High Frequency Modelling of a Transformer Winding for Partial Discharge Localization

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Abstract

The IEEE defines Partial Discharge (PD) as an electric discharge that only partially bridges the insulation between two conductors. In high voltage equipment such as transformers, floating components or defects in transformers can be the cause of partial discharge. Over periods of time the transformer ages and will result in faults. The materials in the transformer such as the windings can be damaged due to mechanical and electrical stresses. For this reason study of PDs is important for the prevention of faults and in maintenance of transformers. In this thesis a 3-phase 6.6kV, 1MVA high voltage transformer winding is modelled using the lumped parameter model. The transformer winding is then simulated using MATLAB/ SIMULINK along with SimPowerSystems toolbox. A simulated current pulse is injected at different positions along the winding, to simulate PDs in the winding.

The responses due to the PD injection at various positions are measured from the line-end and analysed. The voltage response results indicated that PD’s along the winding have more oscillations moving away from the line-end, hence PD at disc pair 10 is the most oscillatory. It was also evident that as the PD moves away from the line-end the waveforms have a greater distortion. The frequency spectra results showed that the poles (crests) always occurred at fixed frequencies no matter the location of the PD, thus the frequency of the poles are independent of the PD location. However the zeros (troughs) altered in frequency depending on the PD location, and as the PD source moved away from the line-end, the zeros increased in frequencies.
Disclaimer

I declare the following to be my own work, unless otherwise referenced, as defined by the University’s policy on plagiarism.

Signed:

Date:
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CHAPTER- 1

INTRODUCTION

Literature review

Motivation and objective of the thesis

Organization of the thesis
Chapter 1: INTRODUCTION

Partial discharge (PD) is an electrical discharge that only partially bridges the insulation between conductors [7]. In high voltage equipment such as transformers, partial discharge can be the cause of floating components or defects in the transformer. Initially after the manufacturing process of the transformer PD detection is a good tool to analyse the health of the transformer and the quality of the manufacturer. Over periods of time the transformer will age and faults are the result. The transformer ages due to mechanical and electrical stresses and the materials in the transformer such as the windings and the insulation paper lining the walls of the transformer tank can be damaged. If the damage is not detected or fixed this will lead to a fault which will cause the transformer to operate outside of its operational conditions and ultimately a disastrous fault occurs causing damages to the transformer and the surrounding facilities. This leads to revenue losses due to the cost of maintenance and replacements of equipment as well as power outage. In high voltage power plants PD detection is undertaken to check the health of a transformer and assist the plant managers in the scheduling of equipment maintenance.

PD detection measurements are concerned with the generation and dissipation of energy in particular the generation of magnetic energy, dissipation of heat in the form of energy or noise signal resulting from lightning. There are various types of PDs, corona, surface, treeing and cavity discharges [1]. In the industry there are three detection methods chemical, electrical and acoustic. Acoustic detection is generally the more favoured method because not only does it detect the PD, the sensors locates the source of the PD, which also decreases the maintenance time.

Partial discharges are current pulses with frequency from few tens of KHz up to GHz range. Therefore to analyse PD in transformers, a high frequency model of the transformer has to
be developed. In this project a method of simulating a high frequency transformer is presented to better locate PD sources.

A 3-phase, 6.6kV, 1MVA high voltage transformer winding is simulated in SIMULINK an extension of MATLAB using the SimPowerSystems tool box. A PD pulse is also simulated and injected at various locations along the winding. The responses from the line end are analysed to identify the relationship between the location of the PD source and the responses.

1.1: LITERATURE REVIEW

Over the past years a lot of studies have been undertaken in the subject of partial discharge below are some relevant to this thesis project.

Authors Hettiwatte, S.N.Wang, Z.D, Crossley, P.A., Darwin, A., Edwards, G. In their paper Experimental investigation into the propagation of partial discharge pulses in transformers investigate partial discharge pulses in 6.6kV continuous winding transformer. To achieve this, a calibrator is used to inject PD pulses into the windings and a wide band current transformer (CT) is used to measure current signals at the line and neutral end points. The authors conclude that the position of trough(zeros) in the frequency spectra of the measured time domain signal change depending on the location of the PD injection and the crests (poles) of the spectra are not affected by the position of the injection [2].

Authors Hettiwatte, S.N., Crossley, P.A., Wang, Z.D., Darwin, A., Edwards, G. In the paper Simulation of a transformer winding for partial discharge propagation studies a model based on multi-conductor transmission line theory is used to investigate the propagation behaviour of partial discharge pulses in a continuous disc type 6.6 kV transformer winding. A transfer function is implemented to observe how the location of the PD affects the current signal measured from the line and neutral end points. The paper concludes that the position of zeros in the frequency response of the measured current signal can be used to locate the position of the PD source [3].

Authors Zhongdong Wang, Jie Li, Sofian, D.M. In their paper Interpretation of Transformer FRA Responses— Part I: Influence of Winding Structure uses a lumped parameter model for
two types of windings continuous and intershielded to study how the structure of a transformer winding affect frequency response analysis (FRA) responses. The findings of this paper state that windings with high series capacitance have FRA responses with increasing magnitude while low series capacitance has stable magnitudes [4].

In the paper *A method for studying partial discharges location and propagation within power transformer winding based on the structural data* authors Naderi, M.S.; Vakilian, M.; Blackburn, T.R.; Phung, B.T.; Zhang, H. develop an algorithm to locate PD propagation by modelling the transformer winding by a lumped parameter model based on its structural data. For this method each turn of the transformer winding is considered as a segment and simulations are carried out with the software Visual Basic. For the simulation PD current pulses are injected at different location in the winding and line-end voltage is measured for PD propagation [5].

Lv Fangcheng; Liu Yunpeng; Liu Lei; Li Chengrong authors of the paper *Pulse propagation model of partial discharge in transformer winding* model a 180 turn single winding 400kV transformer centred on the multi-conductor transmission lines (MTLs) theory to study the localisation of PD in continuous disk winding. Transformation of the mode current and mode voltages are applied for the MTL solution; from this the transfer function of the winding is obtained. The authors use the scattering parameter method to measure the nature of the winding transfer functions and how this can be used to locate PD propagation [6].

### 1.2: MOTIVATION AND OBJECTIVE OF THE THESIS

The occurrence of partial discharge plays a big role in the insulation failure of transformers in power stations. The manufacturers of the insulation are not to blame, rather the occurrence of PDs at voids (bubbles) inside the insulation are the cause. For this purpose the detection of PDs at an early stage is important.

The goal of this project is to:

- Model A 3-phase 6.6kV, 1MVA high voltage transformer winding using the lumped parameter model
Simulate the model using the SimPowerSystems tool box in MATLAB/ SIMULINK.

Simulate a PD pulse

Inject the pulse at various location

To investigate

- The type of responses measured at the line end of the winding
- How the responses can be related to the location of the PD source at the winding.

1.3: ORGANISATION OF THESIS

This thesis is organized into the following chapters

**Chapter 1:** This chapter introduces the Partial Discharge phenomenon, the motivations and the objectives of the project are stated along with a literature review of PD.

**Chapter 2:** This chapter defines the concept of PD, the types of PDs are classified and the importance of PD detection is explained along with current methods of detection.

**Chapter 3:** This chapter looks at the principles of HV Transformers and their construction.

**Chapter 4:** In this chapter the lumped parameters are used to model the transformer winding. The capacitance and inductance values are calculated using the relevant formulas.

**Chapter 5:** This chapter explains the basic function of the computation tool MATLAB and its extensions SIMULINK and SimPowerSystems. The transformer windings are also simulated in SIMULINK in this chapter.

