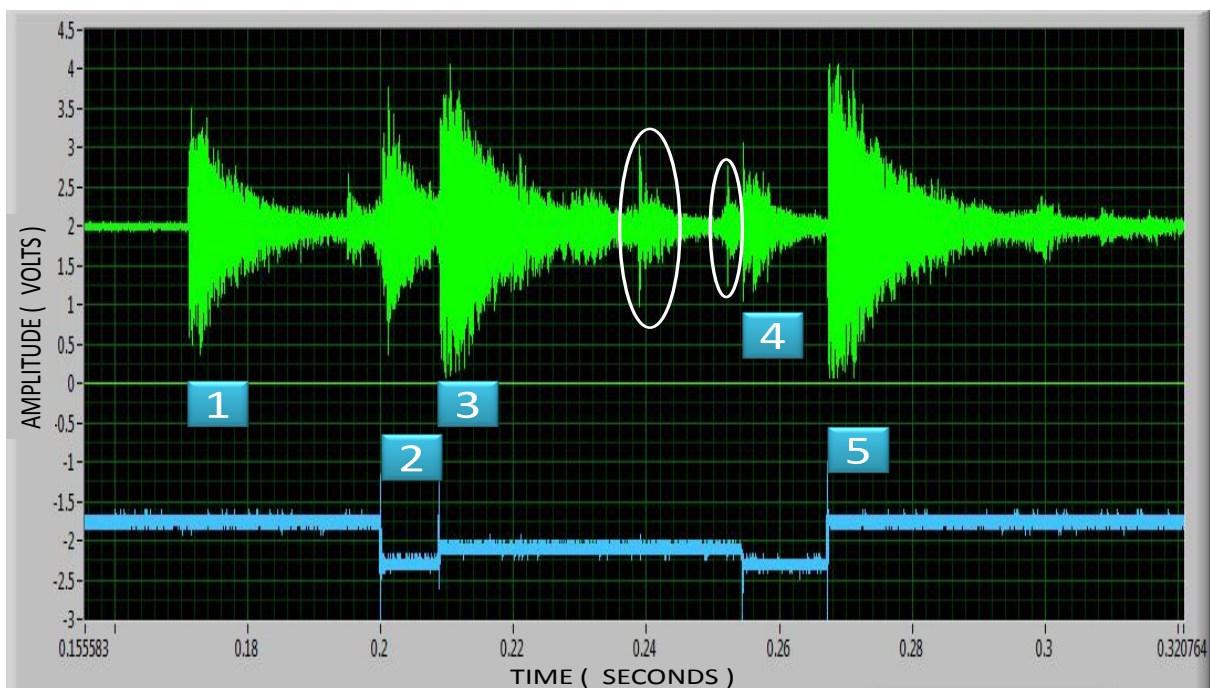


Figure 4.9 : Showing the DRM graph (in blue) along with the acoustic signal (in green) and the sequence of events (1 to 5).

#### 4.2.2.1 Analysis of the waveform

Examining Figure 4.9 above, the acoustic waveform shown in green, is created by the movement of rotor contacts over stator contacts, and has a maximum amplitude of about 2 volts. A DC offset of 2 volts can be observed, this offset has been added to the waveform just for displaying the acoustic waveform separately from the DRM waveform. A

similar negative offset has been added to the DRM waveform, although during signal processing the offset is removed.

The signals are perfectly aligned with the DRM waveform, but the amplitude of the signals changes during the whole sequence of events (1 to 5). This can be explained by the fact that the magnitude of the acoustic signal produced by the action of the roller contacts of the rotor striking the stator contacts is higher than the magnitude of the acoustic signal produced by the action of the roller contacts of the rotor leaving the stator contacts. As summarized above the events 1, 3 and 5 are the rotor contacts striking the stator contacts whereas, events 2 and 4 rotor contacts leaving the stator contacts. Also seen (in white highlight) are other signals which do not coincide with the DRM waveform. To explain this, the motion of the tap changer was studied. The most probable reason for this is the set of contacts  $R_n$  (shown in Figure 4.2) that also move along the neutral ring when the tap changer is moved so this movement could cause these unwanted waveforms.

In the analysis of the waveforms in chapter 3 the cross correlation function was used but it was found that it is not an effective analysis tool when high frequency ( $>2\text{kHz}$ ) signals are concerned, then the analysis in the frequency domain was done using 3D Spectral color maps and it was found out that the frequency content of the signal does not change much with time.

When the same algorithm as previously used for plotting the 3D color map was used for the acoustic signals obtained from this setup, the simulations took a very long time (20 minutes) to compute and ended up in error most of the time. This could be due to the large number of data points used in the acquisition (500kS/s for a time length of 1s), hence another method for analysis was required.

Another necessity for a better method was that a large number of signals were obtained for each tap change movement performed and a program was required that could consolidate the data from all these readings into a single quantifiable output file so that the results from all the readings could be compared. Since it was found that information in the frequency domain was of interest, an algorithm based on this was build. The algorithm first computes the FFT of the given signal (X axis is the frequency and Y axis is the amplitude) and normalizes it in such a way that the highest amplitude of the spectrum is one. This is done by searching the signal with the highest amplitude in the spectrum and dividing the whole spectrum by this value. The algorithm then searches for all the peaks above a certain user defined threshold and arranges the peak location (frequency and amplitude) information in an array. The data obtained is stored in a file and the algorithm repeats itself for another file but stores all the data obtained as points in a single file so that they can be plotted together. Shown below in Figure 4.10 is the schematic of the functioning of the algorithm.

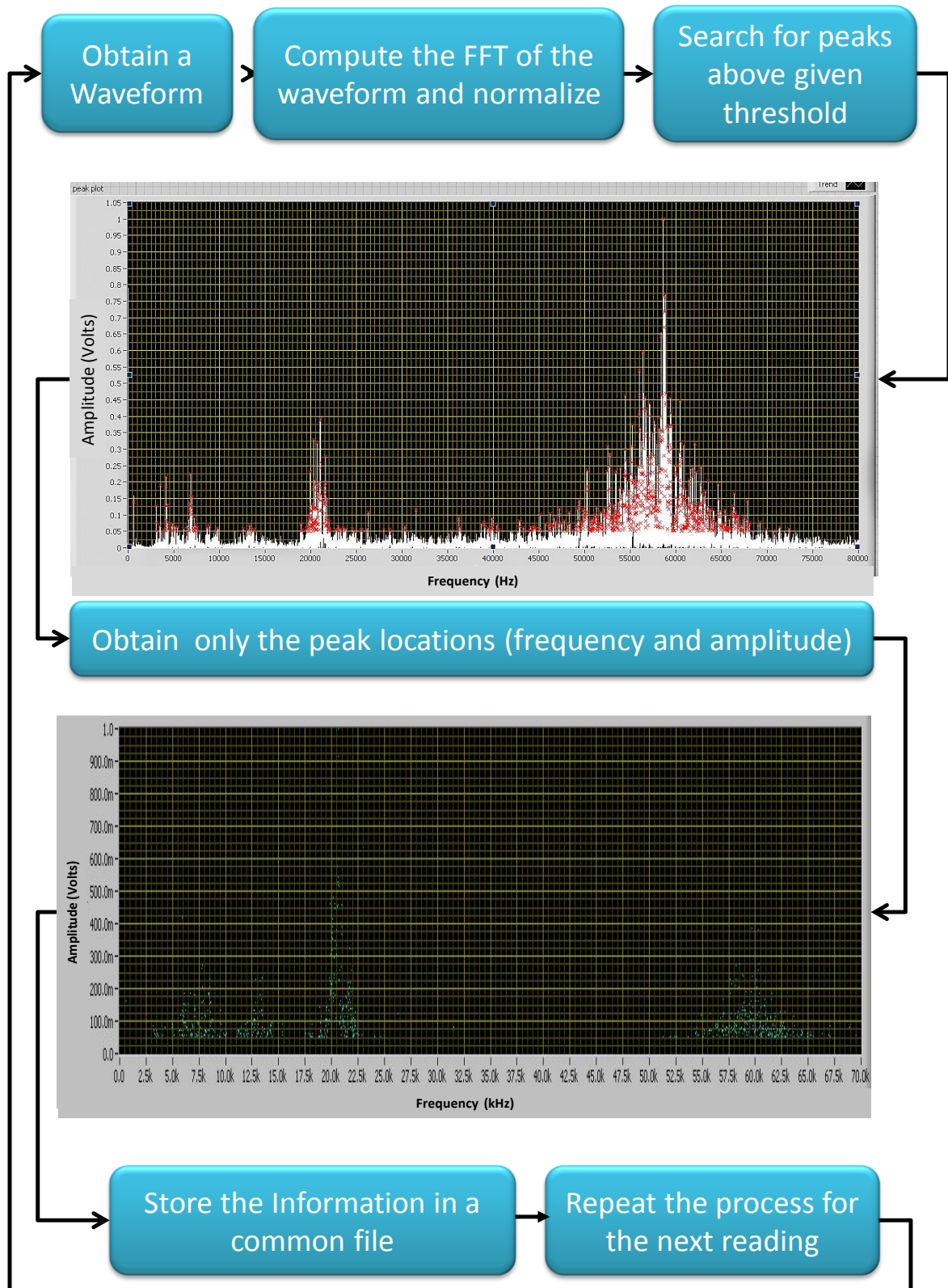
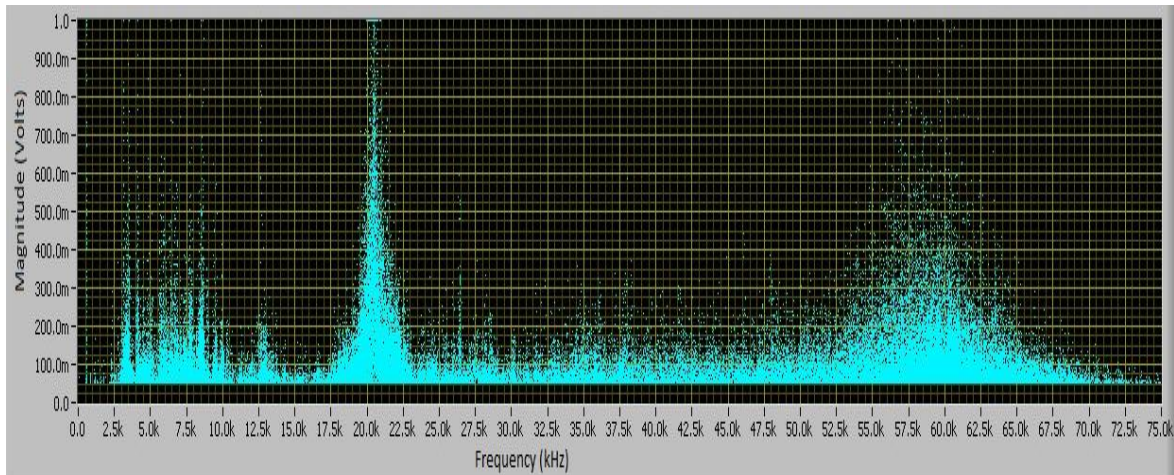


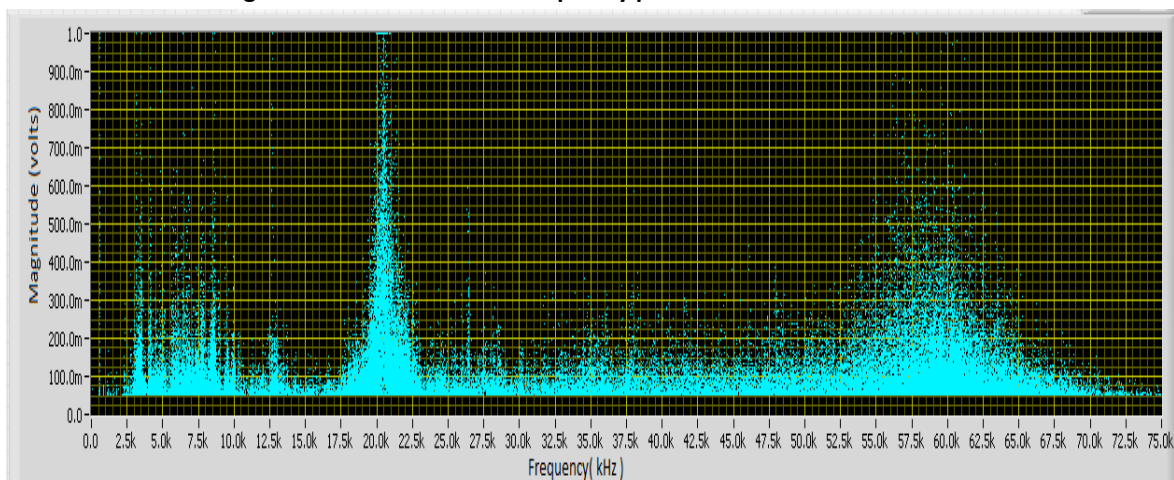
Figure 4.10 : showing the algorithm for frequency analysis.

### 4.2.3 Results for the analysis of acoustic signals

The analysis was repeated for the two types of contacts, "Good" and "Bad" with a large number of readings. The obtained data for all the files were collected and plotted. On comparing the plots it is seen that they are almost the same for the two types of contacts, "Good" and "Bad", as the peaks in the spectrum appear almost along the same frequency band.



**Figure 4.11 : Consolidated frequency plot for the "Good" contacts.**



**Figure 4.12 : Consolidated frequency plot for the "Bad" contacts.**

Since no difference is seen between the plots in Figure 4.11 and Figure 4.12 above a different method for analyzing the waveforms was needed. When the Power V/s frequency plot of a single acoustic signal, obtained from a good contact and bad contact are compared, a notable difference could be observed. When the Power V/s frequency plot, obtained from good contact and bad contacts, of many signals were combined together and plotted as shown above the difference in the Power V/s frequency spectrums disappeared. Two main factors were assumed to be the cause of this discrepancy.

- The normalization of the frequency spectrum changes the highest amplitude of the frequency spectrum to one and when the peak search algorithm searches for peaks in the modified frequency spectrum and when all the peak points are plotted together as in Figure 4.11 and in Figure 4.12 the distinction might be lost.
- When the frequency spectrum is plotted, the entire acoustic waveform was taken into consideration, which has a number of events but since each event is different from the other it might have caused a difference in the amplitude/frequency spectrum over a set of readings.

## 4.2.4 Modified algorithm for frequency analysis

In order to overcome the problems in the previous algorithm a new algorithm was build taking into account the following:

- It was considered better to normalize the waveform instead of normalizing the spectrum of the waveform as the information about the total energy in the spectrum is preserved when the waveform is normalized.
- Performing the analysis on individual events rather than on the entire set of events.
- Trying to obtain the result in a numerical form which could be compared mathematically rather than obtaining a visual result as in previous cases.

Keeping these in mind, the first factor that was to be dealt with was the normalization of the waveform. The waveform could be normalized with respect to the highest amplitude of the waveform or it could be normalized with respect to the energy of the waveform. It was found out that the normalization with respect to energy works best in our case, this can be proved with an example.

Consider the waveform in Figure 4.13, image (I) shows a raw waveform, image (II) shows the waveform normalized with respect to amplitude of the waveform and image (III) shows the waveform normalized with respect to energy. The same waveform can be seen in Figure 4.14 but with an overshoot at a point (image IV). When this waveform is normalized with respect to amplitude, the average amplitude goes to about 0.25 V (Image V) as compared to 0.5 V in the previous case (image II).

Now when the waveforms are normalized with respect to energy and compared, (image III) and (image VI), It is observable that both the waveforms have an average amplitude of 0.02 V, hence normalization with respect to energy is better as peaks (small overshoots) which are not representative of the actual acoustic signals do not affect the normalization process.

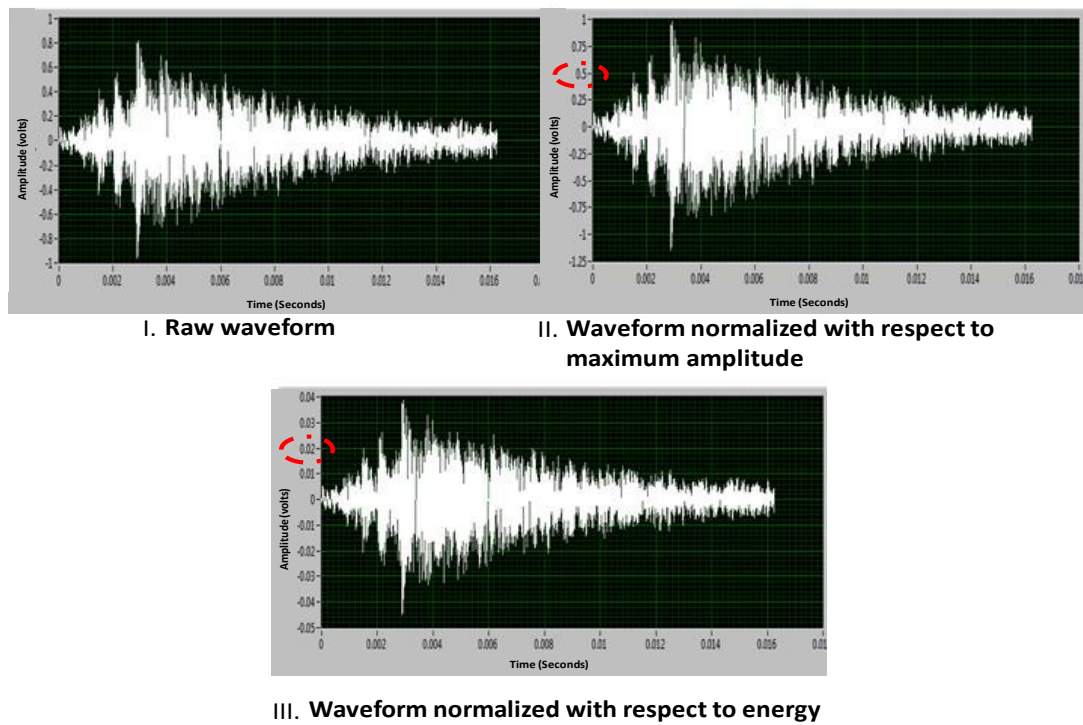


Figure 4.13: Showing the different methods of normalization of a waveform without an overshoot

