High Frequency Modeling of a Transformer Winding

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Abstract

Major faults in power transformer windings usually originate from small charges called partial discharges (PD). These discharges could lead to a breakdown in insulation and ultimate failure in the power transformers if they are allowed to develop. Therefore, this thesis will present and develop a high-frequency model of power transformer winding, which can detect the propagation of high-frequency partial discharges in a continuous disc type of high-voltage transformer winding. The lumped parameter model will be used to simulate the windings of the power transformer. This model represents the transformer winding with two discs of the winding represented by a single circuit. PD will be injected at different locations along the model. Using the knowledge of the frequency response of the winding within the faulty transformer, will help locating the partial discharges on the windings.

Locating PDs in high-voltage power transformers, is useful for those who maintain the equipment.
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Chapter 1

1. Introduction

1.1 Partial discharges in HV power transformers

In power systems, partial discharge (PD) detection is a highly important tool for monitoring the insulation condition in high-voltage (HV) devices.

As time passes, the possibility for breakdowns in an HV device increases. These breakdowns in insulation can occur due to many reasons, such as mechanical, thermal or electrical stress, and may result in a catastrophic failure of the device. Therefore, it is important and wise to have a system that can detect problems before they occur and that is capable of warning device users of potential insulation failures so they may be repaired during a scheduled shutdown.

Understanding how PDs occur and what methods are currently used to detect and locate PDs is very important when designing a system that might identify this phenomenon within an HV transformer.
1.2 Literature review

A lot of research has been done regarding the detection and localization of partial discharges in power transformer windings using HF models. Most of these studies have taken the lumped parameter method or the multi-conductor transmission line theory for modeling the windings of transformers. These past studies have focused mainly on comparing the output results between the simulated models from computers and the results obtained from experiments in the field and then comparing the two to determine whether the simulated model can produce the same output values as those gathered from the field.
1.3 Thesis objectives

The majority of faults in power transformer windings start from small discharges called partial discharges (PD). If allowed to develop, these discharges can lead to breakdowns in insulation and ultimate failure of the power transformer. In this project, I will develop a high-frequency model of a power transformer winding, which can identify the propagation of a high-frequency PD in a continuous disc type of HV transformer winding. The winding model takes turn two-discs as the basis for the lumped parameter model. Using this model and the measured frequency response across the whole winding, it is possible to estimate the intermediary winding responses. Locating the source of the PD within a faulty transformer depends upon knowledge of the winding frequency responses. Therefore, after modelling and simulating the windings of an HV transformer, I will model and simulate PD pulses and introduce them into various positions on the winding to obtain the responses at the line terminal of the winding. The aim of this project is to investigate how these responses are related to the locations of the pulses on the winding.
1.4 Report outline

**Chapter 2:** Definitions and background about power transformers, partial discharges and the lumped parameter method.

**Chapter 3:** A background about the simulation program used, the reasons for using these programs and the steps used in the program to produce the expected results.

**Chapter 4:** Simulation results and discussion.

**Chapter 5:** Conclusion and suggestions for future work.

**Chapter 6:** References
2. Background

2.1 Transformers

Definition of Transformers:

A transformer is a device that uses electromagnetic induction to transfer electrical energy from one circuit to another. The transferred electrical energy involves changes in the magnitudes of the voltage and current but no changes in frequency. Transformers usually either step the voltage up or step it down depending on what they are designed for, some transformers are used to isolate one part of circuit voltage from another part [16].

Main components of a transformer:

A core that supports the coils or windings

A primary winding

A secondary winding [16]

Transformer core types:

There are different types of cores depending on the voltage, current and the frequency of the frequency used.
- Air core transformers: For high-frequency (above 20 kHz).
- Iron-core transformers: For low frequencies (below 20 kHz).
- A soft-iron-core transformer: For physically small transformers [16].

Other types of transformers based on shape

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<td>Core is shaped with a hollow square through the center</td>
<td>E- and I-shaped sections of metal in each layer of the core</td>
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<td>Characteristics</td>
<td>Winding coils are wound around the core</td>
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<td>Advantages</td>
<td>More economical high-voltage power transformer applications at the lower end of their voltage and power rating ranges</td>
<td>For extra high voltage and higher MVA</td>
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Illustration

Windings:

There are two types of windings: primary (which is connected to the source) and secondary (connected to the load).