**Chapter 6:** In this chapter the simulation results are presented and analysed in both time frequency domains.

**Chapter 7:** In this chapter conclusions are made on the findings and scope for future work is discussed.
1.4: REFERENCES


CHAPTER- 2

PARTIAL DISCHARGE
PHENOMENON

Partial discharge (PD)
Classifications of partial discharge
Importance of PD detection
Methods of detection
Chapter 2

PARTIAL DISCHARGE (PD) PHENOMENON

Chapter 2: BACKGROUND
Currently, the population of the world continues to rise drastically, with it comes an increase in the world economy and further advances in science and technology. Due to these advances a mass supply of electricity is required to service our daily requirements. Much of what is done in manufacturing, health services, households, entertainment and transport are all dependent on electricity. The formula for the generation and supply of electricity has three factors.

- Generation
- Transmission
- Distribution

A 50Hz three phase AC system is used for the generation, transmission and distribution of electricity. A transformer is a must have in all power systems for stepping up and down of AC voltages without altering their frequency.

By definition, a transformer is a static device which switches electrical energy between circuits without altering the frequency by electromagnetic induction. Major components of the transformer are the magnetic core laminated with silicon steel and the primary & secondary coil windings. Electrical energy delivered to the primary winding is transformed into magnetic energy and then transformed back to electrical energy in the secondary windings. If the primary winding is less than the secondary it’s termed a step up transformer and if the secondary voltage is lower than the primary voltage, it’s termed a step down transformer [1].
Another major component of the transformer is the insulation of the windings as it plays a major role in high voltage equipment. Insulation materials can be made of gases, solids, liquids or a combination of them. As the transformer begins to age, insulation degradation occurs due to electrical, mechanical or chemical stresses. Partial discharge (PD) is a source of electrical stress which contributes to degradation.

Most literature refers to partial discharge as an electrical discharge that takes place in portion of a dielectric insulation [2]. PD can occur at voids (air bubbles) in the interior of the insulation or on the surface of the insulation due to high voltages. PD is a major cause of insulation breakdown resulting in the decrease of lifespan and eventually the failure of the high powered transformer. This makes for the detection of partial discharge very important for the maintenance of HV transformers and cost reduction in case of transformer life span reduction.

In this thesis a 3-phase, 6.6kV, 1MVA, 22 disc and 13 turn per disc transformer winding is modelled and simulated on MATLAB/ SIMULINK for partial discharge location. The objective is to inject a current PD pulse at different locations along the winding and investigate what information the responses at line-end contain to better localize the source of the PD.

2.1: PARTIAL DISCHARGE
According to the IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery partial discharge (PD) is an electrical discharge that only partially bridges the insulation between conductors [3]. PD is usually the cause of electrical stress and can occur at voids (air bubbles) in the interior of the insulation or on the surface of the insulation due to high voltages.

Partial discharge detection can be utilised for the monitoring of high voltage transformers, as high voltage equipment begin to age, degradation of the insulation occurs due to either external factors like lightning strikes or internal factors like partial discharge. This is why it is important to locate PDs in high voltage equipment so that the correct actions can be taken to prevent failure and increase life time. PD can be observed in HV transformers and appear as voltage or current pulses with duration less than 1 sec [3].
2.2: CLASSIFICATIONS of PARTIAL DISCHARGE

Partial discharge can be grouped in to internal and external.

A) EXTERNAL
External discharge occurs on the outside of the HV equipment e.g. the overhead transmission lines or the armature.

B) INTERNAL
Internal partial discharges are within the equipment in voids and PD measurements are required. These measurements are required to investigate the location of the discharge in the insulation in order to take further action. Partial discharge measurements are concerned with the generation and dissipation of energy, in particular the generation of magnetic energy, dissipation of heat in the form of energy or noise signal resulting from lightning. There are various types of PDs corona, surface discharge, treeing and cavity discharges [3].

I. Corona discharge
Corona is a discharge caused by the ionization of air that surrounds the conductor due to the exposure of high voltage which exceeds that of the conductor’s critical value. This type of discharge can appear on solid, liquid or gaseous conductor materials and usually is an early indication of insulation failure [2].

II. Surface discharge
Surface discharges appear on the interface of solid or gaseous dielectric materials. The interface of oil impregnated pressboard is an issue in HV equipments because it leads to electrical faults under normal operating conditions [4]. Surface discharge can exist for a lengthy period of time, sometimes years resulting in serous electrical arcs [5].

III. Cavity discharge
Cavity discharge is found on solid or liquid dielectrics that are filled with gas. There are many causes of cavity, for example air leaking into the mould during curing [6]
2.3: IMPORTANCE of PD DETECTION

Insulation materials are empirical part of HV insulation. As time goes on voids are created due to the existence of air bubble. This results in the wreaking of the insulation leading to partial discharge in the HV equipment. The occurrence of PD causes the degradation of the insulation material giving rise to failure of the HV equipment. For this reason the detection of partial discharge in the insulations of HV equipment is a must for early treatment and prevention of equipment failure.

2.4: METHODS of DETECTION

Over the past 40 years or so different methods have been developed for detecting partial discharge in high voltage equipment, Below is a list of these methods.

2.4.1: Chemical Detection

In the chemical detection process a current streamer is used to breakdown the surrounding materials into different chemicals. The two most common chemical test used are the dissolved gas analyses and the high performance liquid chromatography (HPLC). In the DGA test oil samples are collected from the transformer and the levels of gases are analysed for presence of PDs. However with this method it is not clear if the levels of gases actually lead to a fault.

The HPLC method is also a collection of oil samples and testing of the levels of glucose in the oil because the insulation of the transformer windings are made of glucose, hence the presence of glucose in the oil means breakdown of insulation. This test also has its disadvantages because there is no evidence which state that glucose in the oil sample leads to a fault [7].

2.4.2: Electrical Detection

The electrical detection method focuses on the capturing of electrical pulses in the transformer. The shape of the transformer is analysed for the extent of the insulation damage and occurrence of a PD fault. There are two types of electrical detection methods direct probing and RF emission where capacitive couplers and antennas are used respectively. The disadvantage of this method is the interference of noise during testing [8].
2.4.3: Acoustic Detection
Rather than electrical detection this method uses sensors at several locations of the transformer to capture and record acoustic signal generated by the vent partial discharge, the pressure in the tank is then analysed for propagation of pressure. The advantage of this method is that sensors can be located at different location in the transformer for PD activity. The disadvantage of this method is the complexity of the wave forms generated by the acoustic detection sensors [7].
2.5: REFERENCES


CHAPTER- 3

POWER TRANSFORMERS

Principle of Transformers

Construction of Transformers
Chapter 3

PRINCIPLE OF POWER TRANSFORMERS

Chapter 3: PRINCIPLE of TRANSFORMER

A Transformer is based on the principle of ‘Mutual Inductance’. Altering the current in coil 1 produces a changing magnetic flux in coil 2. Coil 1 has N1 turns and carries a current I1 which creates a magnetic field $B_1$. The two coils are coupled with each other using magnetic core so some of the magnetic flux lines from coil 1 will also run through coil 2. If $\Phi_B$ is the magnetic flux that goes through a turn of coil 2 due to I1 and by altering I1 an emf is induced because of the change in magnetic flux in coil 2.

$$\mathcal{E} = \frac{d\Phi_B}{dt} \quad \text{(Faraday’s Law)[1]}$$

Assuming that the circuit on the secondary side is connected to a load, then current passes through the secondary winding from the primary coil. In a step up transformer the secondary turns (N2) is greater than the number of primary turns (N1), and it is the opposite for the step down transformer.
3.1: CONSTRUCTION OF POWER TRANSFORMERS

A transformer is a device used to transfer electrical energy from one circuit to another without the alteration in frequency. The process involves inductively coupled circuits called the coils of the transformer. There are two of these coils, primary and secondary coils.

The construction of a transformer may look simple with a magnetic circuit linked with two windings; however there are other parts that make the formation of a functioning transformer:

- The core
- Windings
- Bushings
- Transformer tank
- Breather
- Conservator tank
- Buchholz relay

3.1.1: Core Construction

The core is what provides the path for the magnetic flux and is made of thin strip of steel know as laminations which are separated electrically by insulating materials. There are two types of core cross section: rectangular or circular, with rectangular used for small ratings. Naturally the core will heat up due to heat generated. To remove heat cooling ducts are placed inside the core and lamination is separated to decrease localised losses.