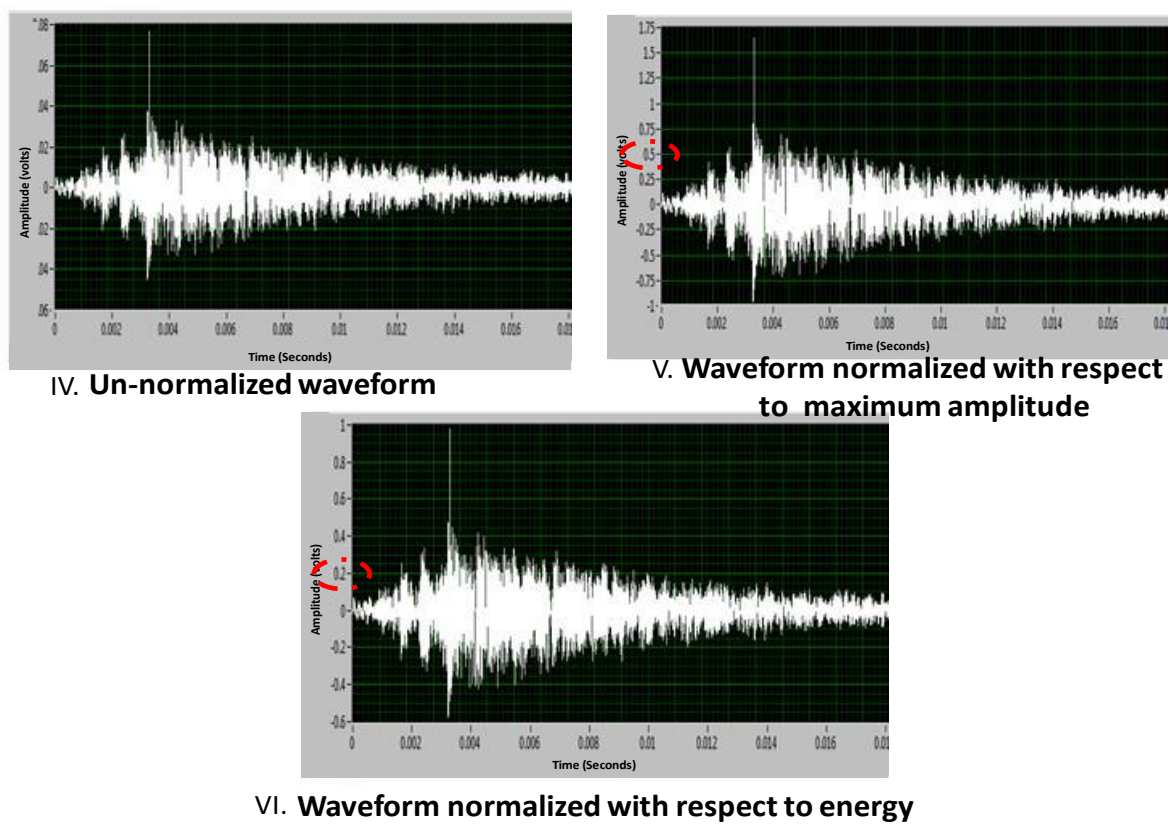


Figure 4.14: Showing the different methods of normalization of a waveform with an overshoot

For normalizing with respect to the energy the signal energy  $E$  must be found. The acoustic waveform being considered here is a discrete waveform with a sampling frequency of 500 ks/S and the signal energy  $E$ , of a discrete time waveform is given by

$$E = \sum_{i=0}^n |x[n]|^2$$

Where  $x$  is amplitude of the sampled signal. The realization of this normalization in LabVIEW is shown in Figure 4.15 below.

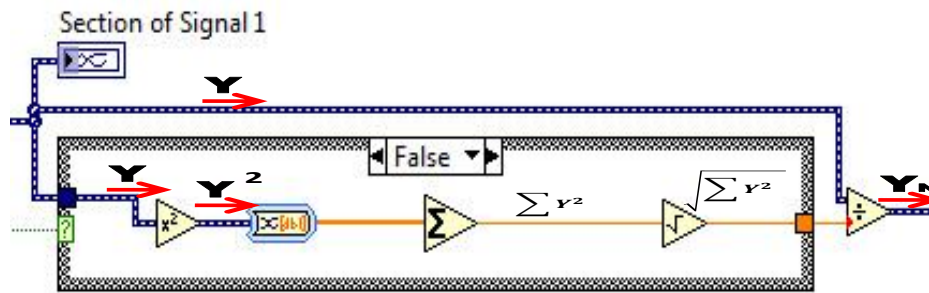


Figure 4.15 : Showing the implementation of normalization procedure in LabVIEW, here the signal is defined as  $Y$  (or  $x[n]$  in discrete form) and  $Y$  normalized =  $\frac{Y}{\sqrt{E}}$

Taking into consideration the point mentioned above: this analysis is performed on individual events rather than on the entire set of events. A portion of the signal is extracted for analysis; this is done manually by specifying the range of data points using two cursors. Then, the extracted portion of the signal is normalized with respect to the energy of the extracted portion of the signal, also the total energy of this normalized signal is always equal to 1. Now the power v/s frequency spectrum is obtained from the extracted portion of the signal.

#### 4.2.4.1 Parseval's Theorem

"Parseval's Theorem states that the total energy computed in the time domain must equal the total energy computed in the frequency domain. It is a statement of conservation of energy.

The following equation defines the discrete form of Parseval's theorem.

$$\sum_{j=0}^{n-1} |X_j|^2 = \frac{1}{n} \sum_{k=0}^{n-1} |X_k|^2$$

Where  $X_k$  is the discrete FFT pair and  $n$  is the number of elements in the sequence. The left side of the above signal is energy of the time-domain signal and the right side of the equation gives us the energy in the frequency-domain signal.

$$1 = \frac{1}{n} \sum_{k=0}^{n-1} |X_k|^2$$

The significance of Parseval's theorem in our algorithm is that, as the total energy of our normalized signal is always equal to 1, according to Parseval's theorem the energy in the computed frequency spectrum is also always 1.

Now the power v/s frequency spectrum is divided into four parts based on frequency bands (shown in Figure 4.19 as A, B, C, D, E) and the power of each part is computed using the left hand side of the above equation

$$f(x) = \frac{1}{n} \sum_{k=0}^{n-1} |X_k|^2$$

This is a fraction of the total power and the sum of the powers of all four parts should be approximately 1. This approximation is because the last portion of the spectrum (E) is neglected as the amount of energy in this band is almost negligible.

By Parseval's theorem:

$$f(x) = f(A) + f(B) + f(C) + f(D) + f(E) = 1$$

$$\text{And } f(E) \cong 0$$

The determination of the frequency bands for the analysis was done by visually inspecting the power/frequency spectrum of numerous signals. It has been observed that the peaks in the power frequency spectrum were seen mainly along four frequency bands as shown below. It noteworthy to observe that the spectrum changes for a set of readings for "good", "bad" and arcing contacts, but the change occurs only in the regions marked with the cursor 0 to cursor 4. Therefore using this observation the five bands chosen are:

$$f(A) = 100\text{Hz to } 17.999 \text{ kHz}$$

$$f(B) = 18 \text{ kHz to } 29.999 \text{ kHz}$$

$$f(C) = 30 \text{ kHz to } 49.999 \text{ kHz}$$

$$f(D) = 50 \text{ kHz to } 69.999 \text{ kHz}$$

$$f(E) = 70 \text{ kHz to } 110 \text{ kHz}$$

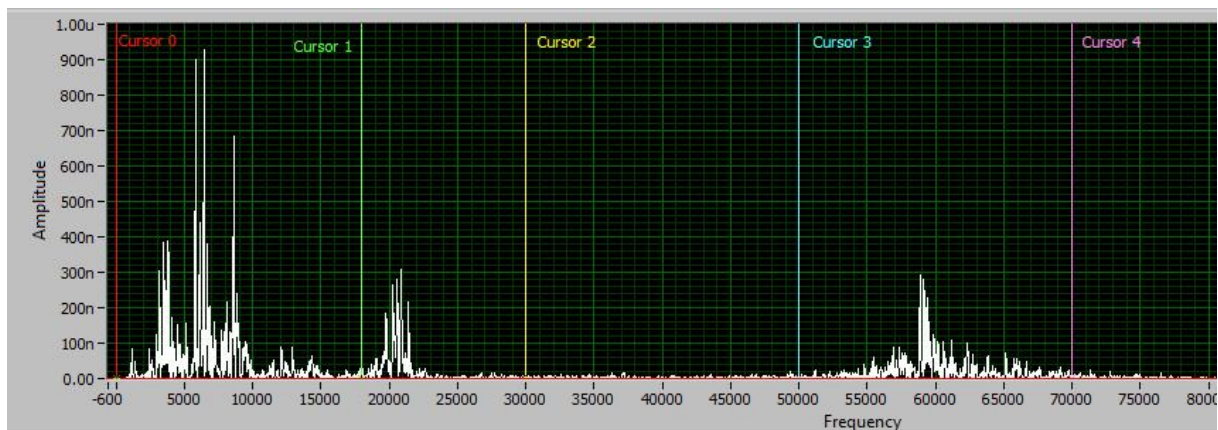


Figure 4.16: Showing the frequency bands for analysis in case of “good” contacts.

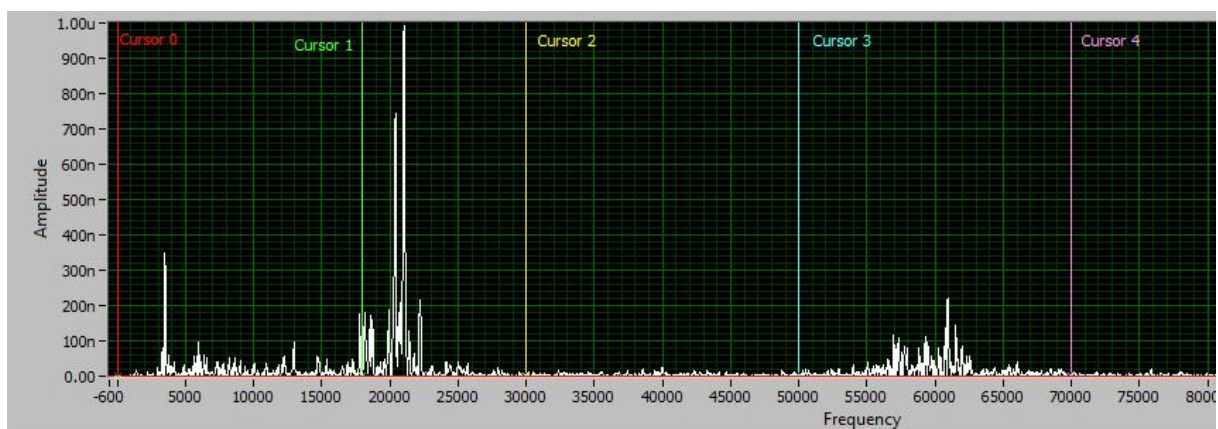


Figure 4.17: Showing the frequency bands for analysis in case of “Bad” contacts.

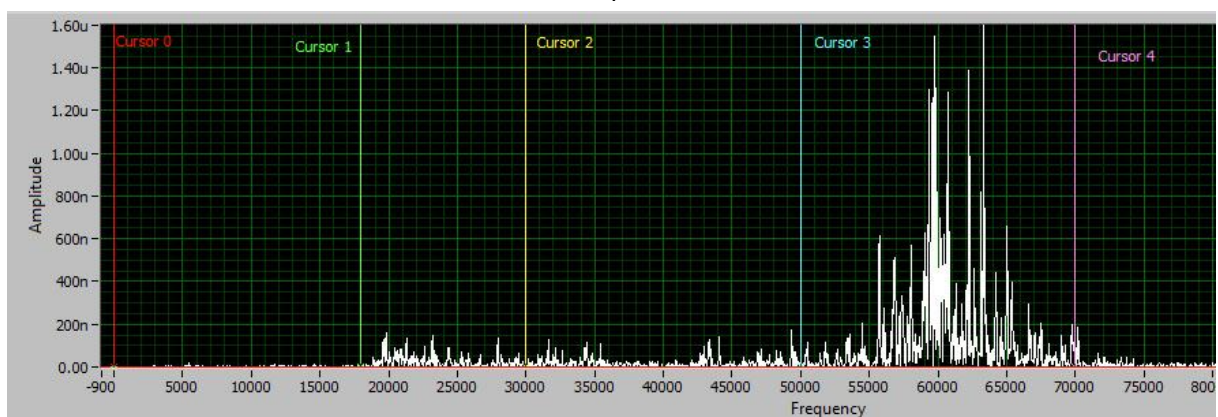
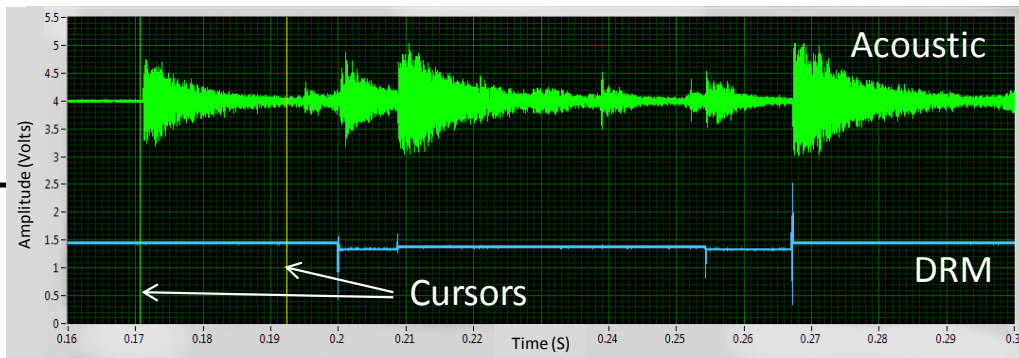


Figure 4.18: Showing the frequency bands for analysis in case of “arcing” contacts.

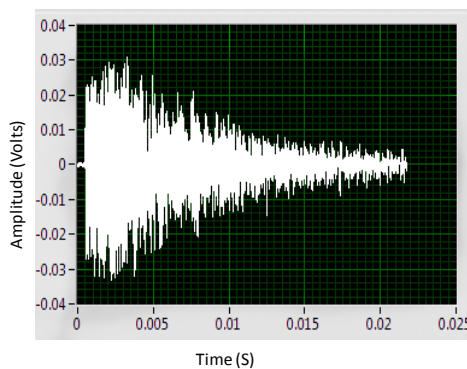
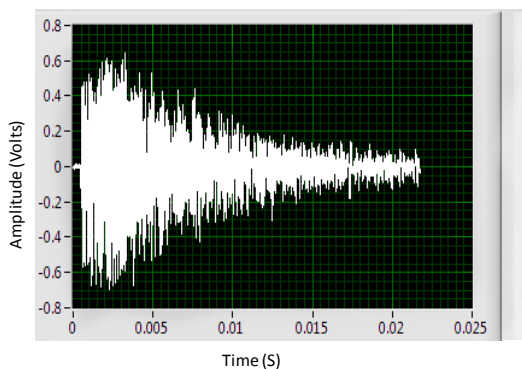
Shown below is the algorithm in a flow chart form; the choice of frequency bands is not rigid and changes in the frequency band can be easily done by setting the position of the cursors (0 to 4) but for the analysis done in this chapter the frequency bands have been kept constant at the values mentioned above.

Obtain a  
Waveform

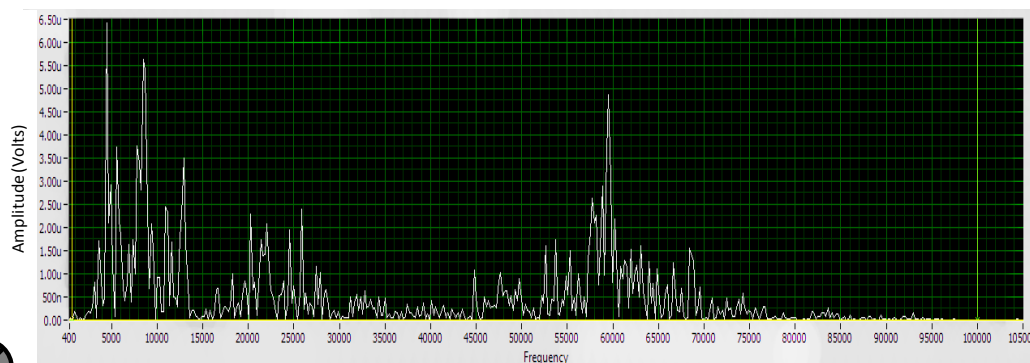
Select a portion of the signal manually by  
selecting the cursors & extract a portion of  
the signal



Find the energy of the extracted portion of the signal and  
normalize the extracted portion W.R.T its energy



Compute the FFT and obtain the Power/Frequency  
spectrum



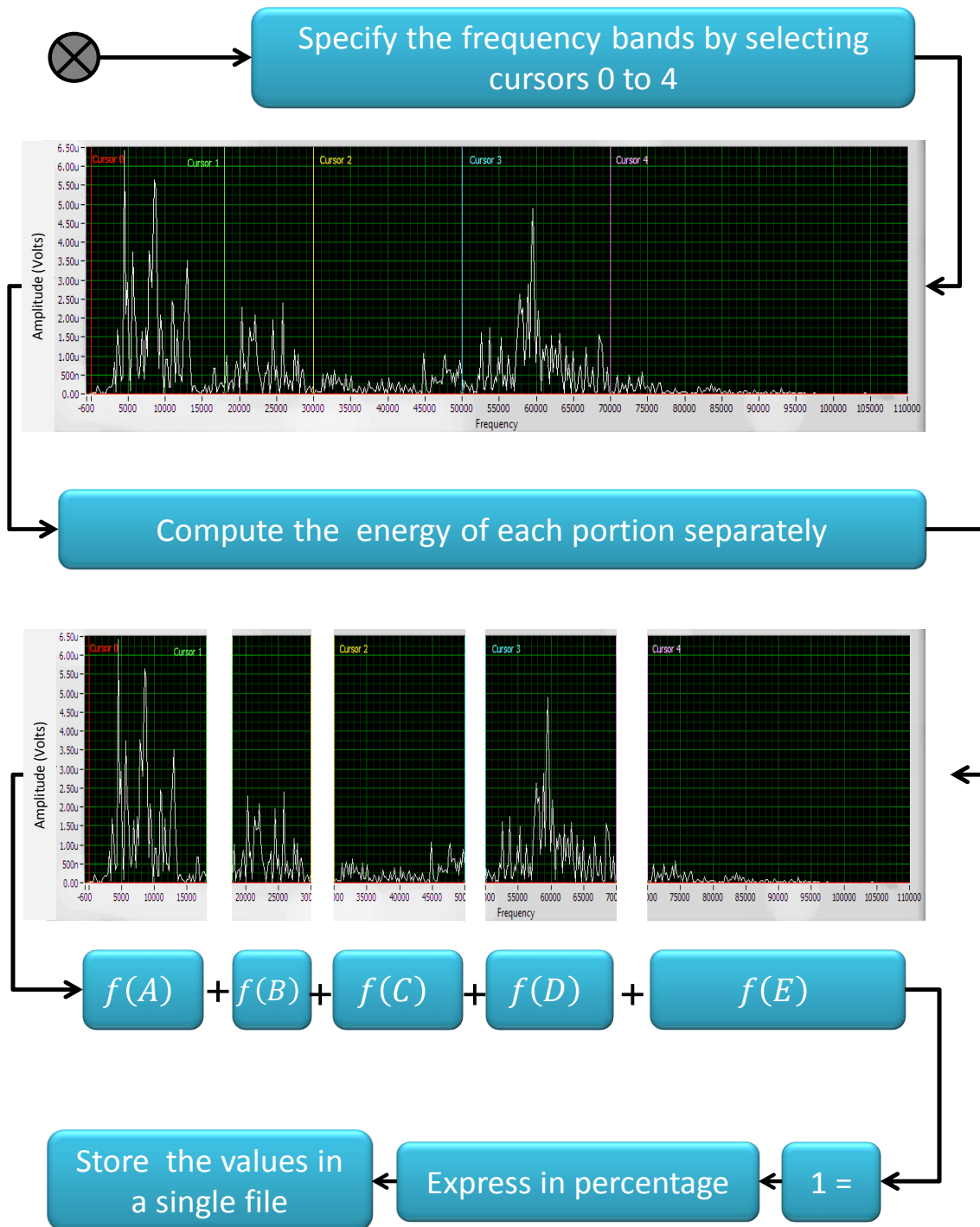


Figure 4.19 : showing the modified algorithm for frequency analysis.