Windings are made of aluminum or copper conductors wound in coils around an iron core. The number of turns in each coil will determine the voltage transformation of the transformer. When the primary winding and the secondary winding have the same amount of turns, there is no change in voltage. If there are fewer turns in the secondary winding than in the primary winding, the secondary voltage will be lower than the primary; these types
are called Step down transformers. Step up transformers are those with fewer turns in the primary winding than in the secondary winding; therefore, the secondary voltage will be higher than the primary circuit[6].

This gives rise to the following formula: \( \frac{V_P}{V_S} = \frac{N_P}{N_S} \)

Where \( V \) = voltage and \( N \) = number of turns on the coil. This formula is used to help calculate the number of turns required to give a certain output voltage from a known input voltage [16].

As mentioned above, step up transformers increase the secondary voltage, which raises the question of what is the difference between a step up transformer and a voltage amplifier.

1 - Transformers cannot amplify an alternating current (AC) input voltage without reducing its current capability, whereas amplifiers increase both voltage and current at the same time.

2 - Transformers do not need direct current (DC) to operate, while amplifiers do.

3 - Based on the input signal, the amplifier produces a completely new output signal [5].

**The principle of transformers operation:**

A magnetic circuit is formed between the two windings by using an iron core on which both windings (primary and secondary) are wound. Iron is typically used as it is a good conductor for magnetic fields. When the primary winding is energized by an AC source, an alternating magnetic field called a flux is established in the transformer core. “The flux created by the applied voltage on the primary winding induces a voltage on the secondary winding. The primary winding receives the energy and is called the input. The secondary winding discharges the energy and is called the output” [16].

An ideal transformer has a resistance in the coils of zero, an infinite relative permeability of the core, zero core or iron loss, and zero leakage flux. In reality, the loss varies with the load current, and the total power loss in a transformer is a combination of three types of losses. The major cause losses is the winding resistance, and the other two losses are hysteresis and eddy current losses. Transformer losses are also classified into copper loss, which occurs in the windings, and an iron loss, which takes place in the magnetic circuit. There is another type of classification: load and no-load losses. The losses associated with the coils are called the load losses, while the losses produced in the core are called no-load losses.
Load Losses

The loading on the transformer affects the variation of load losses. These losses include heat losses and eddy currents in the primary and secondary conductors of the transformer.

No-load Losses

No-load losses are constant; therefore, these are not dependent on the loading on the transformer and instead are a result of magnetizing current needed to energize the core of the transformer.

Hysteresis is the lag in response exhibited by a body in reacting to changes in the forces, especially magnetic forces, affecting it. Hysteresis losses are in the form of heat produced by friction, a result of core molecule resistance being magnetized and demagnetized by an alternating magnetic field. These losses can be deferred by choosing the correct size and type of core material.

Eddy current loss is an electric current in a conducting material that results from induction by a moving or varying magnetic field.

TYPES OF TRANSFORMERS

The following transformers are the most important and applicable forms of transformers:

- **Power and distribution transformers**: These transformers are used for the transmission and distribution of electrical power.

- **Autotransformer**: These transformers are used to change the voltage within relatively small limits, for starting AC motors, and so on. Autotransformers are transformers with a single winding in which the entire winding can be used as the primary and part of the winding as the secondary, or vice versa.

Disadvantages of using an Auto Transformer

1. Making a low voltage circuit able to withstand the higher voltage.
2. Low impedance, as there is a small leakage flux between the primary and secondary windings. This impedance results in severe short circuit currents under fault conditions.

3. Inability to earth the neutral of one side, in star/star connected auto transformers as they have a common neutral.

- **Transformers for feed installations with static converters**: These transformers are used for converting AC to DC and also DC to AC. The first one is used for rectification purposes and the second one for inversion purposes.

- **Testing transformers**: These types are used to conduct tests at high and ultra-high voltages.

**Power transformers for special applications**: These transformers are used in furnaces, welding, and so on, and they are a transformer with two or more windings wound on a laminated iron core. The transformer is used to supply stepped up and stepped down values of voltage to the various circuits in electrical equipment.

- **Radio transformers**: These are used in radio engineering and for other, similar purposes.

From a frequency range point of view, transformers can be divided into (50–400 Hz) audio transformers, wide band and narrow band transformers and pulse transformers. Transformers can also be divided depending on the number of windings such as two windings (conventional) and a single winding (known as an autotransformer).

**TRANSFORMER OIL**

Transformer oil is a mineral oil, which is produced by refining crude petroleum. It has the following purposes:

- It gives extra insulation.
- It removes the heat generated in the core and the coils.
- It protects the paper from dust and moisture.

Transformer oil has the following properties:
• **High dielectric strength.** This strength prevents leakage of current.