The core is held together by mechanical structures and ground onto a point in order to disperse electrostatic build up. The point of grounding must be an easily accessible point in the transformer tank or through the bushing on the wall of the tank. This point must also be removable for testing purposes. The maximum flux density of the core is aligned closely to the knee of the saturation curve taking into consideration over excitation and tolerance caused by the material and the manufacturing process. In power transformers flux density is between 1.3T- 1.8T and the magnetic steel saturation point is 2.03T-2.05T [1].

There are two types of magnetic cores: core type and shell type. The core type has only one path for the magnetic flux. In a single phase transformer the windings are on both legs of the
core and on a three phase transformer windings for every phase are on the same leg. In comparison the shell form construction has multiple paths for the magnetic flux, and the core is stacked around the windings which are typically pancake windings. Shell forms are used for high current applications and have five or seven legged cores subjected to size and tender.

Figure 3.2: (a) 3-phase core form, (b) single-phase core form construction [2]

3.1.2: Transformer Windings
Primarily windings are current carrying conductors coiled around the core and they must be carefully insulated, supported and cooled for both testing and operational conditions. In power transformers the windings are generally made of aluminium or copper. Aluminium is cheaper than copper, however a large cross section of aluminium conductor is needed to perform like the copper conductors. Copper conductors have a high mechanical strength and are used in large transformers, while small transformers use aluminium conductors for windings. In this thesis helical and disc windings are analysed closely.
**Helical windings**
The terms helical, screw or spirals are used because of the manner in which the windings are constructed. These types of windings contain just over 100 insulated strands coiled in parallel continuously around the whole cylinder with spacers implanted between adjacent turns/disks. Helical windings typical are used in high current tenders in lower voltage classes.

**Disk windings**
Disk windings are made of either single strands or numerous strands of insulated conductors coiled in series with parallel disks in a horizontal alignment. The disc can be coupled on the inside or the outside of the cross over point. Each disk consists of multiple turns with the cross over point interchanging from inside to outside. Most high powered core type transformers with 25kV and over rating are disc type, and because of this high voltage careful design is required to avoid high levels of stress between turns at the winding ends. Many methods have established for acceptable voltage distribution along the windings in these conditions. There are two types of disc windings continuous and interleaved windings.

**3.1.3: Transformer Tank**
In the selection of a transformer tank material the weight, stray load losses and minimization of cost are taken into consideration. It is a must that the tank is able to withstand the jacking and lifting stresses and must be able to accommodate for the parts like windings and cores.

There also needs to be enough space between the windings and the tank walls. The body of the tank is usually made of steel plates.

Small tanks are generally welded from steel plates. The larger tanks are assembled from boiler plates. Usage of aluminium for transformer tanks reduces the weight and the stray magnetic losses. However, it increases the cost and also needs special attention for lifting to present stressing. The aluminium tanks are usually made of cast aluminium tank parts, which are mounted on a shallow mild steel tray and are arranged to carry the main lifting.
3.1.4: Conservator
The conservator is a small tank which is mounted on top of the transformer and connected by a pipe to the main tank. The transformer tank is filled with oil with the level of the oil dependent on the operations of the transformer. The oil will expand in summer due to the increase in the load and contract in low load periods. The function of the conservator is to keep the main transformer tank full with oil at all times. At contraction periods the conservator delivers oil to the main tank and when the oil expands the conservator receives oil from the main tank. The oil is the liquid insulation and it also acts as a coolant.

3.1.5: Buchholz relay
The Buchholz relay is protection device which can be activated by oil or gas. This relay is used in all transformers that are immersed in oil having ratings greater than 750kVA. The relay is installed in the pipe work joining the transformer main tank and the conservator and sometimes an additional second relay is installed for the tap changer selector chamber. The role of the Buchholz relay is to detect faults in the transformer due to float displacements by build-up of gas or flap movement by oil surges and disconnect it from the transmission line to stop further severe faults.

3.1.6: Bushings
Transformer bushings consist of conducting rods for carrying current. Generally porcelain insulator is used in voltages of up to 33KV and oil filled capacitor type for anything higher. The bushings are a crucial part of a transformer for conduction. The bushings are necessary to complete the conductive energy output of the volts that are transformed within the transformer so that they can then move through mediums such as air and gas, including the grounding barriers that each unit is designed with.

3.1.7: Breather
During periods when the transformer heats up, the oil & gas expand and the oil at the top of transformer is driven out. When air comes in the transformer cools. The function of the breather is to stop the build-up of moisture in the transformer. If moisture is allowed to build up in the transformer the insulation between the windings is damaged and its starts to
conduct which leads to damages in the windings. When air with moisture content enters the transformer, the breather consists of silica gel which absorbs the moisture content in the air and only allows clean air into the transformer. This is called the breathing process. The breather material is light pink when wet and blue when dry. The breather also has an oil gap to stop dust particles from entering the transformer.
3.2: REFERENCES


CHAPTER 4

PARAMETER CALCULATIONS

Lumped Parameter Model

Capacitance Calculations

Inductance Calculations

Final Calculated Parameters
Chapter 4: PARAMETER CALCULATIONS

The next section of this project is the parameter calculations which are based on the specification of the 3-phase 6.6kV, 1MVA high voltage transformer winding being investigated. The cross-sectional view of any two continuous discs can be represented by figure 4.1 where there are 2 disks and 13 turns per disk.

Figure 4.1: Cross-sectional view of 2 discs in series with 13 turns per disc [7]
4.1: LUMPED PARAMETER MODEL
The use of the lumped parameter model to investigate transformers internal transient response can be dated back as far as 1915 [1]. Unfortunately prior to the beginning of the 1960’s these exertions had inadequate success due to the lack of computer technology for solving complex differential equations. In this period most the work was done in the time domain by means of the following two methods standing wave or traveling wave. The frequency domain was also examined and the results were combined to get the desired time domain response. Abetti in 1960 developed the notion of scale or analog model for fresh designs and his causes were aided with the launch of high speed computers, which meant improved algorithms for increased accuracy, speed and greater detail.

General electrics in 1970 started to develop a program for computation of transient responses for core-form windings and made it available to the industry by the end of the 1970’s. A short time after Wilcox enhanced the model with the inclusion of core loses in the linear frequency time domain by calculating mutual and self-inductance between windings in consideration of the core permeability [2].

Then in 1994 de Leon and Semlyen designed a nonlinear three-phase transformer model with core and windings. This was the first time that frequency dependency and nonlinearity were analysed together in a transformer model [1].

The investigation of transient responses of a physical transformer is very complex and is only possible with the use of a lumped parameter model. The most common technique is to subdivide the winding into number of discs or turns. If not done properly this could result in inaccurate model of the physical transformer. The lumped parameter model consists of inductance, capacitance and resistive elements.

Basically a lumped parameter model is primarily an RLC circuit which as the letters suggest consist of a resistor, an inductor and a capacitor. More specifically, these components are the series capacitance (Cs), shunt capacitance or capacitance to ground (Cg) and self-inductance (Li) [3]. Figure 4.2 represents the lumped parameter model for two discs (26 turns). The resistance is not considered in the lumped parameter model for this investigation.
because its negligible compared to the capacitance and inductance value. Since this study is based on a 22 disc (286 turns) transformer there are 11 of these circuits in series on the complete model. In the next section of this thesis these parameters are calculated and discussed in detail.

![2 disc equivalent circuits (Lumped parameter model)](image)

**Figure 4.2: 2 disc equivalent circuits (Lumped parameter model) [3]**

### 4.2: CAPACITANCE CALCULATIONS

Capacitance between windings and from ground to the windings can be calculated if the windings are modelled by cylinders. In this chapter the formulas used for the calculations are presented. The typical transformer consists of pressboard and oil with specific permittivities which are given on appendix C along with the dimensions of the transformer.