## 4.2.5 Results of the analysis

As the single phase tap changer has 9 stator contacts each contact was numbered from 1 to 9. The “good” contacts were used and the readings (Acoustic + DRM ) were obtained by moving the tap changer a single step at a time, back and forth. So the sequence of the operation was:

- Movement of tap changer from Contact 1 to 2, 5 times.
- Movement of tap changer from Contact 2 to 1, 5 times.
- Movement of tap changer from Contact 2 to 3, 5 times.
- Movement of tap changer from Contact 3 to 4, 5 times and so on till...
- Movement of tap changer from Contact 8 to 9, 5 times.

Now the “good” contacts were replaced with the “bad” contacts and the above process was repeated from Contacts 1 to 9.

After running the algorithm for a number of signals a set of data points for the amount of energy (expressed in percentage of energy of the whole signal) in the four bands were obtained. The selection of the portions of the signals (step 1 in the algorithm) was done randomly and the chart below in Figure 4.20 shows the distribution of energy for good contacts. The line along the plotted points (shown in black) is a polynomial trend line with an order 4 and the dotted line shows the average of the values of the points in a particular frequency band. It can be observed that for a good contact the approximate values of energies  $f(x)$  & Standard deviation  $\sigma$  are:

$$\begin{aligned} f(A) &\cong 27\% \text{ \& } \sigma = 7\%, & f(B) &\cong 30\% \text{ \& } \sigma = 7.1\%, \\ f(C) &\cong 7\% \text{ \& } \sigma = 2\%, & f(D) &\cong 30\% \text{ \& } \sigma = 8.57\% \end{aligned}$$

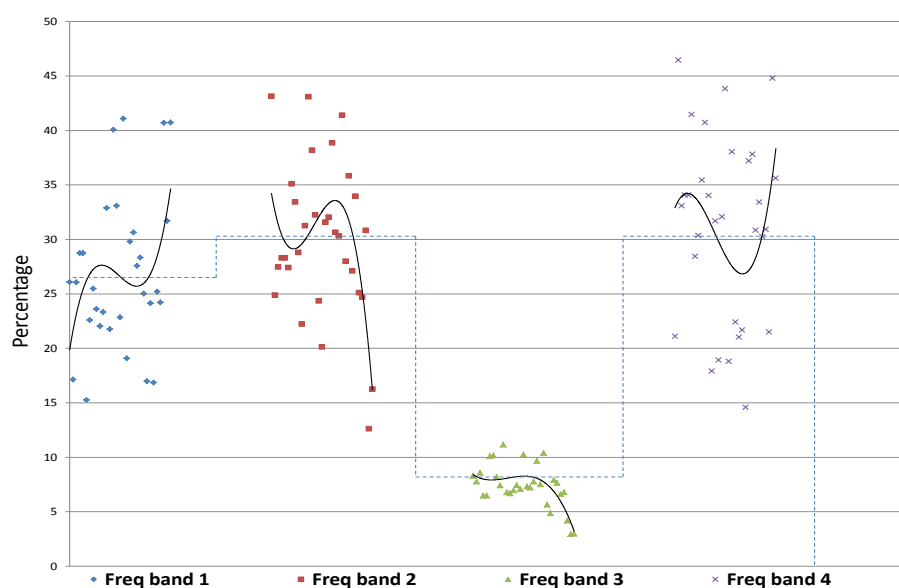
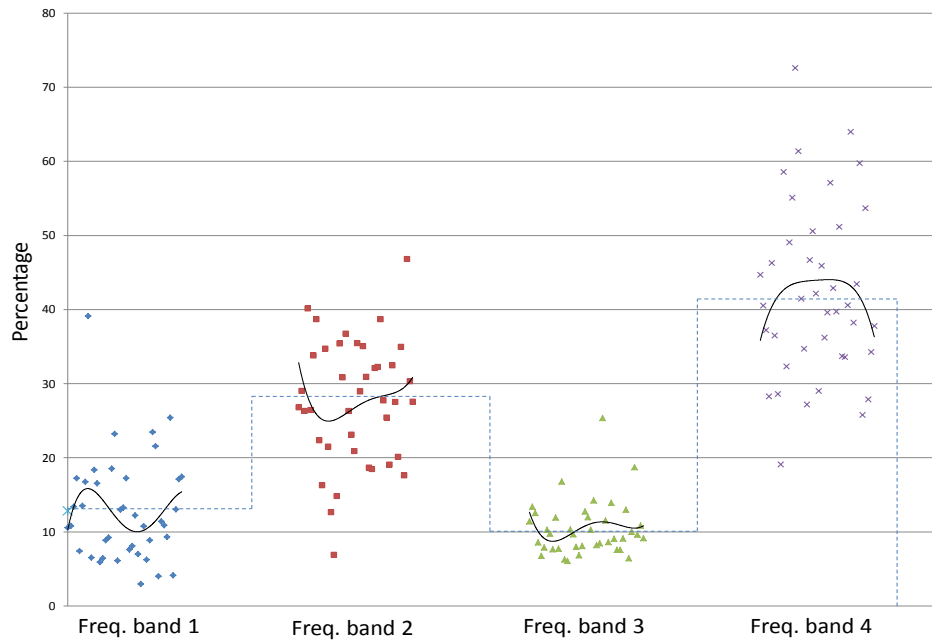


Figure 4.20 : Showing the distribution of energy for good contacts.



**Figure 4.21 : Showing the distribution of energy for bad contacts.**

Similarly on plotting the values obtained from a set of “bad” contacts, a difference can be seen in the average values, the approximate average values energies  $f(x)$  & Standard deviation  $\sigma$  are:

$$\begin{aligned} f(A) &\cong 13\% \text{ \& } \sigma = 7.02\%, f(B) \cong 28\% \text{ \& } \sigma = 8.39\%, \\ f(C) &\cong 10\% \text{ \& } \sigma = 3.72\%, f(D) \cong 42\% \text{ \& } \sigma = 11.78\% \end{aligned}$$

It can be observed that the amount of energy in the band  $f(A)$  of the spectrum goes down in case of “bad” contacts as compared to “good” contacts. The amount of energy in the band  $f(B)$  and  $f(C)$  of the spectrum remains almost the same in case of “bad” contacts as compared to “good” contacts, and the amount of energy in the band  $f(D)$  of the spectrum goes up in case of “bad” contacts as compared to “good” contacts.

As previously mentioned the selection of the portions was done randomly. It was also of interest to find out how the distribution changed if the selection of signals was done based on events. Shown below in Figure 4.22 is the average distribution of energy in the four bands  $f(A)$  to  $f(D)$ . Now considering  $f(A)$  it can be observed that the percentage of energy does not change more than 10% when considering the Events 1 to Events 5, so this justifies the random selection of signal portions or events for comparison. But this statement is valid only for the condition when the tap changer is not arcing; the procedure of measurement when the tap changer is arcing is discussed below.

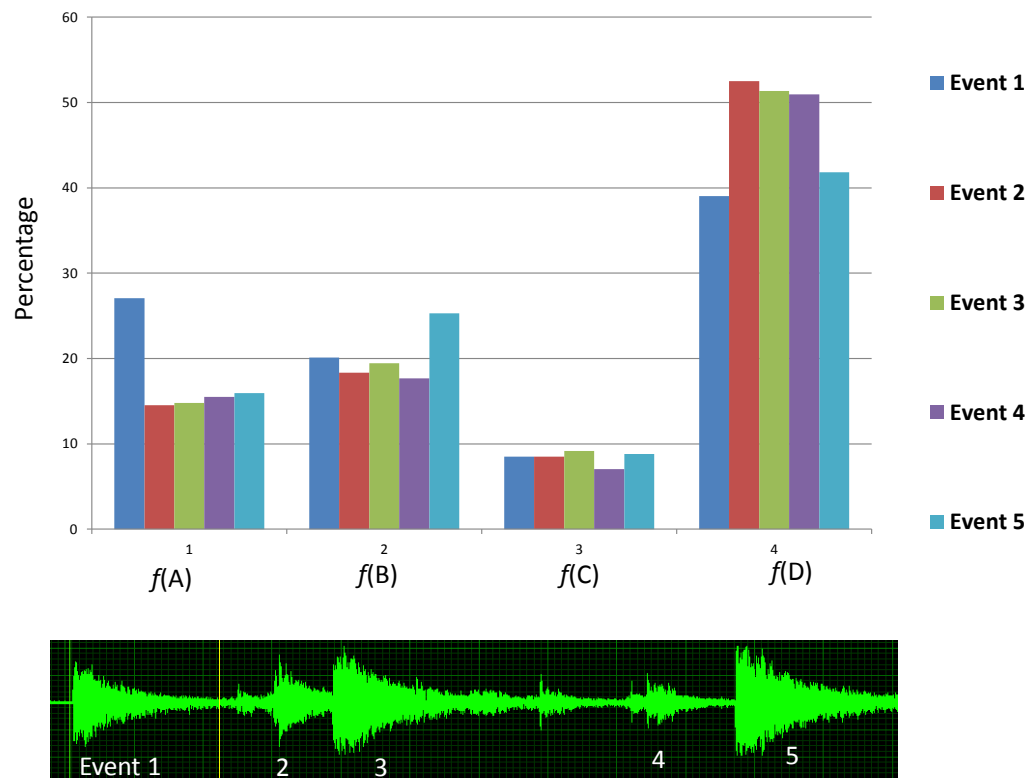


Figure 4.22: Showing the change in average distribution of energy if the individual events are compared.

## 4.3 Experiments with arcing contacts

As discussed in chapter 2, arcing in the tap changer is unavoidable, the aim of these experiments is to determine if the arcing phenomenon can be detected using acoustic sensors and if there is any change in one of the frequency bands ( $f(A)$  to  $f(D)$ ) of the frequency spectrum when the contacts are arcing.

### 4.3.1 Laboratory Set-up and Procedure for arcing

In this setup, the DRM unit was removed and the variable flux transformer, used in chapter 3, was connected to the connections where the DRM setup was connected to the tap changer and a current was fed to the tap changer in a similar way as it was done for the DRM. A current transformer (ratio 100/1) was attached to one of the output cables of the variable flux transformer in order to have a time reference, this CT is terminated on the secondary winding by a one ohm resistor and the voltage is measured on an oscilloscope.

Another addition was the inclusion of an optical sensor to detect the arcing phenomenon, the optical sensor is a simple photodiode directly connected to the oscilloscope with high input impedance.

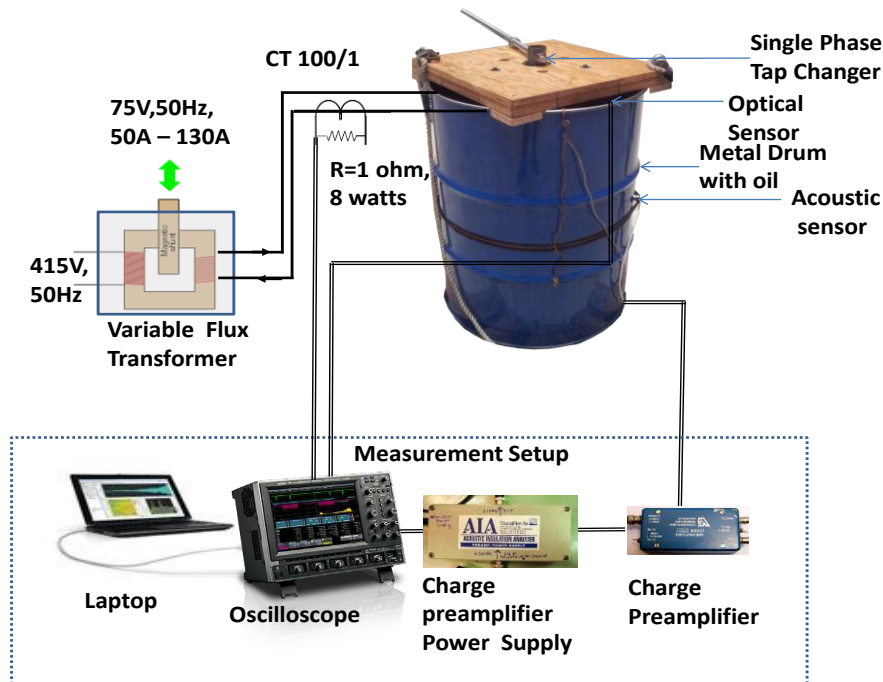
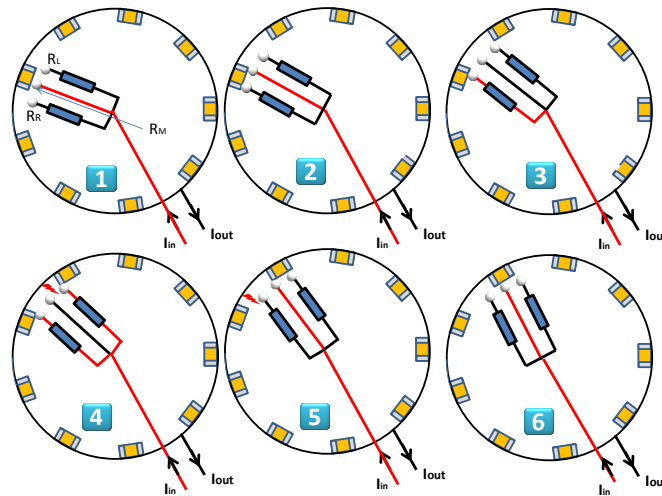


Figure 4.23 : Showing the setup for creating and measuring arcing.

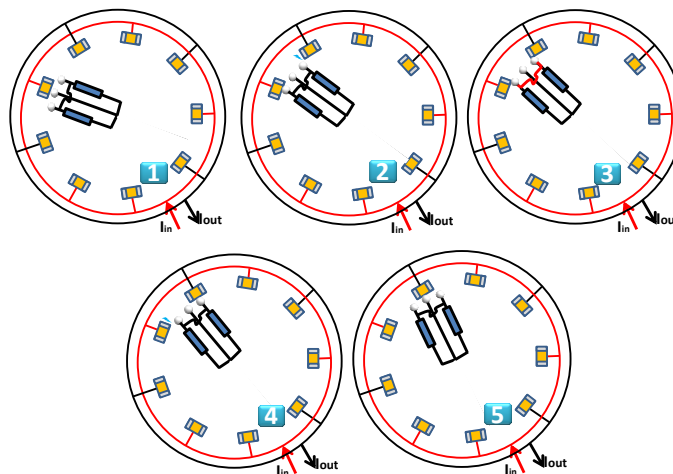
The typical sequence of the tap changer Switching cycle of fine selector tap changer has been discussed in detail in chapter 2 Section 2.1.2.1 and arcing occurs during event 2 and 4 when the circulating current is made/interrupted. The connections made for the simulation of arcing are shown below in Figure 4.24. It can be seen that all the contacts have

been shorted now. During the normal operation of the tap changer an arc is observed during event 4 and 5 due to the circulating current during event 4 and due to breaking of the circulating current in event 5. But, since the contacts were shorted there was no circulating current and the arcing in the contact during tap changer operation failed to occur.



**Figure 4.24 : Showing the sequence of events in a tap changer modified for measurement of DRM.**

To counter this problem the connections in the setup were modified by shorting the right roller  $R_R$  and the left roller  $R_L$ , and the middle roller  $R_M$  was left out. Also the contacts were alternately connected as shown below in Figure 4.25. Now during event 2 the roller contacts bridge the contacts of the stator and as the contacts are connected to different polarities of the variable flux transformer a current link of about 180 Amps is established and an arc is formed. Again during event 4 when the link is broken an arc is formed. This setup is able to closely replicate the process of circulating current in the tap charger.



**Figure 4.25: Showing the sequence of events in a tap changer modified for measurement of arcing.**

### 4.3.2 Results of the analysis for arcing contacts

Again the “good” contacts were used for the readings and a current of 180 amps was passed through the contacts and the readings (Acoustic + Current transformer) waveforms were obtained by moving the tap changer a single step at once, back and forth. The sequence of the operation was kept the same as before:

- Movement of tap changer from Contact 1 to 2, 5 times.
- Movement of tap changer from Contact 2 to 1, 5 times.
- Movement of tap changer from Contact 2 to 3, 5 times.
- Movement of tap changer from Contact 3 to 4, 5 times and so on till...
- Movement of tap changer from Contact 8 to 9, 5 times.

Now the “good” contacts were replaced with the “bad” contacts and the above process repeated from Contacts 1 to 9 with current passing through the contacts and arcing. Shown below is a snapshot of the waveform obtained. In this snapshot the signal in red is the acoustic signal, superimposed on the acoustic signal in white is the signal from the optical sensor and the signal in green is the signal from the current transformer. The triggering is done using the waveform obtained from the current transformer.

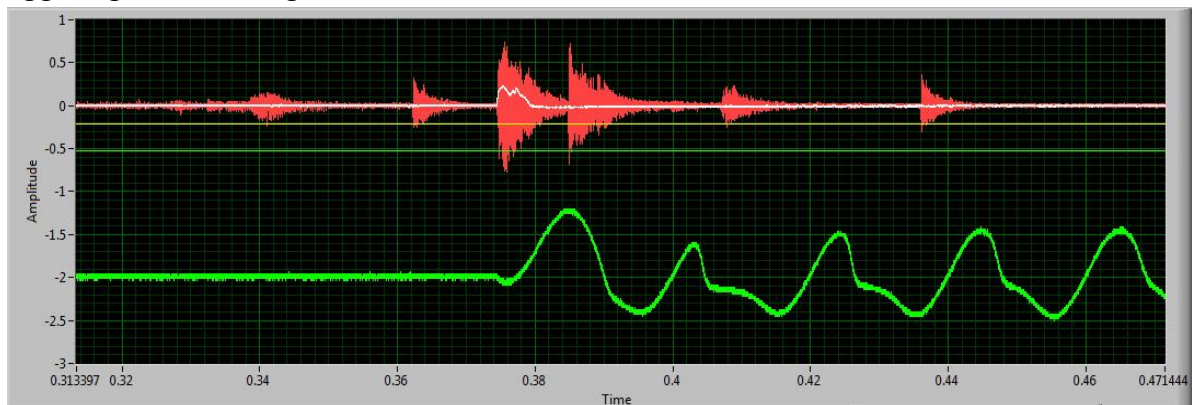
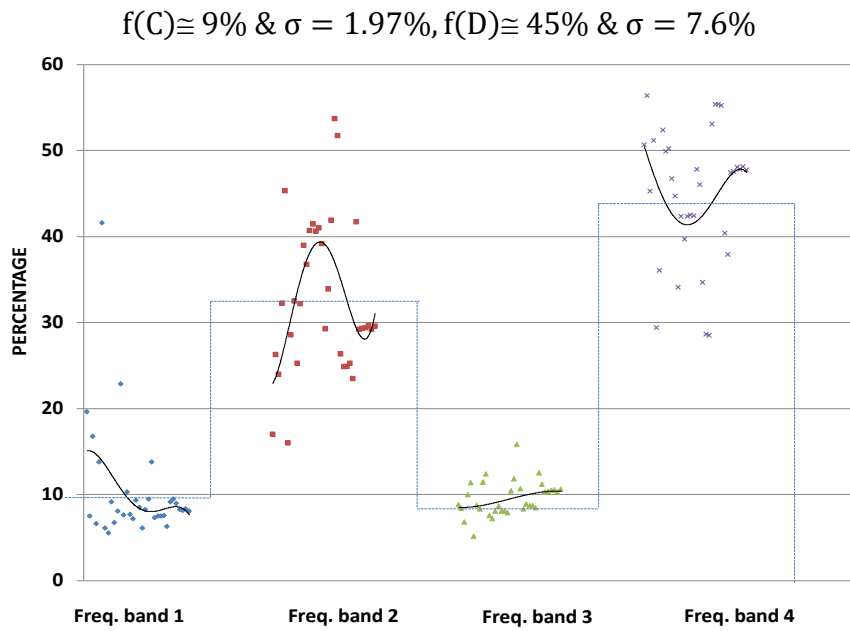


Figure 4.26: Showing the three waveforms synchronised with a common trigger.

After running the algorithm for a number of signals the sets of data points for the amount of energy (expressed in percentage of energy of the whole signal) in the four bands were obtained. The important thing to note is that only the events in which arcing took place were used for the analysis. This was done in order to isolate and study the arcing phenomenon, because an event during which the contact is not arcing is just a normal event that has been dealt in the previous section. The chart below in Figure 4.27 shows the distribution of energy for good contacts with arcing. The line along the plotted points (shown in black) is a polynomial trend line with an order 4 and the dotted line shows the average of the values of the points in a particular frequency band. It can be observed that for a good contact with arcing the approximate values of energies  $f(x)$  & Standard deviation  $\sigma$  are:

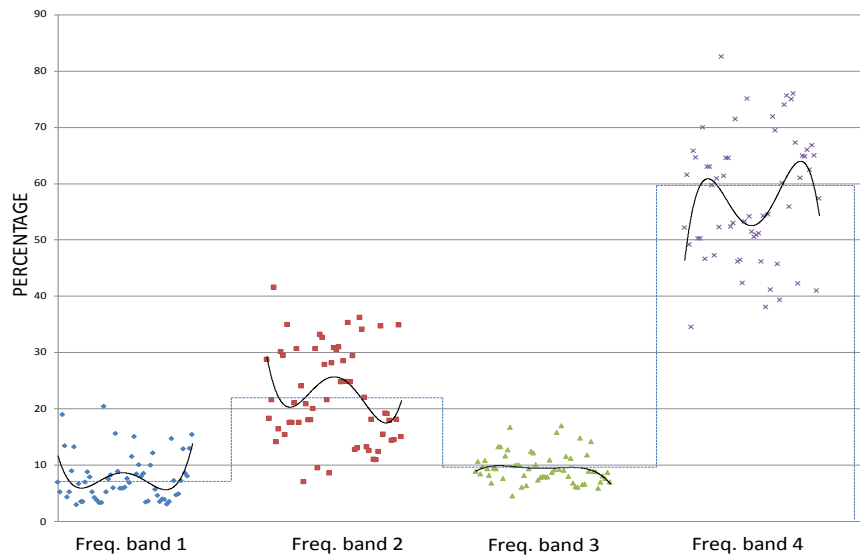
$$f(A) \cong 10\% \text{ \& } \sigma = 6.62\%, f(B) \cong 32\% \text{ \& } \sigma = 8.73\%,$$



**Figure 4.27 Showing the distribution of energy for good contacts with arcing.**

Similarly on plotting the values obtained from a set of “bad” contacts with arcing, a difference can be seen in the average values, the average values of energies  $f(x)$  & Standard deviation  $\sigma$  are:

$$f(A) \cong 8\% \text{ \& } \sigma = 4.13\%, f(B) \cong 22\% \text{ \& } \sigma = 8.36\%, \\ f(C) \cong 9\% \text{ \& } \sigma = 2.71\%, f(D) \cong 57\% \text{ \& } \sigma = 11.01\%$$



**Figure 4.28 : Showing the distribution of energy for bad contacts with arcing.**

It can be observed that the amount of energy in the band  $f(A)$  and  $f(C)$  of the spectrum remains the same in case of “bad” contacts as compared to “good” contacts. The amount of energy in the band  $f(B)$  of the spectrum increases in case of “good” contacts as compared to “bad” contacts. The amount of energy in the band  $f(D)$  of the spectrum goes up in case of “bad” contacts as compared to “good” contacts.

### 4.3.3 Just Arcing phenomenon

As an attempt to verify the frequency spectrum of the arc, acoustic measurements needed to be taken only of the arc without any mechanical noise being present. This was done by touching one of the roller contacts to the stator contact very lightly in such a fashion that there is only a very small contact area. Now a current is passed through the contact as before and roller and stator contacts are separated. An arc is formed between them, and since the contacts were touching each other very lightly the amount of acoustic signal produced by the mechanical noise made is negligible as compared to the acoustic signal produced by arcing. The chart below in Figure 4.29 shows the distribution of energy for only arcing phenomenon. The line along the plotted points (shown in black) is a polynomial trend line with an order 4 and the dotted line shows the average of the values of the points in a particular frequency band. It can be observed that for an arcing phenomenon that the approximate values of energies  $f(x)$  & Standard deviation  $\sigma$  are:

$$f(A) \cong 4\% \text{ \& } \sigma = 1.5\%, f(B) \cong 15\% \text{ \& } \sigma = 7.8\%, \\ f(C) \cong 10\% \text{ \& } \sigma = 3.89\%, f(D) \cong 70\% \text{ \& } \sigma = 10.1\%$$

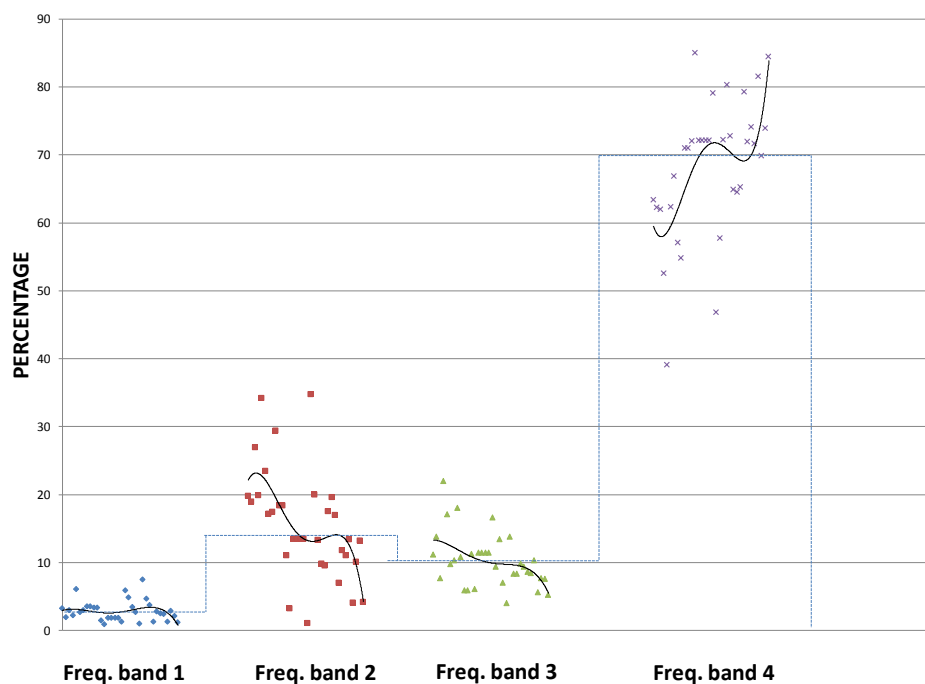


Figure 4.29: : Showing the distribution of energy for arcing phenomenon.

## 4.4 Conclusions and summary

The tests in this chapter were made to study the acoustic characteristics of a single phase tap changer. This was done by first determining a suitable method for the analysis of the signals in the frequency domain.

For this the first method used was the plotting of several Power/Frequency spectrums on the same graph using points that represented the peaks of the spectrum, but this method did not work as expected, therefore another method was applied which split the frequency spectrum to five parts based on frequency bands and found the energy of each part separately, giving appropriate results.

Then, the tap changer was operated with various types of contacts:

- Only Good contacts
- Only Bad contacts
- Arcing with good contacts
- Arcing with bad contacts
- Only arcing phenomenon

The table below shows the consolidated data from the results obtained from all the five sets of measurements.

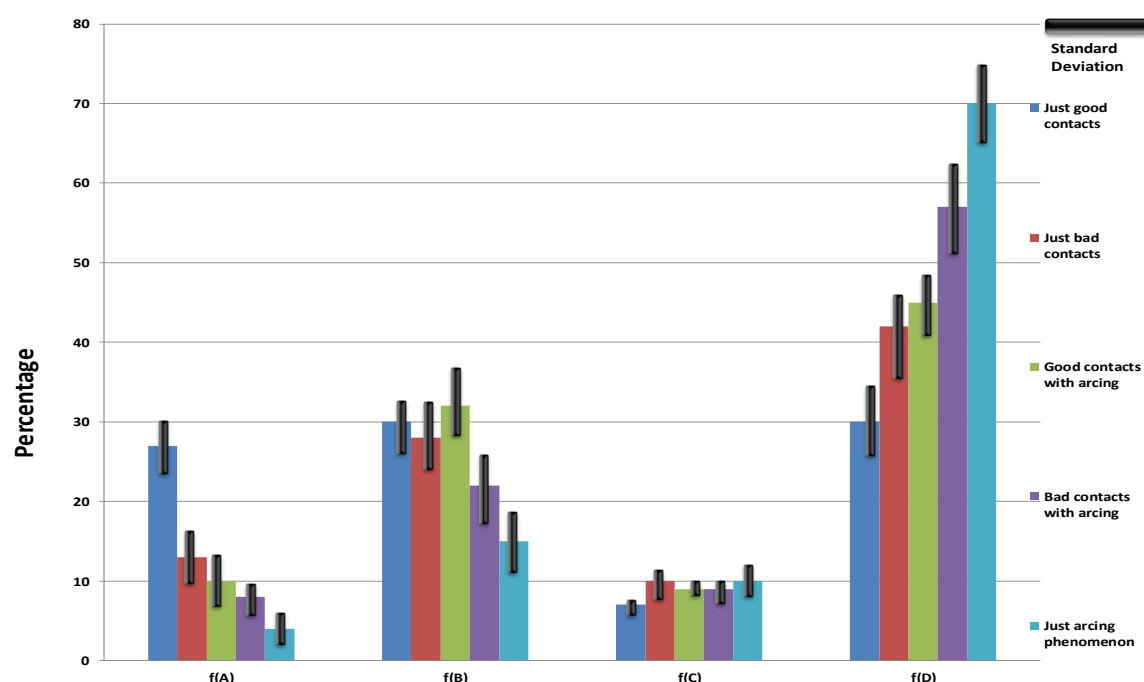


Figure 4.30: Showing the comparison of energy.

On comparing the percentage of energies, a significant change in average is seen between good and bad contacts in case of f(A) and f(D) and, a significant change is seen between, good contacts with arcing, bad contacts with arcing and Just arcing phenomenon in case of f(B) and f(D). In the next chapter similar tests will be conducted on a large three phase tap changer to verify these findings.

# Chapter 5: Experiments on a three phase tap changer

## 5.1 Introduction

This chapter mainly focusses the series of experiments on a larger tap changer, in order to see if the results that were obtained previously in the single phase tap changer, are reproducible on this tap changer. The experiments also deal with the requirements for acoustic measurements on an online tap changer, inside a transformer.

## 5.2 The three phase tap changer

The three phase tap changer used in this experiment is a complete unit of a selector type tap changer, consisting of a coarse and a fine selector switch, a gear box and an actuating motor. The entire operating sequence of such a tap changer is discussed in chapter 2 section 2.2.2.1. The details of this OLTC are mentioned in appendix B. Consider the sequence of events as discussed in the case of the single phase tap changer; the sequence of events in the fine selector switch remains exactly the same. The only parameters that change are the speed and accuracy of the operation of the tap changer, where in the hand operated tap changer described in chapter 4, the entire operation of one tap change took about 180 milliseconds, in case of the three phase tap changer it takes about 70 milliseconds and also the braking is very precise in case of the three phase tap changer as the middle roller contacts  $R_m$  stop exactly at the middle of the stator contacts after the tap change operation is complete. Also an important point to note is that the four sets of rollers are mounted along a common axis of the rotor and they rotate together. The coarse selector unit lies under the fine selector unit, and since it was not possible to dismantle the fine selector unit to access the coarse selector, the experiments were conducted only on the fine selector unit.

Again, as in chapter 4 five events can be defined to describe the motion of a single tap change it is considered that the rotor is moving anticlockwise direction. The motion is being observed from the top (top view), and the direction of observation (front view) is from the rotor towards the stator. The contact numbering is  $N$ ,  $N+1$ , and  $N+2$  etc. in the anticlockwise direction.

- Event 1 when the left roller contact  $R_L$  "strikes" the contact  $N$
- Event 2 when the middle roller contacts  $R_M$  leave  $N$
- Event 3 when the right roller  $R_R$  "strikes" the contact  $N+1$
- Event 4 when the right roller contacts  $R_R$  leave  $N$
- Event 5 when the middle roller contact  $R_M$  "strikes" contact  $N+1$

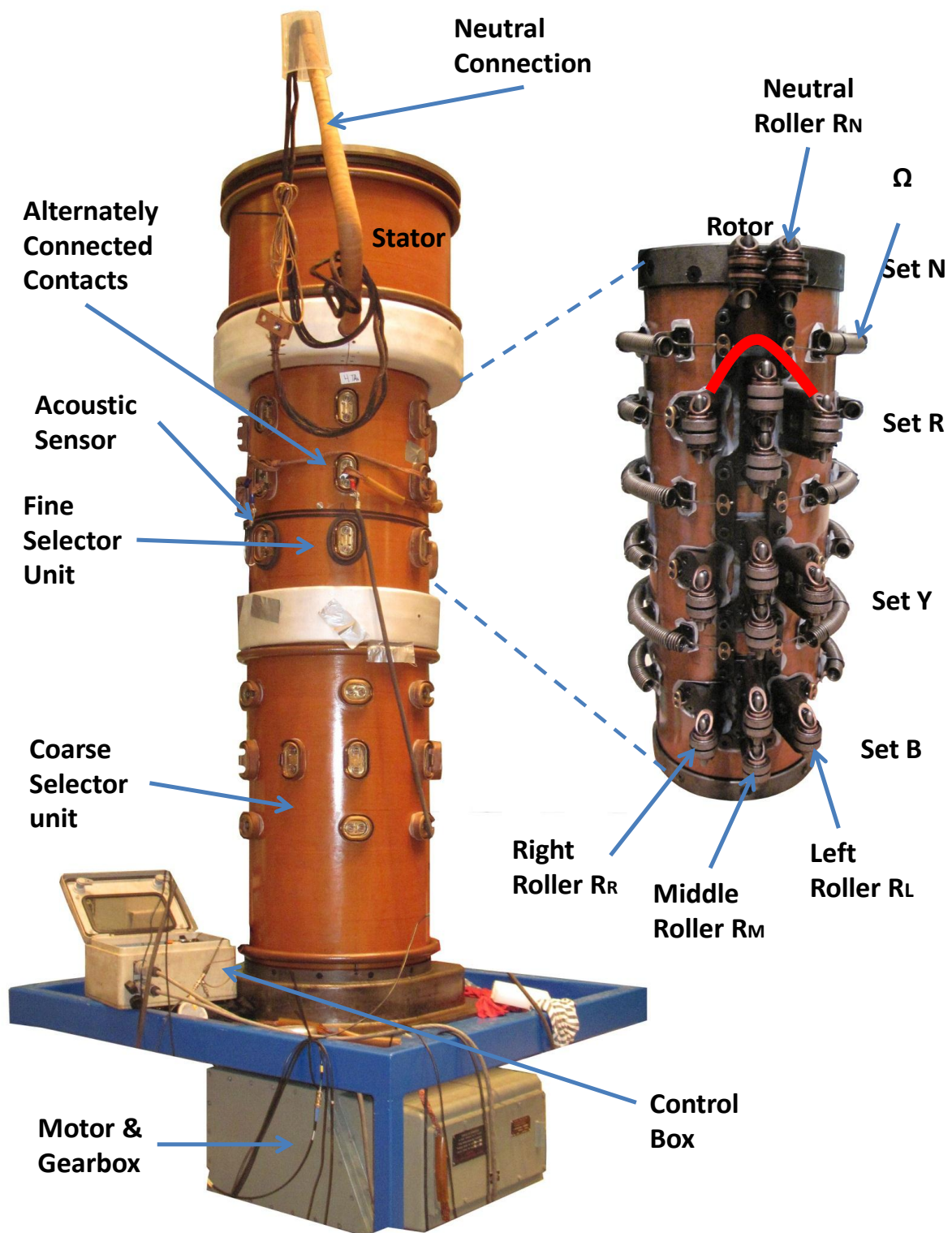


Figure 5.1: Showing the rotor and stator of a selector type, three phase tap changer.