#### 4.2.1: Turn-to-Turn Capacitance

The first parameter to be calculated is the turn -to-turn Capacitance (Ctt) which is the capacitance between two turns within the same disk as shown on figure 4.3. Equation 1[4] can be used to calculate this capacitance using the transformer winding data in appendix C of this report.
Figure 4.3: Capacitance between two turns

\[ C_{TT} = \frac{\varepsilon_0 \varepsilon_r A}{2 \times \tau} \] \hspace{1cm} (1)

Where \( A \) is the cross-sectional area of the turn
\( \tau \) is the single side inter-turn insulation thickness
\( \varepsilon_0 \) is the permittivity of free space
And \( \varepsilon_r \) is the permittivity of the inter turn insulation
\( A = 2 \pi rh \)
\( r = \frac{(r_o + r_i)}{2} \)

Where \( h \) is the height of the conductor 0.01375mm
\( r_i \) is the inner radius of the HV winding & \( r_o \) is outer radius of the HV winding
4.2.2: Disc-to-Disc

The disk capacitance $C_d$ is the capacitance between adjacent turns in separate disks of the winding as shown on figure 4.4. The capacitance between the adjacent turns in separate disks can be modelled by three separate capacitors in series: $C_1$, $C_2$ and $C_3$.

![Diagram of capacitance between adjacent turns](image_url)

**Figure 4.4**: Capacitance between adjacent turns
The three capacitances are calculated separately using equation (2) [3].

\[ C_1 = \frac{\varepsilon_o \varepsilon_r A}{\tau} \] \hspace{1cm} (2)

Where \( A \) is the cross-sectional area of the turn

\( \tau \) is the single in-turn insulation thickness

\( \varepsilon_r \) is the permittivity of the inter turn insulation

And \( \varepsilon_o \) is the permittivity of free space

\[ A = 2\pi rh \]

\[ r = (r_o + r_i) / 2 \]

\( r_i \) is the inner radius of the HV winding & \( r_o \) is outer radius of the HV winding

Equation (3) can be used to calculated the capacitance of the air gap

\[ C_2 = \frac{\varepsilon_o \varepsilon r A}{d} \] \hspace{1cm} (3)

Where \( d \) is the inter disk distance

\( \varepsilon_o \) is the permittivity of the free space

And \( \varepsilon_{\text{Air}} \) is the permittivity of air [air gap]

\[ A = 2\pi rh \]
\[ r = \frac{r_o + r_i}{2} \]

ri is the inner radius of the HV winding & ro is outer radius of the HV winding

The total disk-disk capacitance is then calculated using equation (4) for total series capacitance.

\[ C_T = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_1} \ldots \ldots \ldots (4) \]

**4.2.3: Series Capacitance**

Once the turn and disk capacitances are calculated, the total series capacitance of the windings can be calculated using equation (5) [5].

\[ C_S = \frac{2}{N_{DW}} \left( \frac{N_D - 1}{2N_D^2} \right) C_T + \frac{4(N_{DW} - 1)(N_D - 1)(2N_D - 1)}{N_{DW}^2} C_D \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5) \]

Where \( N_{DW} \) is the total number of discs in the winding

\( N_D \) is the total number of turns in the winding

\( C_T \) & \( C_D \) are turn-to-turn and disc- to – disc capacitances respectively.

**4.2.4: Ground capacitance/ shunt capacitance**

The next task is to calculate the ground capacitance of the windings. Figure 4.5 shows the inner layers of the windings and the materials between the LV and HV windings. To accurately model the ground capacitance four material capacitances are calculated separately and placed in series. The HV paper, LV-HV back spacers, Cylinder between HV and LV and HV dovetail spacers.
The capacitance calculations of C1 from figure 4.5 is a complex process due to the fact this is at the location there are two different dielectric materials present that of the air and that of the spacers as seen on figure 4.5. To solve this problem firstly the spacer can be configured into a right angle triangle to calculate Θ₁ from equation 6 as shown on figure 4.6.

![Diagram of LV and HV winding configuration](image)

**Figure 4.5: LV and HV winding configuration**

**Table 4.1: Radius values**

<table>
<thead>
<tr>
<th>Radius(mm)</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>203.3</td>
<td>213.6</td>
<td>219.6</td>
<td>232.4</td>
<td>267.7</td>
</tr>
</tbody>
</table>
Figure 4.6: Width of Spacers

\[ s = r\theta_1 \ldots \quad (6) \quad [6] \]

\[ \theta_1 = \frac{s}{r} = \frac{\text{width of spacer}}{\text{mean radius}} = \frac{w}{(R_1 + R_2)/2} \ldots \quad (7) \]

\( w \) is the width of the spacer and \( R_1 \) & \( R_2 \) can be seen on Table 4.1

Once \( \theta_1 \) is calculated equation 8 is used for the \( C_1 \)

\[ C_1 = \frac{\varepsilon_0 (2\pi - N\theta_1) + \varepsilon_0 \varepsilon_1 N\theta_1}{\ln\frac{R_2}{R_1}} \ldots \quad (8)[6] \]

Where \( R_1 \) and \( R_2 \) can be found from Table 4.1

\( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_1 \) is the permittivity of the HV paper, LV spacers and \( N \) is the number of spacers.

The capacitance of the cylinder between HV and LV winding (\( C_2 \)) is simpler than that of \( C_1 \) and equation (9) is used for this calculation.
\[
C_2 = \frac{\varepsilon_0 \varepsilon_2 2\pi}{\ln\frac{R_3}{R_2}} \tag{9}[6]
\]

Where \(R_3\) and \(R_2\) can be found from table 4.1

\(\varepsilon_0\) is the permittivity of free space, \(\varepsilon_2\) is the permittivity of the cylinder

The same method as \(C_1\) is implemented to calculate \(C_3\) by configuring the spacer into a right angle triangle and calculating \(\Theta_2\) using equation 7 then equation 8 to calculate the capacitance.

\[
\Theta_2 = \frac{s}{r} = \frac{\text{width of spacer}}{\text{mean radius}} = \frac{w}{(R_3+R_4)/2}
\]

\[
C_3 = \frac{\varepsilon_0 (2\pi - N\Theta_2) + \varepsilon_0 \varepsilon_3 N\Theta_2}{\ln\frac{R_4}{R_3}}
\]

Where \(R_4\) and \(R_3\) can be found from table 4.1

\(\varepsilon_0\) is the permittivity of free space, \(\varepsilon_3\) is the permittivity of the HV dove tail spacers and \(N\) is the number of spacers.

Again equation (9) is used to calculate \(C_4\) the capacitance of the HV paper

\[
C_4 = \frac{\varepsilon_0 \varepsilon_4 2\pi}{\ln\frac{R_5}{R_4}}
\]
After the calculation of the four capacitances consisting of the HV paper, LV-HV back spacers, Cylinder between HV and LV and-HV dovetail spacers, the series combination of them is calculated with equation (10).

\[
\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (10)
\]

Now we have the total capacitance to ground of the system but we do not have the ground capacitance for per unit length of turn, so to achieve this equation (11) is used.

\[
C_g = l \times C \ldots \ldots (11)
\]

\(l\) is the axial length of a turn and \(C\) is calculated from equation (10).
4.3: INDUCTANCE CALCULATIONS
To create an accurate model of a transformer winding the self-inductance must be calculated.

The self-inductance of rectangular square conductors can be computed accurately using the Lyle’s method. This expression can be used for a single turn with a rectangular cross sectional area \( w \times h \) as shown on figure 4.7.

\[
\text{Figure 4.7: Lyles Method for rectangular coils}
\]
\[ L_S = \mu_0 a(\ln \frac{8a}{GMD} - 2) \] ........................................... (12)[5]

Where

\[ \ln GMD = \frac{1}{2} \ln(h^2 + w^2) + \frac{2w}{3h} \tan^{-1} \frac{h}{w} + \frac{2h}{3w} \tan^{-1} \frac{w}{h} - \frac{w^2}{12h^2} \ln \left(1 + \frac{h^2}{w^2}\right) - \frac{h^2}{12w^2} \ln \left(1 + \frac{w^2}{h^2}\right) - \frac{25}{12} \]

And h is the height of the turn & w is the width.