Shown above are the images of a selector type three phase tap changer. On observing the rotor it can be seen that the contact arrangement of a set of rotor contacts is the same as the rotor of a single phase tap changer as shown in chapter 4 section 4.2. One of the limitations of this setup is that the tap changer is not inside a metal tank as it should have been in case of an actual transformer tap changer setting. So the acoustic sensors had to be mounted directly on the tap changer.

## 5.2.1 Laboratory set-up and procedure for DRM, Motor current measurements & Acoustic measurements on good contacts

As previously mentioned, methods of measurement will be discussed that could be practically applied to a tap changer that is connected to an energized transformer in the field. During field measurements it is not possible to conduct DRM or measure the current through a current transformer (CT) as it was done in the previous measurements, so one of the ways to have a time reference in order to identify the sequence of events is through measuring the current of the tap changer motor [25].

### 5.2.1.1 Motor current measurements for time reference

The motor current measurements are done by placing a current transformer on one of the power cables of the motor. The schematics of a tap changer power and control circuit along with the location of the CT are shown in Figure 5.2 below. The CT was terminated with a one ohm resistor and the motor current output was obtained as a voltage across the one ohm resistor on an oscilloscope.

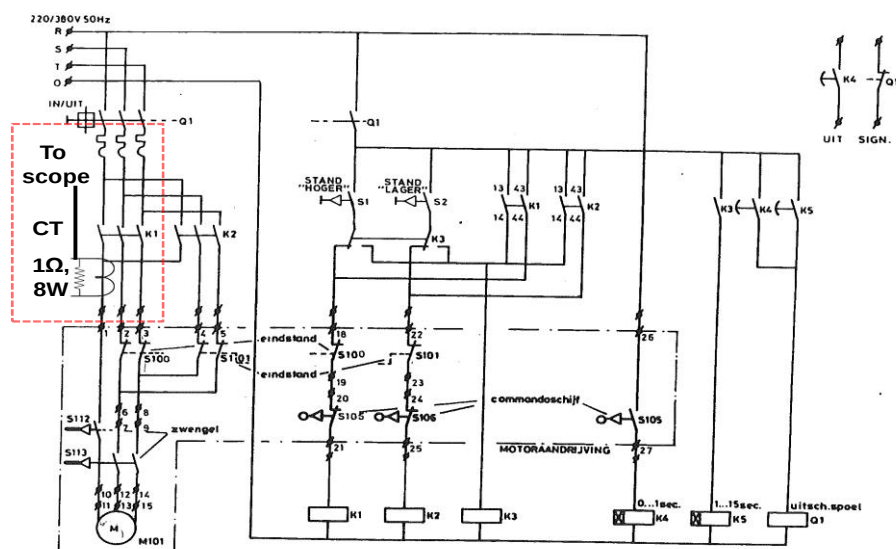
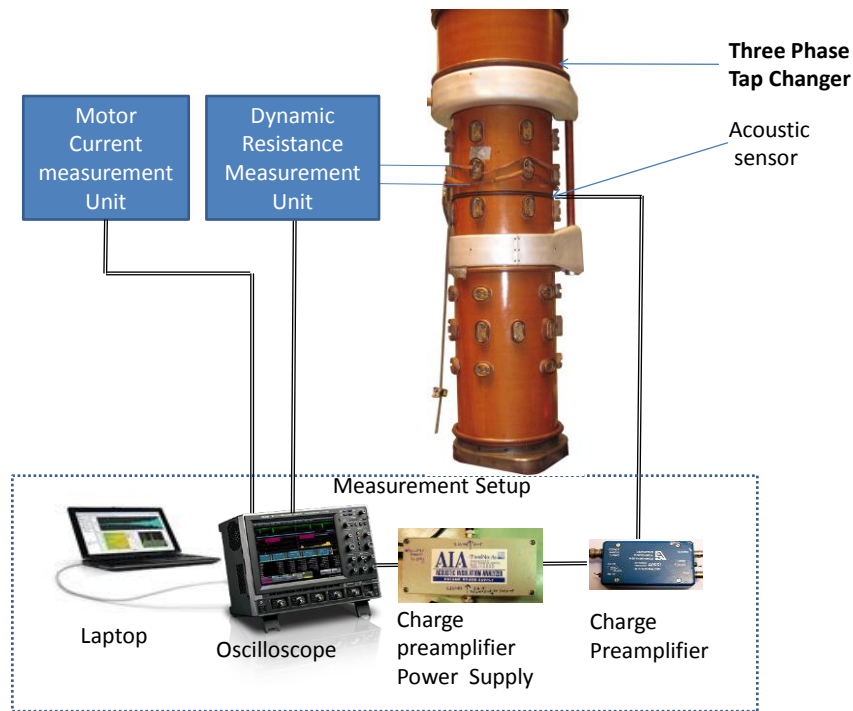


Figure 5.2: showing the connection of the current transformer to the tap changer motor(Motor Current Measurement Unit) [1].

In the schematic shown in Figure 5.3 below, the acoustic sensor is D9241A is attached to the body of the stator. The fine selector unit of the stator is filled with oil. As it was observed in chapter 4 section 4.3.1, shorting all the contacts does not help in arcing so in this setup the changes were made before initial measurements. The left and right roller contacts were shorted (as shown by the thick red line in Figure 5.1 ) and the stator contacts were connected alternately. The setup for the DRM is kept the same as in chapter 4 section 4.2.1.1 and the DRM unit was connected to the alternately connected contacts.



**Figure 5.3 : Schematic showing the setup for the DRM and Acoustic signal measurement.**

Since the contacts of the three phase tap changer are alternately connected and the right roller and left roller arms shorted, the DRM graph changes from what is discussed in section 4.2.1.1 of chapter 4 as the current through the measuring shunt of the DRM unit flows only when the left and the right roller contacts are bridging the two stator contacts N and N+1 as shown in Figure 4.25.

The figure below shows the acoustic waveform in along with the DRM graph and the plot obtained from the output of motor current measurement unit.

### 5.2.1.2 Analysis of the waveform from the three phase tap changer

Shown below in Figure 4.9 are three plots, the first plot is obtained from the three phase tap changer, the second is a plot of the DRM graph, when the roller arms ( $R_R$  and  $R_L$ ) were not shorted and the third is the plot obtained from the single phase tap changer. From the second plot it can be seen that the sequence of events 2 and 4 last for approximately 32 milliseconds. This information was used in plot 1 and the two events 2 and 4 can be traced.

Looking at plot 1 it can be observed that the sequence of events (1 to 5) are not as distinct as in plot 3 and without the help of the DRM graph, it would be very difficult to distinguish the sequence of events in plot 1.

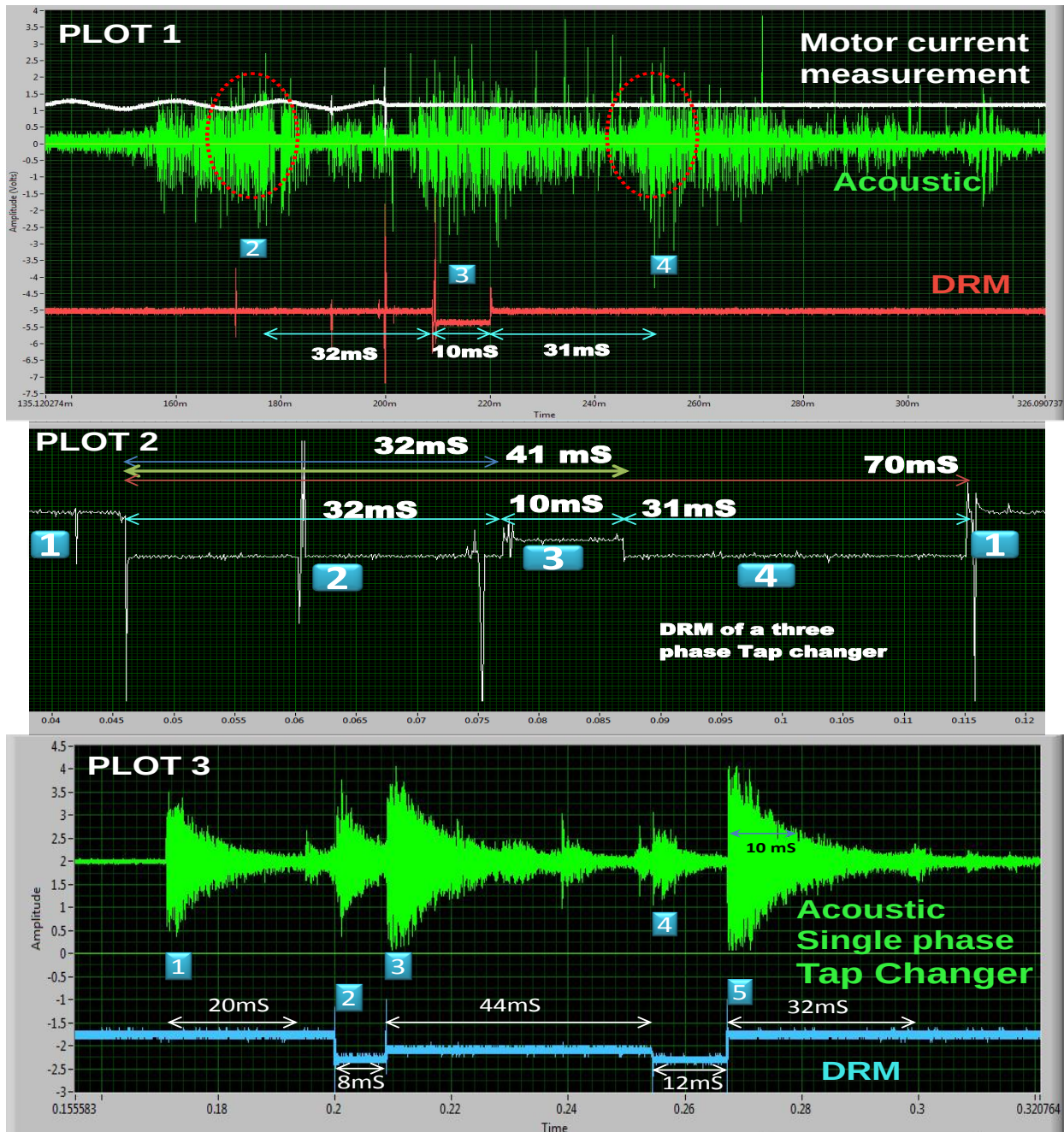
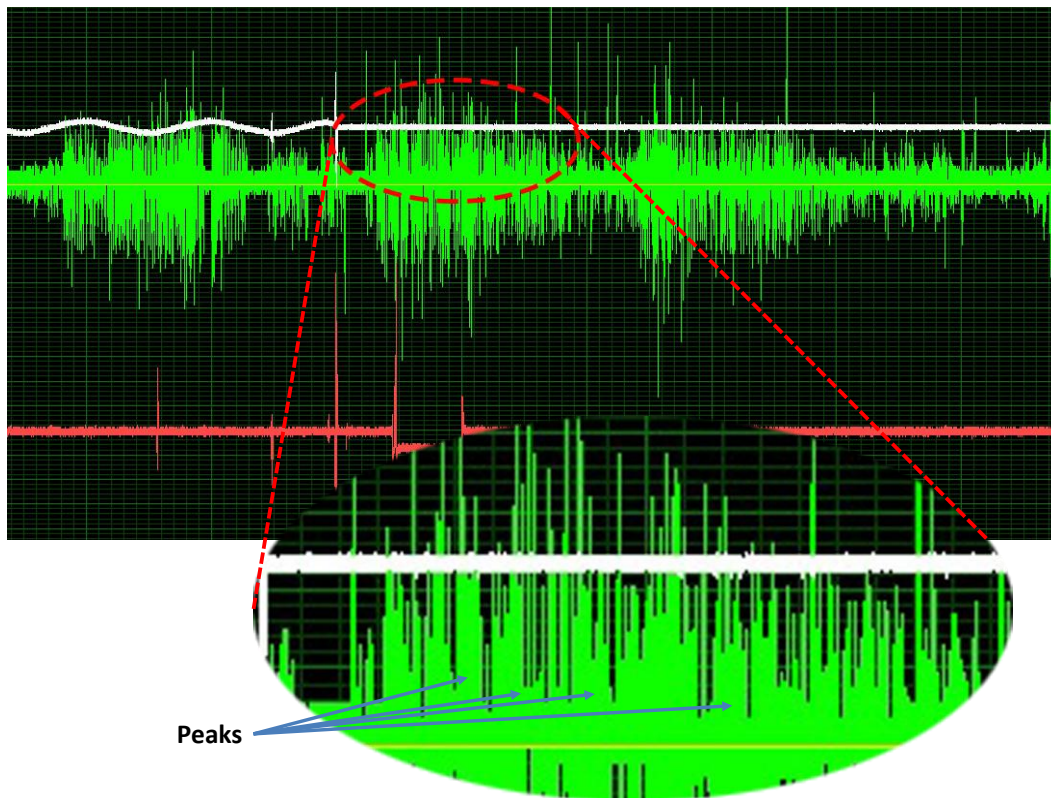


Figure 5.4 : Showing the three plots.

In order to answer the question as to why a distinct sequence of events was not visible when the experiments were made on a three phase tap changer, two main factors were attributed to the cause of this discrepancy:

- As the sensors are attached directly on the rotor of the tap changer, along with the acoustic signal of the contact, near which the sensor is mounted, the sensors also pick up the acoustic signals from other moving sources like the gear box, the moving contacts of the other phases, the movement of the neutral roller contacts, the braking mechanism etc. This can be observed at looking closely at the signal; a number of peaks can be observed in the plot as seen in Figure 4.22 below, it is postulated that these peaks may represent all these events.



**Figure 5.5: Showing a zoomed in portion of acoustic waveform obtained from a three phase tap changer.**

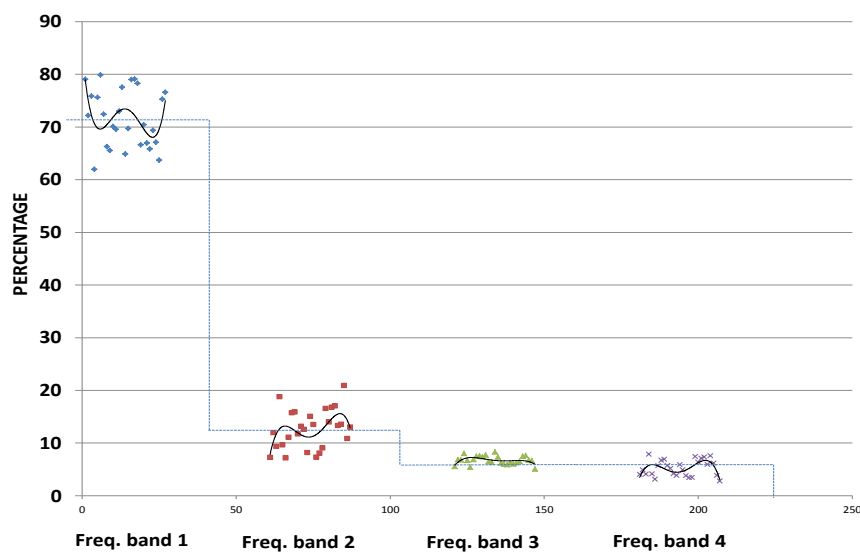
- Another reason was speculated to be the time of operation of the three phase tap changer, as seen in plot 3. For an acoustic signal with amplitude of about 2 V it takes about 10 milliseconds for an attenuation of -3dB. So for acoustic events that occur in a time less than 10 milliseconds it would be difficult to observe the difference between two events with this setup.

## 5.2.2 Results of the analysis for acoustic signals from good contacts

Although the sequence of events was not distinguishable in the acoustic signals obtained from the three phase tap changer, a frequency analysis could still be performed. Therefore a set of readings were taken in a similar way as in a single phase tap changer

using good contacts for the measurements. Using the algorithm (Discussed in chapter 4, section 4.2.4) to find the energy of the frequency spectrum a set of data points were obtained for a number of signals which were plotted on scatter chart. The chart below in Figure 5.6 shows the distribution of energy for good contacts. The line along the plotted points (shown in black) is a polynomial trend line with an order 4 and the dotted line shows the average of the values of the points in a particular frequency band. It can be observed that for a good contact the approximate values of energies  $f(x)$  & Standard deviation  $\sigma$  are:

$$\begin{aligned} f(A) &\cong 71.5\% \text{ \& } \sigma = 5.34\%, & f(B) &\cong 12.67\% \text{ \& } \sigma = 3.6\%, \\ f(C) &\cong 6.7\% \text{ \& } \sigma = 0.8\%, & f(D) &\cong 5.2\% \text{ \& } \sigma = 1.51\% \end{aligned}$$



**Figure 5.6: Showing the distribution of energy for “good contacts”**

It can be observed that the amount of energy in the band  $f(A)$  of the spectrum is much higher as compared to the other bands. If this observation is compared to the previous experiment in chapter 4, Figure 4.20, the percentage of energy for good contacts in the band  $f(A)$  is about 27.

## 5.3 Experiments with arcing of good contacts

The experiments with “bad” contacts could not be performed in case of this setup as it had been done in chapter 4 section 4.2.5, for the reason that it was very difficult to work inside the tap changer due to space constraints, so the contacts could not be removed for creating the damaged or “bad” contacts. Therefore the next step was to conduct the experiments with arcing of the good contacts.

### 5.3.1 Laboratory Set-up and Procedure for arcing

As in chapter 4, section 4.3.1 the DRM unit was removed and the variable flux transformer was connected to the connections where the DRM setup was connected to the tap changer and a current was fed to the tap changer in a similar way as it was done for the DRM. A current transformer (ratio 100/1) was attached to one of the output cables of the variable flux transformer in order to measure the current during arcing. This CT is terminated on the secondary by a one ohm resistor and the voltage is measured on an oscilloscope to have a time reference.