4.4: CALCULATED PARAMETERS
Table 4.2 below shows the calculated parameter values using the relevant equations in the previous section of this chapter. These calculated values will be used for the SIMULINK model in the next chapter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>symbol</th>
<th>value</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series Capacitance</td>
<td>Cs</td>
<td>7.9pF</td>
<td>Farads</td>
</tr>
<tr>
<td>Ground Capacitance</td>
<td>Cg</td>
<td>13.92pF</td>
<td>Farads</td>
</tr>
<tr>
<td>self-inductance</td>
<td>Li</td>
<td>0.85 mH</td>
<td>Henry</td>
</tr>
</tbody>
</table>
4.5: REFERENCES


CHAPTER- 5

MATLAB/SIMULINK MODEL

Introduction to MATLAB

SIMULINK

SimPowerSystems

Frequency Analysis

SIMULINK Model
Chapter 5: MATLAB/SIMULINK

MATLAB is an acronym for Matrix Laboratory, is a high performance language for technical computing. MATLAB incorporates programming, visualization and computation in an easy to use interface where problem solving is done in mathematical code [1]. Uses of MATLAB generally includes

- Mathematical computation
- Writing and developing algorithms
- Simulations, modelling and creating prototypes
- Data analysis and visualization
- Generating graphics for engineering and scientific research
- Developing applications with graphical user interface building

In essence MATLAB is a user friendly system with its basic data elements in an array which doesn’t require dimensions. This makes it a powerful tool which solves lengthy computer problems, especially in matrix and vector format in a fraction of the time compared to that of a code programmed in C or Java languages.

Over periods of time MATLAB has come to evolve to what it is today due to user inputs. Today in most universities around the world it is a standard tool used in introductory and advanced mathematics, science and engineering. At an industry level MATLAB is also used for
researching, developing and analysing.

The toolboxes are an important MATLAB feature popular with users because it allows users to learn and apply specialised technology. Toolboxes are a collection of M-files for solving particular classes of problems in specialised areas like signal processing, simulations and control systems to name a few [1].

The MATLAB system consists of five main parts:

1) **MATLAB language**
This is a high level sophisticated matrix/array language with functions, data structures, and control flow statements, input/output and objective orientated programming aspects. This language allows for both the creation of small uncomplicated simple programs used in class rooms and the larger more complex programs specific to an application used at an industry level.

2) **MATLAB Development Environment**
The working environment is a specific set of tools for both users and experienced programmers. It provides facilities for handling variables in the workspace and it allows for the importing and exporting of data to workspace. The tools are best used for writing M-files, developing, managing and debugging.

3) **Handle graphics**
This graphics system includes high level commands for 2D and 3D data visualizations, animations, image processing and presentations. It also caters for low level customizations of graphics and the construction of graphical user interface.

4) **Mathematical library**
This library is a collection of computational algorithms from fundamental functions like sum,
cosine, sine and complex arithmetic’s to more sophisticated functions such as matrix
eigenvalues, Bessel functions, matrix inverse and fast Fourier transforms.

5) Application Program Interface (API)
This library has the capabilities to let users write Fortran and C programs that will interact
with MATLAB. It include facilities for calling routines from MATLAB (dynamic linking), calling
MATLAB as a computational engine, and for reading and writing MAT-files.

5.1: SIMULINK
SIMULINK is a graphic extension of MATLAB for the modelling and simulation of systems. It
has many advantages, for example, giving users the ability to model a nonlinear system which
cannot be done with a transfer function. Another feature of SIMULINK is it has the capability
to take on initial conditions. In SIMULINK block diagrams are drawn to represent a system.
There is a large library of blocks like a transfer function or a summing junction and input and
output devices such as pulse generators and oscilloscopes. SIMULINK is integrated with
MATLAB so it is easy for user to transfer data between the two.

SIMULINK is supported on Windows, Macintosh and Unix; and is included in the MATLAB
student version for PCs [2]

5.1.1: Basic Elements
In SIMULINK there are two major classes of items to select from blocks and lines. The blocks
are used to generate, combine, modify, output and display signals. Lines are used to transfer
signals from one block to another.

5.1.2: Blocks
There are many branches of blocks in the SIMULINK library.
• Sources: for generating various signals
• Sinks: used for outputting results or signal display
• Continuous: contains continuous time system elements (PID controllers, transfer functions, state-space models, etc.)
• Discrete: comprises of discrete-time systems, linear elements (discrete state-space, discrete transfer functions, etc.)
• Math operations: consists of common math operations (sum, product, gain, absolute value, etc.)
• Ports & Subsystems: contains blocks which are useful for building a system

5.1.3: Lines
The lines are used to transmit signals in the direction of the arrow. The lines transmit a signal from the output terminal of a block to the input terminal of another block. However, a line can tap off another line so a signal can split to two separate destination blocks. It is not possible for a line to inject into another line; they must be combined with the use of blocks like the sum and product blocks. The signal carried by the lines can either be scalar or vector signals and the type of signal carried by the line is determined by the blocks on either end of the line [2].

5.2: SimPowerSystems
Electrical power systems are the combinations of electrical circuits and electromechanical devices such as motors and generators. The engineers who are employed in this discipline are continuously improving the efficiency and the performance of the systems. The fulfilment of increasing the efficiency has compelled the designer of the power systems to implement power electronic devices and complex control system concepts outside the traditional tools and techniques. The engineers role is further complicated with the fact that the system is
generally so nonlinear that the only way to analyse it is through simulations.

For the purpose of these simulations, SimPowerSystems was designed as a modern tool that allows engineers and scientists to quickly build simulation models of their specific power system. SimPowerSystems use the Simulink environment which lets users to build models using the click and drag method. User can draw their circuit topology and analyse the circuit as it interacts with thermal, mechanical, control and other disciplines. This is possible because all the electrical parts of the simulation interact with the SIMULINK library. SIMULINK uses MATLAB as its computational engine so the designers can also use the MATLAB tool boxes and the SIMULINK block library.

The SimPowerSystems library consists of typical power equipments like transformers, lines, power electronics and machines. These library models are proven to match text books and their validity has been tested by Power Systems Testing and Simulation Laboratory of Hydro-Québec, an American utility company based in Canada. Before starting a simulation using the Simpowersystems library the Powergui block which allows for steady state circuit analysis must be included in the model [3].

5.3: Frequency Analysis
If the harmonic content of a signal are known then the signal can be presented in the frequency domain by the method of Fourier transform. Engineers usually collect data and generate signals with experimental measurements rather than mathematical functions. These measurements are acquired with specific time duration $T$, sampling rate of $\Delta t$ sampling and a sampling frequency $f_s = \frac{1}{T}$. The signal in most cases is not continuous but discrete. To reproduce and double check practical testing measurements these days simulation models
are produced using computational tools such as MATLAB/SIMULINK and Excel. These tools are used to produce discrete signals which sometimes are not periodic and have different periods to that of the Fourier theorem. Due to this problem frequency analysis is required and the aim of frequency analysis is to construct a scheme to estimate the frequency components of a signal in time domain and this process is called the discrete Fourier transform (DFT).

### 5.3.1 Fast Fourier Transform
As stated previously a signal in time domain can contains frequency components (collection of rotating vectors) and to estimate theses vectors, mathematics needs to be used. In mathematics the signal is stationed, for a specific duration and integrated over the duration. The continuous Fourier transform of a signal \( x(t) \) in extracting a component \( Y \) at a frequency of \( \omega \) can be defined as [4]

\[
Y(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt
\]

For a signal with a discrete sample time \( t_n \) over duration of \( k\Delta t \), \( N \) being the number of sampled data points, the discrete Fourier Transform is estimated, by [4]

\[
Y(\omega) \approx \sum_{n=1}^{k} y(t_n) e^{-j\omega t_n}
\]

The frequency \( f \) is generally in hertz rather than \( \omega \) rad/s so the below equation is more appropriate [4]:

\[
Y(\omega) \approx \sum_{n=1}^{k} y(t_n) e^{-j2\pi ft_n}
\]

The Fast Fourier Transform is applied to both negative and positive frequency components.

The fast Fourier transform is an algorithm developed by J.W.Cooley and J.W.Tuckey in 1965 to
calculate the Discrete Fourier Transform (DFT). This discovery modernised signal processing and analysis and the introduction of modal analysis. The algorithm only works for signals that have a sampled length of \(2^n\) \(\left(2^{10} \text{ or } 2^{11}\right)\). The FFT algorithm reduces the computation time by a factor of \(\frac{n}{\log_2 n}\). The FFT outputs complex numbers and the second half of the complex numbers belong to negative frequency with complex conjugates of the first half (positive frequencies) meaning they do not contain any new information. This is why only half the sampling frequency is analysed and this called the Nyquist frequency.

### 5.4: SIMULINK Model

The lumped parameter model from the previous chapter was modelled in SIMULINK using the SimPowerSystems toolbox. Figure 5.1 below is a representation of a two disk model in SIMULINK consisting of a self-inductance \(L_i\) in parallel with series capacitance \(C_s\) and ground capacitance \(C_g\).

![Parallel RLC Branch](image)

*Figure 5.1: A Disc pair model*

Below is the block parameter inputs for the self inductance, series capacitance and ground
capacitance and input values were calculated in the previous section.

Figure 5.2: self-inductance and series capacitance parameter inputs.

Figure 5.3: ground capacitance parameter inputs.
The above model is for 2 discs and since the investigation is based on a 22 disc model, eleven of the above circuits are connected in series to represent the 22 disc transformer. The complete 22 disk transformer SIMULINK model is shown on figure 5.4.

![Figure 5.4: complete 22 disc transformer model](image)

In the next part of the simulation setup, the bushing capacitance was added to the transformer winding model. Transformer bushings are an essential part of a transformer and its function is to allow a conductor to pass through its centre, so one end of the conductor can be connected to the transmission line and the other to the transformer windings. For this simulation set up the bushing is represented by a 220pF capacitor placed in parallel with the 1st disc and the ground, as shown on figure 5.5. The voltage response plots will be obtained through the bushing capacitance.
Figure 5.5: Inclusion of the bushing capacitance

To check the validity of the winding model, impedance measurements are required and to achieve this impedance block is connected to the bushing capacitance as seen in figure 5.6.

To obtain the impedance measurements the Powergui block on figure 5.7 needs to be accessed and the impedance vs frequency measurement option is selected.

Figure 5.6: impedance measurements at the bushing capacitance
Figure 5.7: Powergui block options

The results of the impedance vs frequency measurements on figure 5.8 show that the winding impedance is inductive at low frequency ranges and capacitive at high frequency ranges. The phase angle vs frequency plots shows -90deg phase at high frequencies meaning capacitive and +90deg phase at low frequencies meaning inductive. The measured plots confirm the validity of the transformer model.
5.4.1: Partial discharge modelling

For the purpose of the simulation a partial discharge pulse was modelled using SIMULINK. The pulse generator block from the SIMULINK library was used for this task. The pulse generator block requires 4 inputs: amplitude, the period of the pulse in seconds, pulse width in % and phase delay in seconds. The amplitude is the magnitude of the voltage and for this simulation 1 volt was used. The period is the time between two pulses and for this simulation the period used was 1ms. The pulse width is the percentage of the pulse period and for this simulation a
0.01% was used. This was because the width of the pulse in time is 100ns and the period is 1ms so \( \frac{100e^{-9}}{1e^{-3}} \times 100 = 0.01\% \). Finally the phase delay is required. This is the time delay before the pulse generated and for this simulation it was 1µs. The block parameters are shown in figure 5.11.

The generated pulse on SIMULINK is shown below on figure 5.9.

![Figure 5.9: Current PD pulse](image)

The period of the pulse is 1ms. However the length of the simulation is 200µs, which means the simulation is only sampling with one voltage pulse and this can be seen on figure 5.10 below. In this figure the pulse is represented by a thin blue line on the y axis because the pulse width is only 100ns, which is small compared to that of the 200µs simulation time.
Figure 5.10: PD pulse during simulation

Figure 5.11: Pulse Generator block parameters
In order to generate a voltage pulse, the pulse generator needs to be connected to a controlled current source, as shown on figure 5.13. The reason for this is because the pulse generator cannot directly be injected on to the winding model without a source block and since this is a current pulse a current source is necessary. The inputs parameter of the controlled current source is shown in figure 5.12.

![Controlled Current source block parameters](image)

**Figure 5.12: Controlled Current source block parameters**

![PD simulation](image)

**Figure 5.13: PD simulation**
5.4.2: Simulation model
Partial discharge investigation can start after the validation of the simulation winding model using impedance measurements and the modelling of the PD. Figure 5.14 represents the practical setup of the experiment where there is a 22 disc transformer winding. The bushing capacitance is connected to disc 1 at the top of the winding and impedance & PD response measurements are carried out at the bushing or as it is known in the industry as the line-end. A 50Ω resistor is connected in parallel to the measurement impedance to represent the resistance of the oscilloscope during measurements.

![Experiment setup diagram](image)

**Figure 5.14: Experiment setup**

The above practical experiment is assembled together in SIMULINK for PD response measurements and the complete model is shown on figure 5.15 below where a voltage measurement block is connected to the bushing capacitance for PD measurements.
Figure 5.15: Complete Simulink model
5.5: REFERENCES


CHAPTER- 6

SIMULATION RESULTS

AND

DISCUSSIONS
Chapter 6: RESULTS AND DISCUSSION

Results
PD pulse is injected at different locations along the winding starting from disc pair 1 (position A) on the line-end to disc pair 10 (position J) at the neutral-end and during each injection the voltage response in time domain is measuring from the bushing capacitance. The voltage response can be seen on the scope but for better analysis a “To work space” block is used to export the Voltage responses to MATLAB. Figure 6.1 below shows the SIMULINK model for injection at disc pair 1 (position A).

Figure 6.1: PD at Disc pair 1 (position A)
Time domain Voltage responses

The figures below show the voltage response plots imported to MATLAB for PD injection at different disc pairs. In each Figure (Fig.6.2 to Fig.6.11) the location of the PD is indicated on the top right hand side of the measured.

Figure: 6.2 the time domain voltage response for PD at disc pair 1

Figure: 6.3 the time domain voltage response for PD at disc pair 2
Figure: 6.4 the time domain voltage response for PD at disc pair 3

Figure: 6.5 the time domain voltage response for PD at disc pair 4
Figure: 6.6 the time domain voltage response for PD at disc pair 5

Figure: 6.7 the time domain voltage response for PD at disc pair 6
Figure: 6.8 the time domain voltage response for PD at disc pair 7

Figure: 6.9 the time domain voltage response for PD at disc pair 8
Figure: 6.10 the time domain voltage response for PD at disc pair 9

Figure: 6.11 the time domain voltage response for PD at disc pair 10
The measured voltage signals above in the time domain show that PD’s along the winding have more oscillations moving away from the line-end because of the traveling path of the winding. It’s also evident that as the PD moves away from the line-end the wave forms have a greater distortion.

By observing the difference in shape of the measured voltage signal its can be determined if the PD source is closer to the direction of the line-end or further down the winding toward the neutral-end.

For greater precision of PD source location the frequency composition of the signal can be extracted to create frequency spectra. In other words the Fast Fourier Transform (FFT) of the signal and this is done in the next section of the project.

**Fast Fourier Transform (FFT)**
The next task of the investigation is analysing the voltage responses in the frequency domain.

The FFT method explained previously is implemented to transform the time domain signal into its frequency domain. The process for this task can be done in three steps.

- export the voltage time domain signal from SIMULINK to MATLAB using a “To work space” block
- write a MATLAB code to do the FFT of the imported signal
- plot the magnitude vs frequency plots from the code

When exporting the signal into MATLAB the sampling time (Δt) must be selected. The sampling time is an important parameter because it will affect the sample frequency of the FFT. To select the sampling frequency double click the “To work space” block. For this simulation a sampling time of 0.1μs was selected meaning that the sampling frequency (fs) = \( \frac{1}{Δt} = \frac{1}{1e-7} = 10\text{MHz} \).