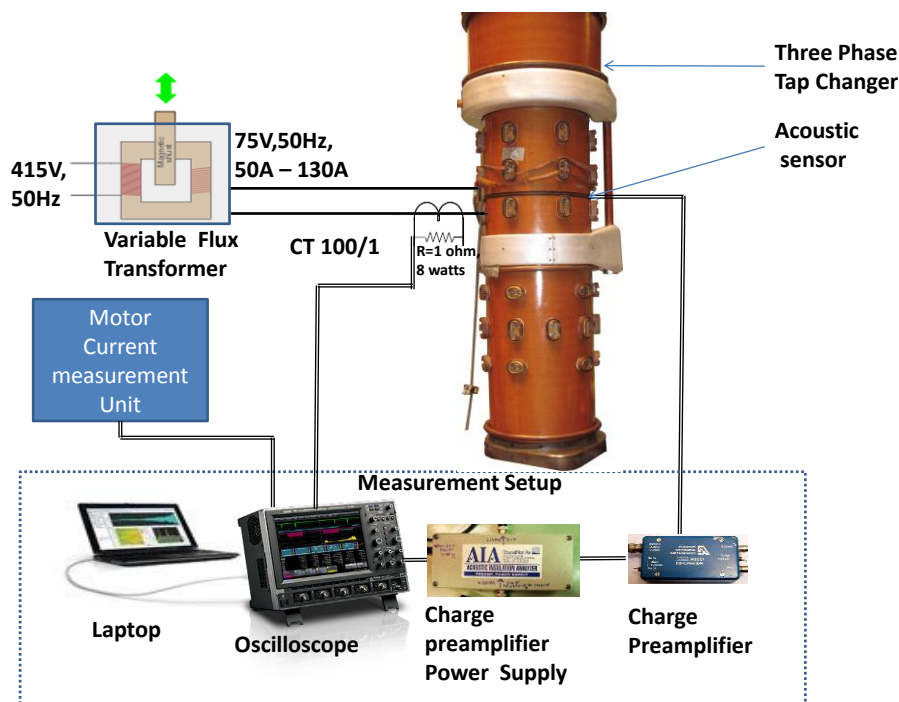


Figure 5.7 : Showing the setup for creating and measuring arcing.

The connections of the tap changer were already modified for supporting the arcing phenomenon as discussed in section 5.2.1.

### 5.3.2 Results of the analysis for acoustic signal from arcing contacts

Again the “good” contacts were used for the readings and a current of 180 amps was passed through the contacts and the readings (Acoustic + Current transformer) were obtained by moving the tap changer a single step at a time, back and forth. The triggering is done using the waveform obtained from the current transformer. The following average values of energies  $f(x)$  & Standard deviation  $\sigma$  were obtained from good contacts with arcing:

$$f(A) \cong 72.99\% \ \& \ \sigma = 5.92\%, f(B) \cong 10.77\% \ \& \ \sigma = 2.6\%, \\ f(C) \cong 6.95\% \ \& \ \sigma = 1.32\%, f(D) \cong 4.9\% \ \& \ \sigma = 1.65\%$$

On comparing this to the results obtained from good contacts in section 5.2.2, the results look similar and comparing these results with the results obtained from good contacts with arcing in case of a single phase tap changer the percentage of energy in band  $f(D)$  should be much higher, at least above 45 % as seen in Figure 4.27. But in the case of the three phase tap changer  $f(D)$  it is only about 5 %. In order to investigate this deviation in the results another experiment was conducted.

### 5.3.3 Just Arcing phenomenon

In section 4.3 of the previous chapter an experiment was conducted in order to find out the frequency spectrum of just the arc, without any mechanical noise being present. A similar experiment was conducted by creating an arc using a copper wire which was lightly touching one of the contacts of the stator and firmly connected to another stator contact of different polarity. When a current was passed through this wire, an arc was created between the wire and the contact on the point of light contact as this point has the highest resistance and starts to melt. As there was no mechanical motion in creating this arc, the acoustic signal can be said to be obtained entirely from the arc. When the waveforms were analysed using the same algorithm as before the following values average values of energies  $f(x)$  and standard deviation  $\sigma$  were obtained from the arcing phenomenon:

$$f(A) \cong 12.43\% \ \& \ \sigma = 4.8\%, f(B) \cong 27\% \ \& \ \sigma = 15.19\%, \\ f(C) \cong 8.5\% \ \& \ \sigma = 2.9\%, f(D) \cong 45.84\% \ \& \ \sigma = 14.8\%$$

Shown below is a snapshot of the waveform obtained:

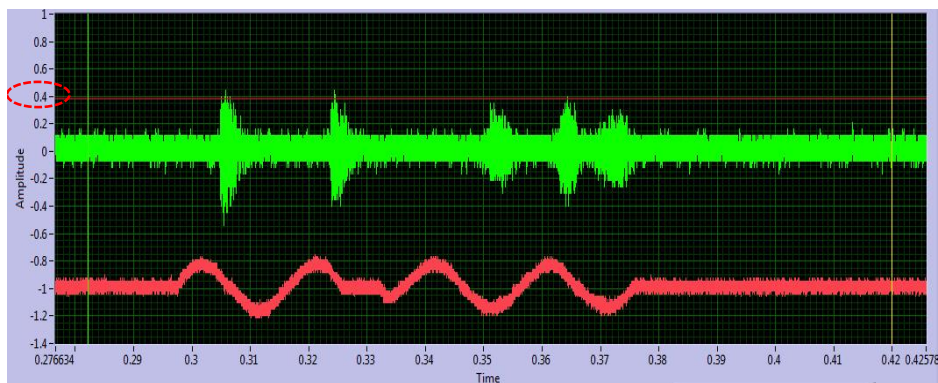


Figure 5.8 : Showing the distribution of energy for arcing phenomenon.

As expected a significant increase in the percentage of energy level in the frequency band  $f(D)$  can clearly be seen. Also comparing the waveform of the acoustic signal acquired from just the arcing phenomenon (Figure 4.29) with the acoustic signal acquired from the good contacts (Figure 4.9), the average amplitude of the acoustic signal acquired from the

good contacts is about 1.5 v whereas the amplitude of the acoustic signal acquired from just the arcing phenomenon is about 0.4 volts. So it can be said that in this setup even when there is arcing during contact movement the amount of energy in the frequency band  $f(D)$  is much smaller than the amount of energy in the frequency band  $f(A)$ , hence cannot be distinguished.

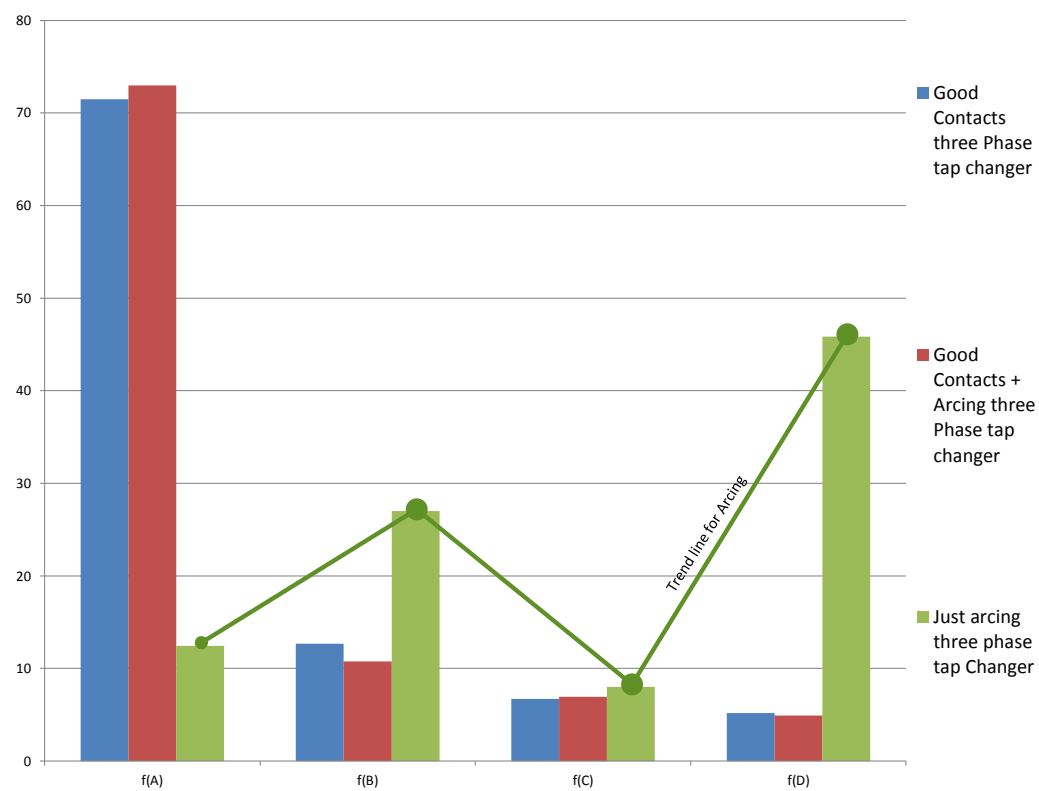
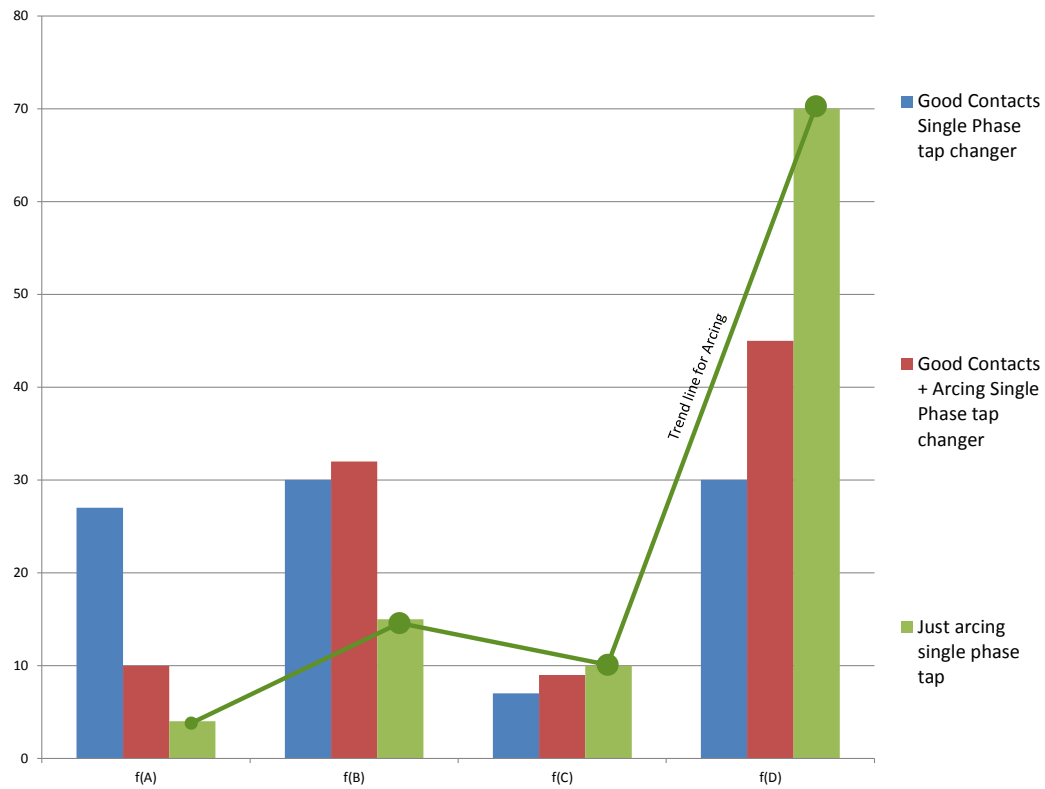
## 5.4 Conclusions and summary

The experiments in this chapter were performed on a large three phase automatic tap changer. Although this was a good test object to observe the working and characteristics of the tap changer, there were three main limitations with this setup:

- The tap changer was not inside the transformer and was standing free, hence the sensors had to be mounted directly on the tap changer and not on the transformer body.
- The inside of the stator of the tap changer was small so it was difficult to work inside the tap change and hence the defects in the contacts could not be introduced.
- Only the fine selector unit was accessible from the top so the experiments were conducted only on the fine selector unit.

The experiments done in chapter 4 were repeated on this tap changer to see the reproducibility of the results. On obtaining the results one of the first things that was amiss was that a clear distinction of the sequence of events as seen in chapter 4 was not visible.

One of the reasons speculated for this was the interference of acoustic signal from other sources such as the gear box. Figure 5.9 below, shows the comparison of the results obtained from chapter 4 and chapter 5. On comparing the three phenomena in the single phase and the three phase tap changer, namely good contacts, good contacts with arcing and just arcing phenomenon, it can be observed that for good contacts and good contacts with arcing there is hardly any correlation between the results as is shown by the blue and red bars in the chart. This difference is observed mainly due to the limitations of the test setup. But on comparing the results for the just arcing phenomenon, although the values of percentages of energies in the four bands are not the same for both the cases, the results seem to follow the same trend line. This proves that this measurement and analysis method is reliable for the measurement of tap changer defects.



**Figure 5.9 : Showing the comparison of the results obtained from good contacts, good contacts with arcing and just arcing phenomenon in case of the single phase and the three phase tap changer.**

# Chapter 6: Conclusion and summary

The objective of this thesis was to obtain diagnostic information from a tap changer using acoustic methods. This method was chosen over the other methods available, because it is a technique that is non-intrusive and can potentially be used online. The thesis research project was accomplished by using several test techniques and experimental setups using an extensive analysis in the time domain and in the frequency domain. Section 6.1 contains the summary of the main findings of the experimental observations and Section 6.2 contains some recommendations for future research.

## 6.1 Summary and Conclusions

The conclusions from all the experiments performed in the thesis can be summarized as follows:

The first tests involved measuring and analyzing the acoustic signals obtained from the impact of two copper-tungsten contacts. From these experiments, it was deduced that the shape acoustic signals obtained from these impacts were quite similar. This comparison was made using the cross correlation factor. Further, it was observed that the cross correlation factor remained high as long as the position of the sensor was not disturbed during measurements.

In the next phase of experimentation, a similar comparison was made for the arcing phenomenon and this resulted in a very low cross correlation factor (or a large scatter in the results). The cause of this decrease in cross correlation factor was due to the higher frequency components present in the acoustic signal obtained from arcing. This observation led to the decision of using an acoustic sensor with higher bandwidth (15 60 kHz) for the next experiments.

The next stage of experimentation involved the measurement of acoustic signals from an actual single phase tap changer. A large number of signals were obtained for various test conditions of the single phase tap changer and a method for analyzing this large amount of data was required. For this an algorithm was developed which could plot several Power/Frequency spectra in one graph. But, on comparing the plot obtained from various defects, no significant difference could be observed and hence analysis by this method was unsuccessful. Therefore another algorithm was developed which splits the frequency spectrum into five frequency bands. For each frequency band the energy was calculated. Using this method, it was possible to discriminate between the various defects that were tested.

The final step in this thesis project was conducting acoustic measurements on a large three phase tap changer in order to verify, whether or not the acoustic measurements and analytic method thus developed worked. Acoustic measurements of only one of the defects, that is arcing could be conducted in this setup due to practical limitations. The results obtained from these measurements did not seem to correlate with the previous results from the single phase tap changer. One of the reasons for this anomalous result was that, typically acoustic measurements are performed on a tap changer that is inside a transformer. But in this case the measurements were performed directly on a free standing tap changer, this was again due to a practical limitation.

Even though this method of analysis did not give a significantly strong result in case of contact defects, a good correlation between the results of the arcing phenomenon in case of the single phase tap changer and the three phase tap changer (Figure 5.9) was seen. Nevertheless more testing is still to be done under actual field conditions to verify the findings of this thesis.

## 6.2 Scope for Future research

Before arriving at the recommendations, a recent development in the tap changer technology, vacuum switching technology for on-load tap-changers will be discussed:

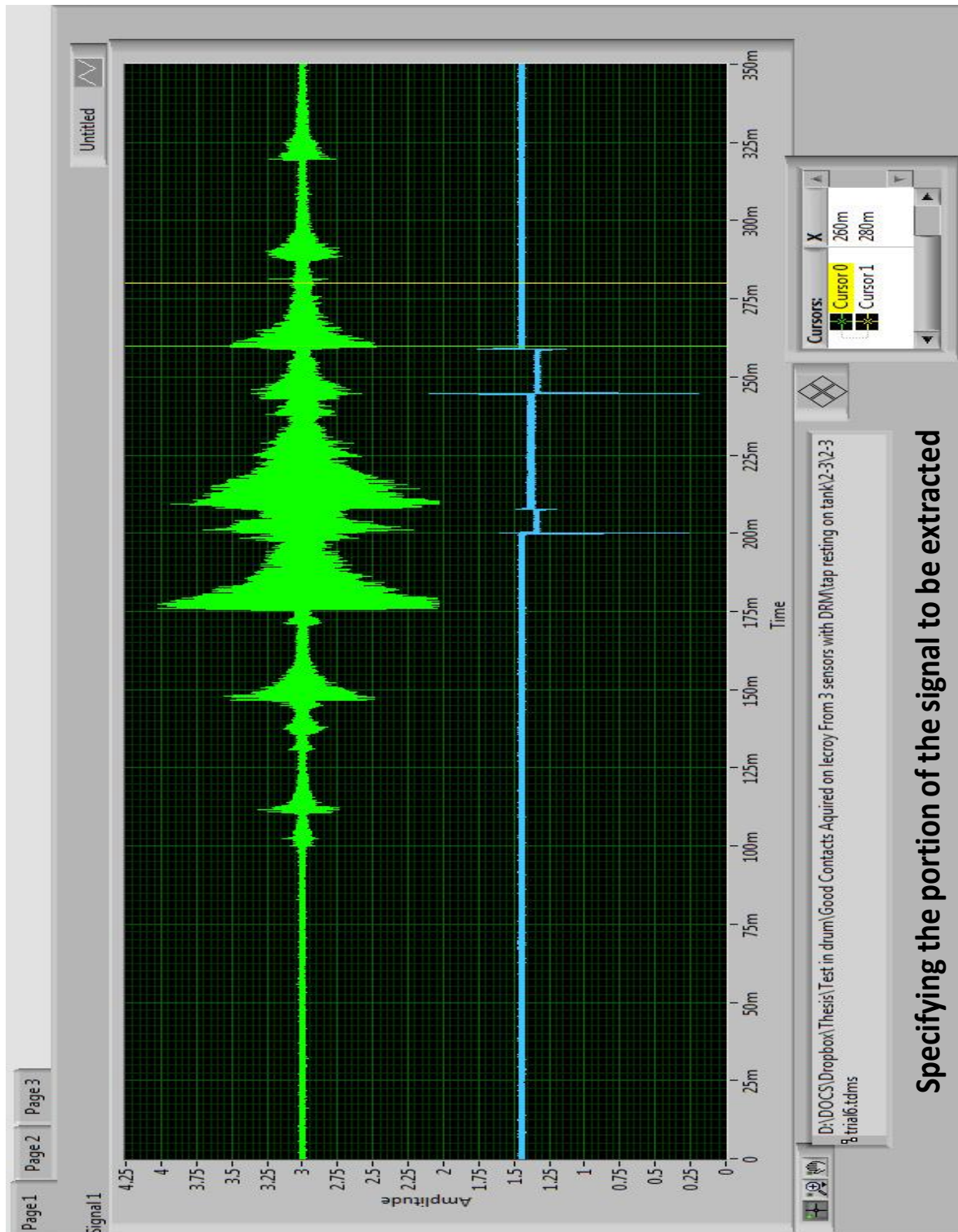
In vacuum switching technology, vacuum interrupters are added in the switching circuit. The design of the switching circuit is done in such a way that the arc, which was traditionally formed in oil, is now diverted to the vacuum switching unit. The arc is now formed as well as interrupted in the vacuum chamber, therefore the insulating oil will not be carbonized. Also as the rotor and stator contacts do not arc their lifetime is greatly increased. Although this is a very promising technology, it is relatively new and the majority of tap changers installed in the field are old, this justifies the need for further research into OLTC diagnostic techniques.