After exporting the signal to MATLAB a script (FFT.m) on Appendix B was implemented to generate the FFT of the time domain signal. Initially in the script the sampling frequency is defined, and then the time domain signal (v) is sampled at 0.1μs and 2001 samples are collected. Next the script increases the length of the sampling by adding zeros and this is done because the FFT computes faster if the length of the sampled signal is to a power of 2 \( (2^n) \). So
for this simulation 2001 samples were collected and these were increased to $2^{11}$ samples. The FFT function plots for a mirror image and only one side of the image. Finally a plot of magnitude vs frequency is obtained with a frequency range of 2MHz. The frequency spectra are presented on the figures below for PD injection at different locations.

**Frequency spectra simulation plots**

**Figure 6.12:** Frequency spectra of line-end signal for PD at Disc pair 1 (in dB)

**Figure 6.13:** Frequency spectra of line-end signal for PD at Disc pair 2 (in dB)
Figure 6.14: Frequency spectra of line-end signal for PD at Disc pair 3 (in dB)

Figure 6.15: Frequency spectra of line-end signal for PD at Disc pair 4 (in dB)
Figure 6.16: Frequency spectra of line-end signal for PD at Disc pair 5 (in dB)

Figure 6.17: Frequency spectra of line-end signal for PD at Disc pair 6 (in dB)
Figure 6.18: Frequency spectra of line-end signal for PD at Disc pair 7 (in dB)

Figure 6.19: Frequency spectra of line-end signal for PD at Disc pair 8 (in dB)
Figure 6.20: Frequency spectra of line-end signal for PD at Disc pair 9 (in dB)

Figure 6.21: Frequency spectra of line-end signal for PD at Disc pair 10 (in dB)
Initially, before injecting the PD pulse at different locations, the impedance measurement was undertaken to obtain the impedance vs frequency plot. This plot is required to find the Pole location in the winding before the injections. The locations of the poles in the impedance measurements must match with that of the pole locations at different injection points. The locations of the poles from impedance measurements are presented in table 6.1 below.

Table 6.1: location of poles from impedance measurements (kHz)

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>124</td>
<td>534</td>
<td>948</td>
<td>1275</td>
<td>1514</td>
<td>1682</td>
<td>1798</td>
<td>1879</td>
<td>1933</td>
<td>1968</td>
</tr>
</tbody>
</table>

Table 6.2: location of Poles in the line-end signal (kHz)

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>124</td>
<td>534</td>
<td>948</td>
<td>1275</td>
<td>1514</td>
<td>1682</td>
<td>1798</td>
<td>1879</td>
<td>1933</td>
<td>1968</td>
</tr>
</tbody>
</table>

The location of poles and zeros in the frequency spectra from the simulation are presented in table’s 6.2 & 6.3.

Table 6.3: location of Zeros for the signal at line-end (kHz)

<table>
<thead>
<tr>
<th></th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc pair 1</td>
<td>546.9</td>
<td>1030</td>
<td>1357</td>
</tr>
<tr>
<td>Disc pair 2</td>
<td>620.1</td>
<td>1235</td>
<td>1494</td>
</tr>
<tr>
<td>Disc pair 3</td>
<td>673.8</td>
<td>1245</td>
<td>1592</td>
</tr>
<tr>
<td>Disc pair 4</td>
<td>756.8</td>
<td>1328</td>
<td>1831</td>
</tr>
<tr>
<td>Disc pair 5</td>
<td>864.3</td>
<td>1411</td>
<td>1895</td>
</tr>
<tr>
<td>Disc pair 6</td>
<td>1011</td>
<td>1432</td>
<td></td>
</tr>
<tr>
<td>Disc pair 7</td>
<td>1094</td>
<td>1489</td>
<td></td>
</tr>
<tr>
<td>Disc pair 8</td>
<td>1123</td>
<td>1499</td>
<td></td>
</tr>
<tr>
<td>Disc pair 9</td>
<td>1143</td>
<td>1748</td>
<td></td>
</tr>
<tr>
<td>Disc pair 10</td>
<td>1147</td>
<td>1763</td>
<td></td>
</tr>
</tbody>
</table>
The frequency spectra of the line-end signals from the SIMULINK simulations are presented in figures 6.12-6.2.

1. The first noticeable feature of the frequency spectra is that the location of the PD injection does not dictate the location of the poles in the frequency spectra. What this means is that whether the PD is injected close to the line-end at disc pair 1 or closer to the neutral-end at disc pair 10 the location of the poles remains unchanged and this is evident on the frequency spectra on figures 6.12 to 6.21 and table 6.2. The location of the poles in the frequency spectra on table 6.2 also matches with that of the impedance measurements on table 6.1 which was expected.

2. Another feature to notice is that when the PD is injected at disc pair 1 (point A) close to the line-end the magnitude of the poles in dB is small compared to that of when the PD is injected further down the winding at disc pair 5 for example, this can be seen on figures 6.12 to 6.16. This is because when the signal is injected close to the line-end, the frequency components having pole frequencies has two paths to take through the bushings to ground or through the neutral to ground. The bushing capacitance path has high impedance which the current avoids so it goes through the winding to the neutral to ground end. Due to this, the magnitude of the poles especially at low frequencies decreases at the line-end of the winding.

3. It’s also noticeable that the zeros in the frequency spectra increase in frequency as the PD injection moves away from the line-end. The number of zeros in the frequency spectra also decreases as PD injection moves away from the line-end, and becomes undetectable after disc pair 5 as shown on table 6.3.
CHAPTER- 7

CONCLUSION

AND

SCOPE FOR FUTURE WORK
Chapter-7

CONCLUSION AND SCOPE FOR FUTURE WORK

7.1: CONCLUSION

In this paper a 3-phase, 6.6kV, 1MVA, 22 disc and 13 turn per disc transformer winding is modelled with the use of a lumped parameter equivalent model for partial discharge (PD) localisation. The parameters of the circuit, series capacitance (Cs), self-inductance (Li) and ground capacitance (Cg) were calculated using the relevant equations. The 22 disc transformer winding was then implemented using MATLAB/ SIMULINK software, where each pair of discs are modelled as 1 lumped parameter circuit. A partial discharge current pulse was also modelled using a pulse generator and injected at various positions along the winding. Once the PD is injected at a position the voltage response was measured in time domain at the bushing capacitance (line-end). The voltage response results indicate that PD’s along the winding have more oscillations moving away from the line-end. It is also evident that as the PD moves away from the line-end, the wave forms have a greater distortion. The waveforms of the time domain voltage responses can be used for locating PD in the winding, however for greater precision; the frequency domain analysis was implemented.

The frequency spectra results show that the poles (crests) always occurred at fixed frequencies no matter the location of the PD source, so the frequency of the poles are independent of the PD location. However the zeros (troughs) altered in frequency depending on the PD location, and as the PD location moved away from the line-end, the zeros increased in frequencies.

The findings of this thesis indicate that the location of the PD source can be found by analysing the frequency spectra of the resulting PD signal; the frequency of the zeros (troughs) give the location.
7.2: SCOPE OF FUTURE WORK
The goal of this thesis project was to design a simulation model of a 3-phase, 6.6kV, 1MVA, 22 discs and 13 turn per disc transformer winding with SIMULINK and investigate how the position of a PD source in the transformer winding is related to the response at the line-end of the winding. This thesis project can be expanded in the following ways.