- One of the important research areas that is still to be covered is conducting measurements on tap changers in the field to verify these results obtained.
- The algorithm presented in this thesis could be improved to detect the defects automatically during field measurements. Also efforts could be made to reduce the amount of hardware needed for implementation of these acoustic measurements.
- A correlation needs to be made between the acoustic diagnostics of arcing and the amount of damage actually caused by arcing, in field conditions.
- Measurements made here were on a selector type tap changer, similar measurements can also be performed on a diverter type tap changer.
- A publically accessible database of acoustic signal characteristics from different manufactures and different models of tap changers, for both healthy and aged tap changers could be created, for future research. Also methods of combining acoustic results with other forms of online measurements could be looked into.

# Appendix A:

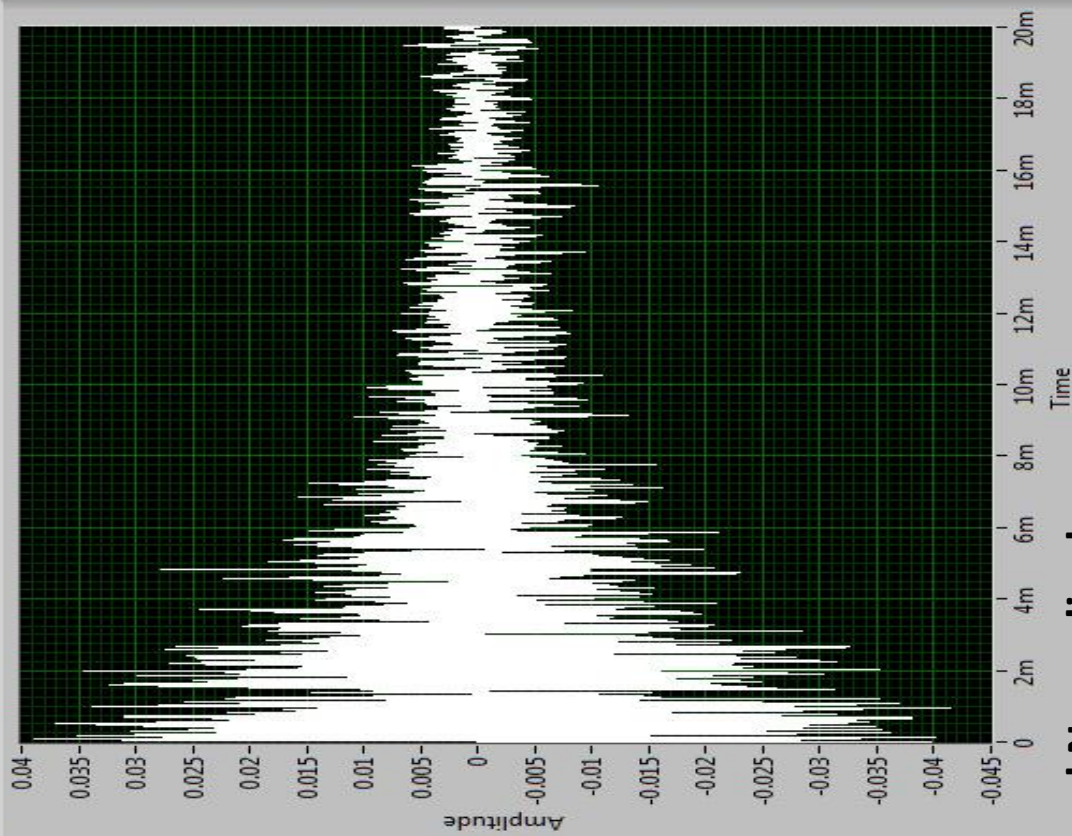
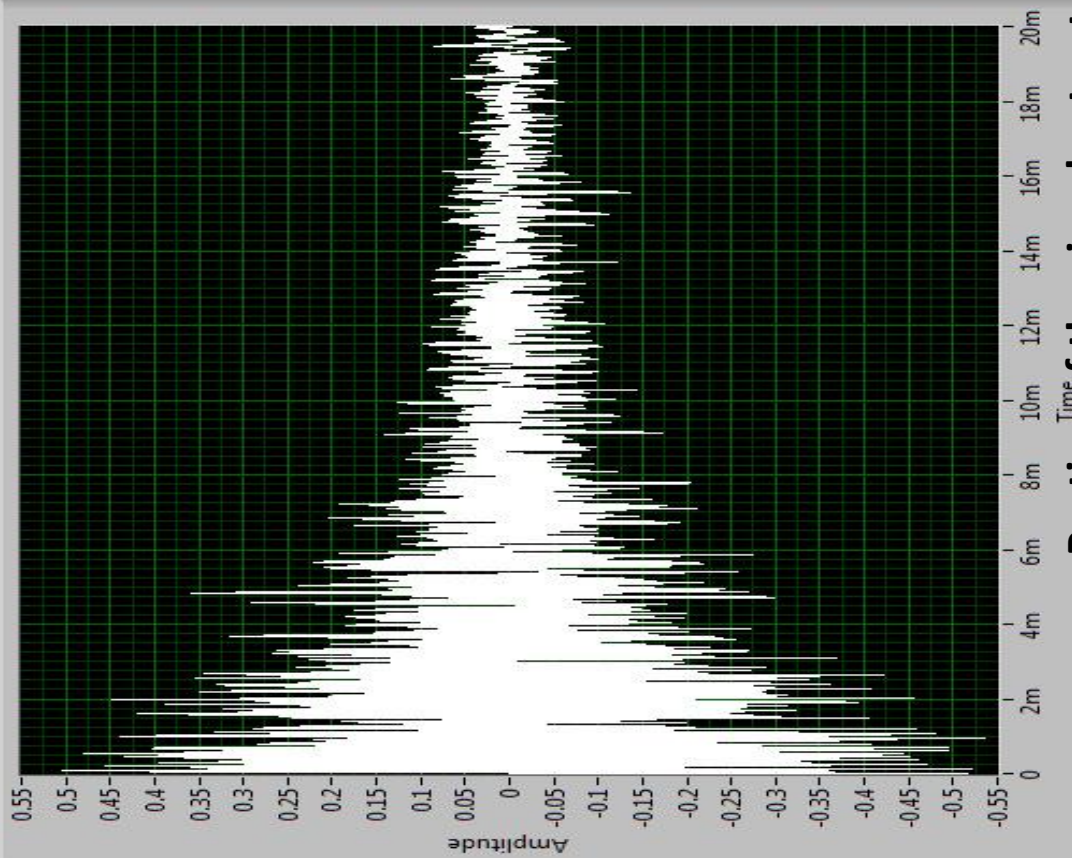
## Implementation of algorithm for frequency analysis in LabVIEW

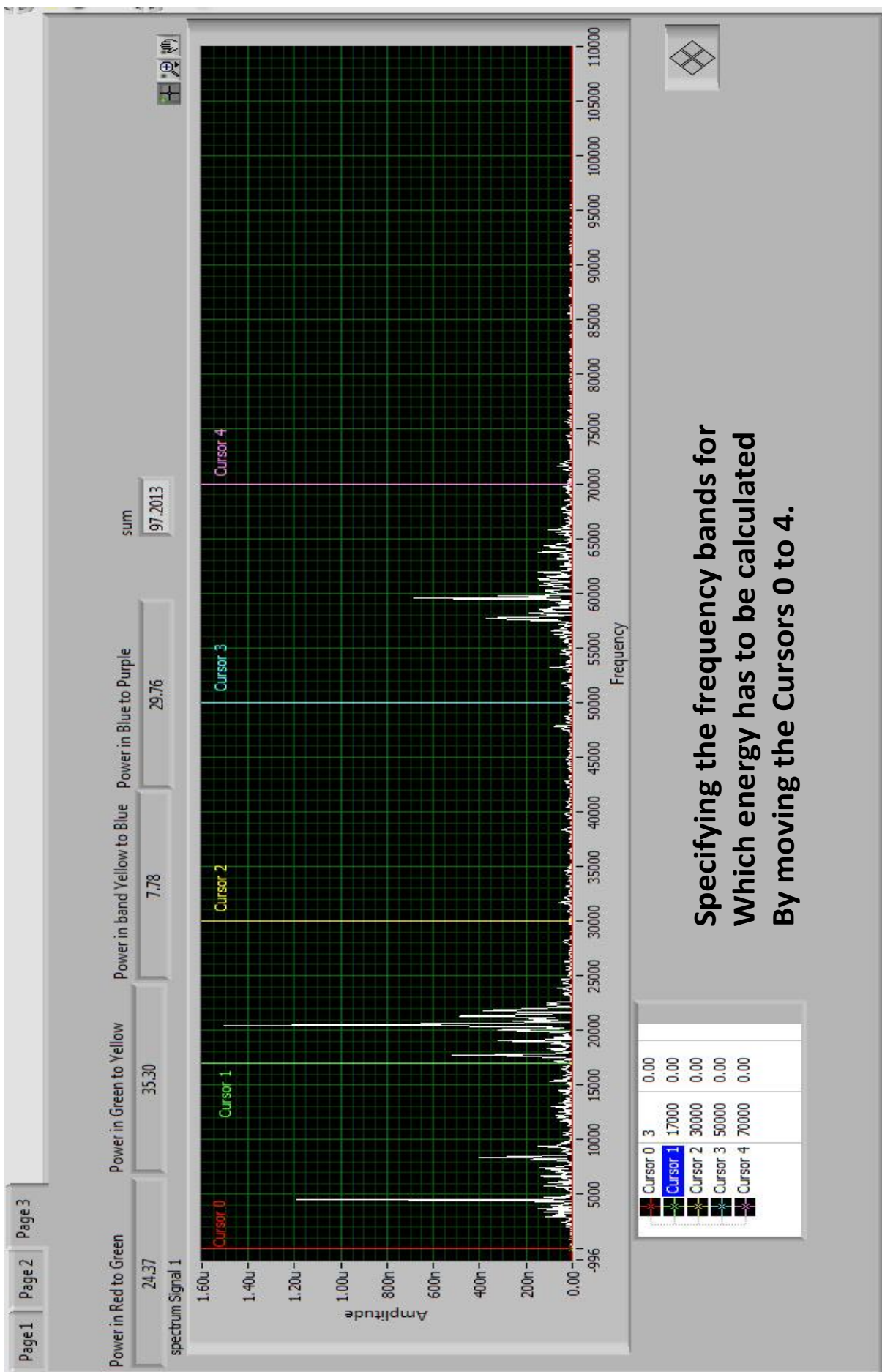
The following figures show how the interface, which was created for analyzing the acoustic waveforms, looks like. These figures also show the stepwise procedure for using this interface.