• For this model the resistance in the lumped parameter model was neglected, however this model can be expanded to take resistance into consideration in order to observe if the responses at the line-end are affected.
• The results from this model can be checked against different PD detection methods using the physical transformer windings.
• This model can be used for different size transformer windings, although recalculating the parameters is the key.
• This model can be perfected for uses in an industrial level to help plant managers better understand the relationship between detection responses and PD location.
Appendices

Appendix A

Turn-to turn capacitance

\[ C_{TT} = \frac{\varepsilon_0 \varepsilon_r r A}{2\pi t} \]  \hspace{1cm} (1)

\[ A = 2\pi rh \]

\[ r = (r_o + r_i) / 2 \]

\[ = (0.2677 + 0.230) / 2 \]

\[ = 0.2488 \]

\[ = \]

\[ 0.0004 \]

= 930pF
Disc-Disc capacitance

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{\tau} \quad \text{............... (2)} \]

\[ C_1 = \frac{(1.9548)(8.854 \times 10^{-12})(2\pi \times 0.2488 \times 0.0025)}{0.0002} \]

= 338.207\,\text{pF}

\[ C_2 = \frac{(8.854 \times 10^{-12})(1)(2\pi \times 0.2488 \times 0.0025)}{0.0045} \]

= 7.686\,\text{pF}

\[ C_D = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_1} \quad \text{..... (4)} \]

\[ C_D = \frac{1}{338.207} + \frac{1}{7.686} + \frac{1}{338.207} \]

Therefore

\[ C_D = 7.35\,\text{pF} \]
Series capacitance

\[ C_s = \frac{2}{N_{DW}} \frac{(N_D - 1)}{2 N_D^2} C_T + \frac{4 (N_{DW} - 1)}{N_{DW}^2} \frac{(N_D - 1)(2 N_D - 1)}{6 N_D} C_D \]

\[ C_s = \frac{2}{22} \frac{(13 - 1)}{2(13^2)} (930 \times 10^{-12}) + \frac{4(22 - 1)}{(22)^2} \frac{(13 - 1)(2(13) - 1)}{6 N_D} (7.35 \times 10^{-12}) \]

= 7.9pF

Capacitance to ground

\[ \Theta_1 = \frac{0.010}{0.20333 + 0.2136} = 0.0576 \]

\[ C_1 = \frac{\varepsilon_0 (2\pi - N\Theta_1) + \varepsilon_0 \varepsilon_1 N\Theta_1}{\ln \frac{R_2}{R_1}} \]
\[
C_2 = \frac{\varepsilon_0 \varepsilon_r 2\pi}{\ln \frac{R_3}{R_2}}
\]

\[
C_2 = \frac{8.854 \times 10^{-12} \times 4 \times 2\pi}{\ln \frac{0.2916}{0.2136}}
\]

= 8032.65pF

\[
\Theta_2 = \frac{s}{r} = \frac{\text{width of spacer}}{\text{mean radius}} = \frac{w}{(r_3+r_4)/2}
\]

\[
\Theta_2 = \frac{0.010}{\left(\frac{0.2196+0.2677}{2}\right)} = 0.0442
\]
\[ C_3 = \frac{\varepsilon_0(2\pi - N\Theta_2) + \varepsilon_0\varepsilon_3 N\Theta_2}{\ln \frac{R_4}{R_5}} \]

\[ = \frac{8.854 \times 10^{-12} \times (2\pi - 0.0442 \times 10)) + (8.854 \times 10^{-12} \times 4 \times 10 \times 10 \times 0.0442)}{\ln \frac{0.2324}{0.2196}} \]

\[ = 1189.214 \text{pF} \]

\[ C_4 = \frac{\varepsilon_0\varepsilon_2 2\pi}{\ln \frac{R_4}{R_5}} \]

\[ C_4 = \frac{8.854 \times 10^{-12} \times 4 \times 2\pi}{\ln \frac{0.2677}{0.2324}} \]

\[ = 1573.652 \text{pF} \]

\[ \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} \]

\[ = \frac{1}{1435.2} + \frac{1}{8032.65} + \frac{1}{1189.214} + \frac{1}{1573.652} \]
C = 435pF

\[ C_R = l \times C \]

Capacitance to ground for two discs

\[ C_g = 0.032 \times 435 \]

= 13.92pF

Self-Inductance

\[ L_s = \mu_0 a \left( \ln \left( \frac{8a}{GMD} \right) - 2 \right) \]

Where \( a \) is the area of the conductor

Where

\[ \ln GMD = \frac{1}{2} \ln(h^2 + w^2) + \frac{2w}{3h} \tan^{-1} \frac{h}{w} + \frac{2h}{3w} \tan^{-1} \frac{w}{h} - \frac{w^2}{12h^2} \ln \left( 1 + \frac{h^2}{w^2} \right) \]

\[ - \frac{h^2}{12w^2} \ln \left( 1 + \frac{w^2}{h^2} \right) - \frac{25}{12} \]

\[ \ln GMD = -6.3538 \]

\[ L_s = 4\pi \times 10^{-7} \times 0.471 \times 13^2 \left( (\ln 8 \times 0.471) - (-6.3538) - 2 \right) \]

= 0.568mH
Appendix B

FFT.M SCRIPT-for FFT analysis

```
fs =1e7; % Sample Rate
lengthofData =length(v);

nPower2 = 2 ^ nextpow2(lengthofData); % next closest power of 2 to the length

freqRange = 0.5*fs*linspace(0,1,nPower2 / 2+1); % Frequency range % Only plotting upto n/2 (as other half is the mirror image)

y1=fft(v,nPower2)/lengthofData;% fast fourier transform

plot( freqRange,20*log(2*abs(y1(1:nPower2 / 2+1)))); % Updating the plot &

% Logarithmic voltage ratios are specified in decibels (dB)

xlim([0,2e6]);% range x axis to 2MHz

xlabel('Frequency Hz'); ylabel('magnitude dB');
```
### Transformer data
Data from one phase of a 3-phase 6.6kV, 1MVA high voltage winding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of discs</td>
<td>22</td>
</tr>
<tr>
<td>No. of turns per disc</td>
<td>13</td>
</tr>
<tr>
<td>No. of discs per unit coil</td>
<td>2</td>
</tr>
<tr>
<td>Turn width</td>
<td>0.0025</td>
</tr>
<tr>
<td>Turn height</td>
<td>0.01375</td>
</tr>
<tr>
<td>Single-sided inter-turn insulation thickness</td>
<td>0.0002</td>
</tr>
<tr>
<td>Inter-disc distance</td>
<td>0.0045</td>
</tr>
<tr>
<td>Width of LV/HV back spacers</td>
<td>0.012</td>
</tr>
<tr>
<td>Width of HV dovetail spacers</td>
<td>0.010</td>
</tr>
<tr>
<td>Width of Inter-disc spacers</td>
<td>0.040</td>
</tr>
<tr>
<td>Thickness of LV/HV back spacers</td>
<td>0.0103</td>
</tr>
<tr>
<td>Thickness of HV dovetail spacers</td>
<td>0.0128</td>
</tr>
<tr>
<td>Thickness of cylinder between LV &amp; HV</td>
<td>0.006</td>
</tr>
<tr>
<td>Outer radius of LV winding</td>
<td>0.2033</td>
</tr>
<tr>
<td>Inner radius of HV winding</td>
<td>0.230</td>
</tr>
<tr>
<td>Outer radius of HV winding</td>
<td>0.2677</td>
</tr>
<tr>
<td>No. of inter-disc spacers</td>
<td>10</td>
</tr>
<tr>
<td>No. of spacers between LV &amp; HV</td>
<td>10</td>
</tr>
<tr>
<td>Permittivity of free space (air)</td>
<td>8.85e-12</td>
</tr>
<tr>
<td>Relative permittivity of inter-disc spacers</td>
<td>6</td>
</tr>
<tr>
<td>Relative permittivity of inter-turn insulation</td>
<td>1.95-j0.1365</td>
</tr>
<tr>
<td>Relative permittivity of inter-disc insulation (oil)</td>
<td>2.2</td>
</tr>
<tr>
<td>Relative permittivity of cylinder between LV &amp; HV</td>
<td>4</td>
</tr>
<tr>
<td>Relative permittivity of spacers(back + HV dovetail)</td>
<td>4</td>
</tr>
</tbody>
</table>

All distances are given in metres (m).