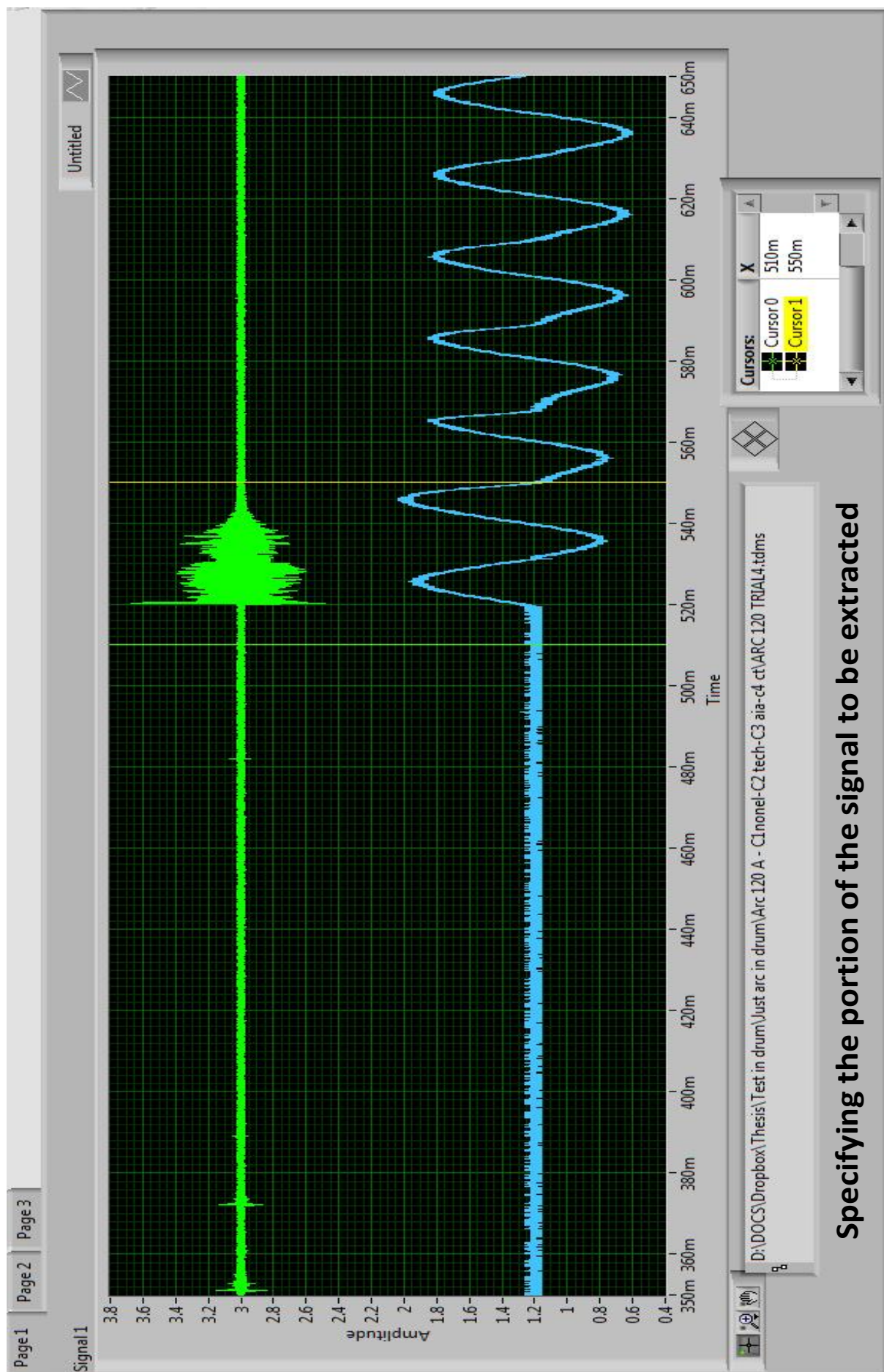


Section  
of Signal 1

WAVEFORM SIGNAL 1 AFTER NORMALIZATION

**Portion of the signal extracted and Normalized**

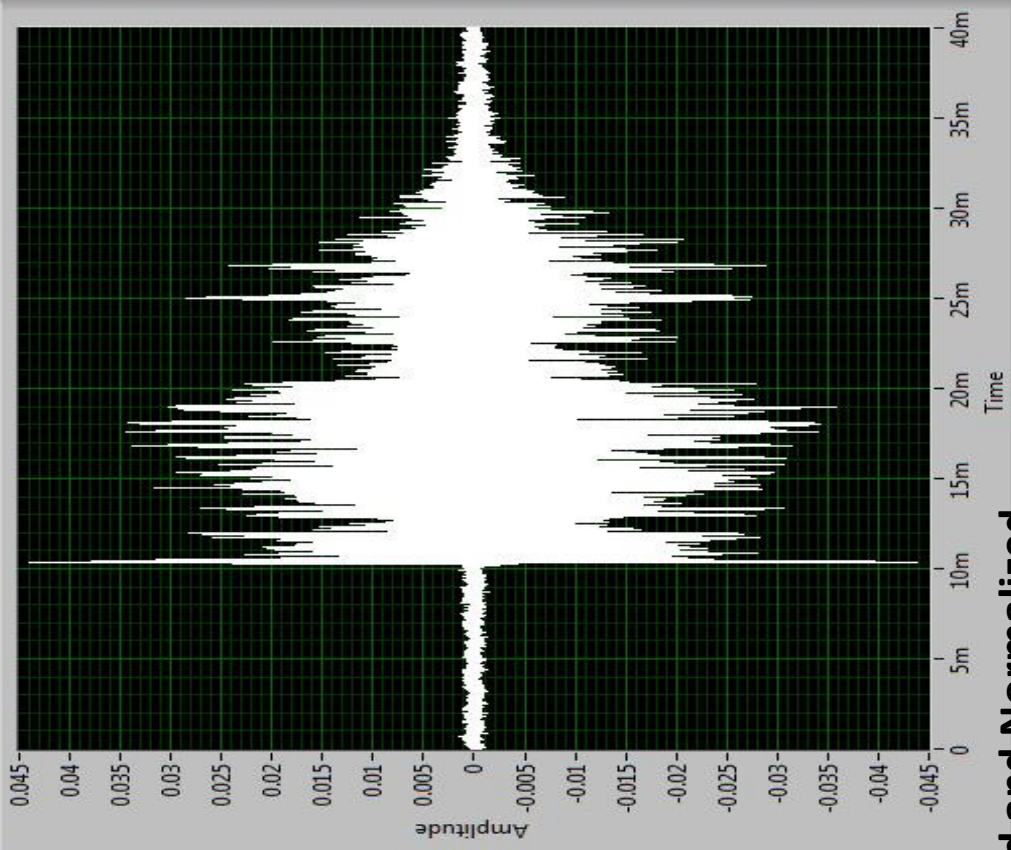
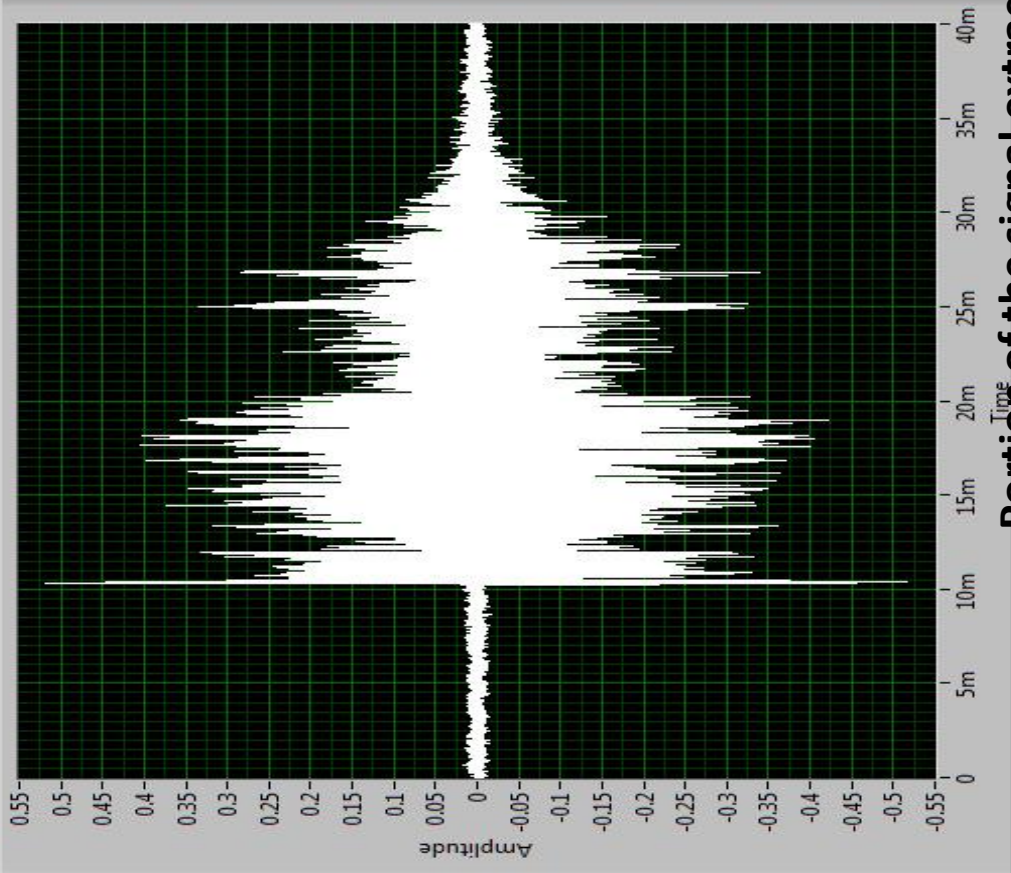




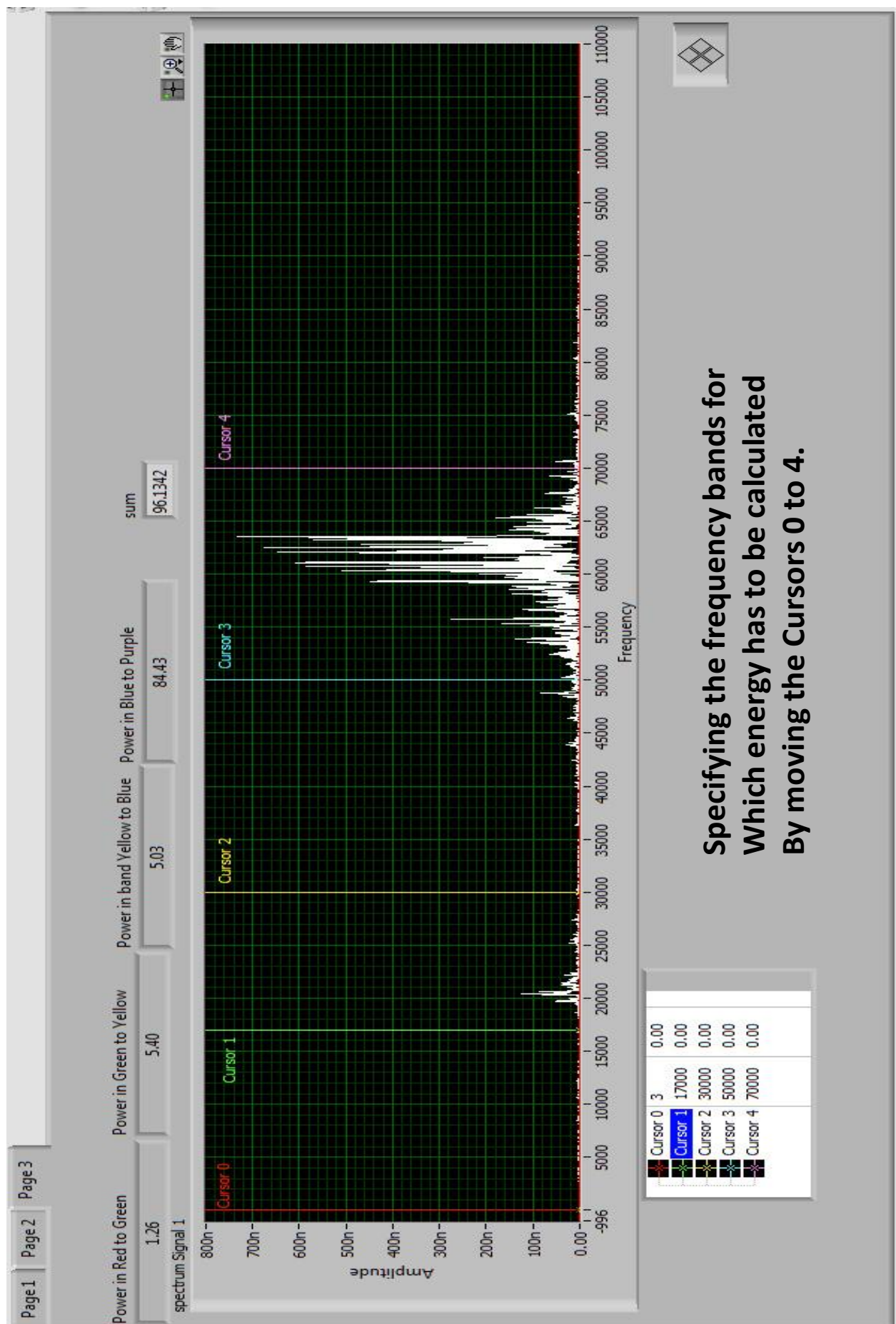
**Specifying the portion of the signal to be extracted**

Section of Signal 1

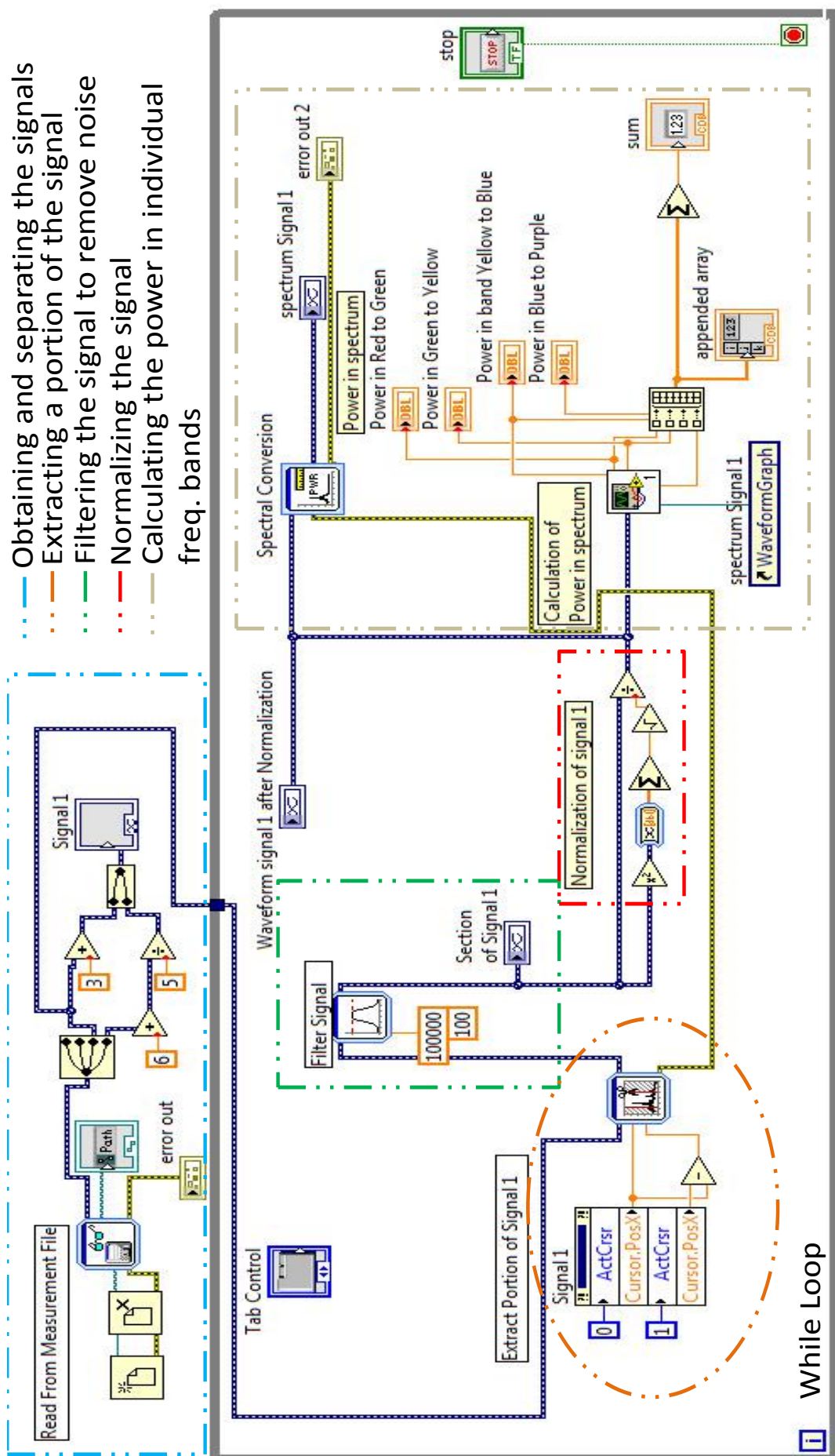
WAVEFORM SIGNAL 1 AFTER NORMALIZATION



Portion of the signal extracted and Normalized

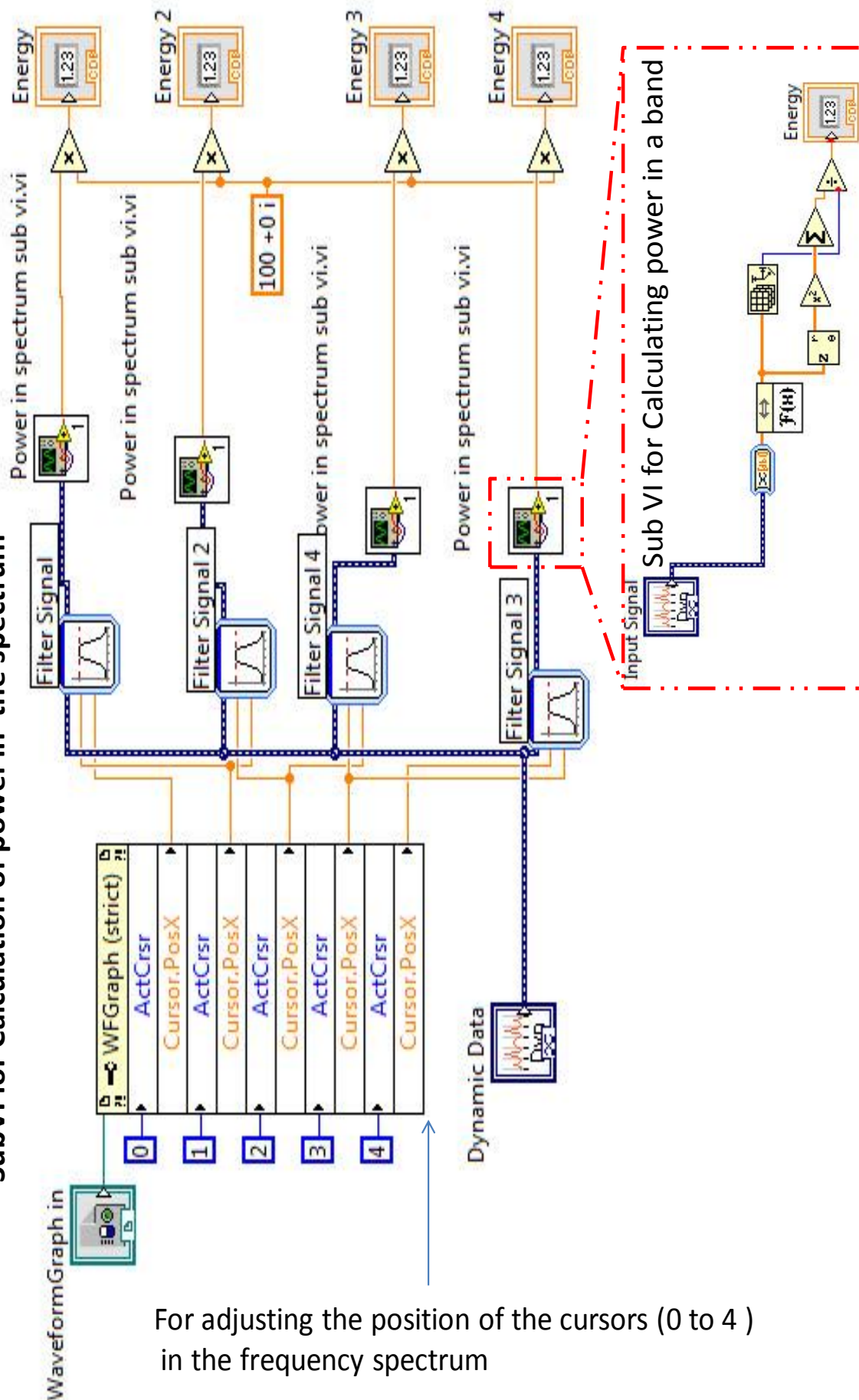


**Specifying the frequency bands for  
Which energy has to be calculated  
By moving the Cursors 0 to 4.**



## Showing Implementation of the algorithm in LabVIEW

## SubVI for Calculation of power in the spectrum



|                                                                                                             |                                       |                                                                                                                                                                                                                                                         |
|-------------------------------------------------------------------------------------------------------------|---------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                            | Filename Out                          | Returns the name of the file.                                                                                                                                                                                                                           |
|                            | Section [Section of Signal 1]         | Returns the extracted portion of the input signal.                                                                                                                                                                                                      |
|                            | Waveform signal 1 after Normalization | Returns the normalized signal.                                                                                                                                                                                                                          |
|                            | Spectrum Signal 1                     | Returns the spectrum of the normalized signal.                                                                                                                                                                                                          |
|                            | Power in Band Blue to Purple          | Returns the aggregate power in the specified range.                                                                                                                                                                                                     |
|                            | Power in Band Red to Green            | Returns the aggregate power in the specified range.                                                                                                                                                                                                     |
|                            | Power in Band Green to Yellow         | Returns the aggregate power in the specified range.                                                                                                                                                                                                     |
|                            | Power in Band Yellow to Blue          | Returns the aggregate power in the specified range.                                                                                                                                                                                                     |
|                            | Appended array                        | Returns all the data in an array                                                                                                                                                                                                                        |
|                            | Sum                                   | Returns the sum of the aggregate power in all the bands.                                                                                                                                                                                                |
|                            | Spectral Measurements                 | Performs FFT-based spectral measurements, such as the averaged magnitude spectrum, power spectrum, and phase spectrum on a signal.                                                                                                                      |
|                            | Sub VI                                | An Executable VI                                                                                                                                                                                                                                        |
|                            | Convert from Dynamic Data             | Converts the dynamic data type to numeric, Boolean, waveform, and array data types for use with other VIs and functions.                                                                                                                                |
|                            | Filter Signal Filter                  | Processes signals through filters and windows                                                                                                                                                                                                           |
| <b>Type: Band pass ; IIR/FIR: Infinite Impulse Response (IIR) Filter ; Topology: Butterworth ; Order: 8</b> |                                       |                                                                                                                                                                                                                                                         |
|                            | Extract Portion of Signal             | Extracts portions of data from the input signals and returns the extracted data. You can extract a single point or a range of data, and you can extract data by time or index. You also can find the time and index of the first occurrence of a value. |
|                            | Read From Measurement File            | Reads data from a text-based measurement file (.lvm) or binary measurement file (.tdm or .tdms).                                                                                                                                                        |
|                            | FFT VI                                | Computes the fast Fourier transform (FFT) of the input sequence                                                                                                                                                                                         |
|                            | Array Size Function                   | Returns the number of elements in each dimension of array.                                                                                                                                                                                              |
|                           | Add Array Elements Function           | Returns the sum of all the elements in numeric array.                                                                                                                                                                                                   |
|                          | Square Function                       | Computes the square of the input value.                                                                                                                                                                                                                 |
|                          | Complex To Polar Function             | Breaks a complex number into its polar components                                                                                                                                                                                                       |
|                          | Build Array Function                  | Concatenates multiple arrays or appends elements to an n-dimensional array.                                                                                                                                                                             |

Table 3: Showing the name and functionality of the various symbols used in the logic diagram.

## Appendix B

| Name plate details of the three phase transformer used for the experiments. |                |
|-----------------------------------------------------------------------------|----------------|
| Willem smit & Co's                                                          |                |
| Transformatorenfabriek NV                                                   |                |
| Nijmegen-Netherlands                                                        |                |
| Voltage                                                                     | 170 kV         |
| Number of Phases                                                            | 3 + NEUTRAL    |
| Number of steps                                                             | 21             |
| Operating frequency                                                         | 50 Hz          |
| Nominal Current                                                             | 600 A          |
| Connection                                                                  | Star connected |
| Type                                                                        | Selector type  |
| Short Circuit Current                                                       | 12KA for 8 s   |
| Resistance                                                                  | 2.55 ohm       |

# Bibliography

- [1] "On load tap changing equipment," Willem Smit and CO'S.
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