• **Low viscosity to provide heat transfer.** Low viscosity is less resistant to the convectional flow of oil, thereby not affecting the cooling of the transformer. It is also important that the viscosity of the oil should increase with decreases in temperature because most liquids become more viscous if temperature decreases.

• **Good resistance to emulsion.**

• **Free from inorganic acid, alkali and corrosive sulphur.** The acidity of oil decreases the insulation property of the paper insulation of winding and leads to rusting of iron in the presence of moisture.

• **A high flash point.** This flash point specifies the chances of a fire hazard in the transformer.

• **Free from sludging under normal operating conditions.**

The most important factors are as follows:

• Operating temperature
• Atmospheric conditions, particularly inside substations
• Electric strength
• Moisture and other contamination
• Sludge formation

There are two common types of transformer oil used in transformers:

• Paraffin-based transformer oil: This oil takes time to oxidize, and its product is insoluble, so it affects the transformer cooling system.

• Naphtha-based transformer oil: It is easily oxidized, and its oxidation product does not interfere with the cooling system.
2.2 Partial discharges

Partial discharge is an electrical spark that bridges a small portion of the insulation between two conducting electrodes. PDs in a HV transformer (HVT) take place when the electric field in a localized area changes the way that a localized current is created. This localized current presents itself as an electrical pulse that can be measured at the output of the transformer. The most common sources of PDs can be divided into three categories: floating components, coronas and voids. Nevertheless, the detection of PDs caused by the first two sources mentioned above does not yield any helpful information about the insulation because their appearance is not frankly related to the condition of the insulation. Only void sources can be considered usual as the insulation breakdown is physically manifested as small cracks (i.e., voids) in the insulation. Voids are known as gaps that occupy dense dielectric materials. For example, a transformer’s tank may be filled with oil that has gas bubbles, or paper insulation may line the transformer’s walls that have minimal cracks. Usually the void region produces a capacitance, which is a consequence of a lower dielectric constant in comparison to the surrounding area. If the electric field difference across the void reaches a minimal point, it breaks down the field strength, which as a result causes partial discharge \[10\]. Nevertheless, this result does not always appear.

The following two criteria may lead to a PD. First, the electric field difference across the void should be higher than the breakdown value, which mainly depends on the field’s ability to speed up an electron to impact with other molecules so that more electrons are lost than are being absorbed.

Second, a free electron with specific characteristics of a certain volume and size that are proportional to the voltage across the void must be present for it to accelerate within the field. If these two conditions are met, they will dramatically increase the electron’s motion, which creates streamer and current flows across the void, returning the voltage back to zero. However, ambient radiation plays a role in controlling the presence and location of the free electrons; more specifically, electrons are lost from the surrounding materials by the effect of those rays. However, in most systems, very few free electrons are created by a large source of radiation.
To conclude, PD commonly appears when a free electron is present in a specific voltage value while the strength of the electric field is sufficiently high to cause current flow. PD can probably occur within a matter of minutes or hours of reaching the breakdown field strength within the void; therefore, the PD phenomenon cannot be predicted [11].

The signs of the discharge manifest are characterized by acoustic, electric or optical signals. Unfortunately, the exact mechanism of the discharge is not completely known nor understood at this point. Loose guidelines and instructions are available for device designers that might help them in building a detection system in the future[5].

**Detection Methods**

Sooner or later, the mechanical, thermal and electrical stress causes a breakdown in the insulation within an HVT. Partial discharges are both symptomatic of insulation breakdown and a mechanism for additional insulation damage, and PD detection is used to evaluate the condition of and to diagnose problems with HVT insulation [5]. For the past 40 years, many methods have been developed and created to detect PDs within HVTs. These methods can be divided into four categories based on the PD’s appearance: chemical, electrical, acoustic, and optical detection. In current systems, optical detection is not widely used and is difficult to implement in HVTs due to the opaque nature of mineral oil. Chemical and electrical detection are described in the following section[5].
Chemical Detection

Detecting PD can be done chemically, while the current streamer across the void can break down the adjoining materials into dissimilar chemical components.

The main two chemical tests used nowadays to detect PD are dissolved gas analysis and high-performance liquid chromatography (HPLC). The dissolved gas analysis technique is used to identify the gases the oil produced by the breakdown of mineral oil in the transformer, which later dissolves back into the oil. This test is performed by taking an oil sample from the tank and determining the levels of the dissolved gases in the oil; carbon oxides, ethylene, acetylene, methane and hydrogen are some of the dissolved gases.

This test indicates the presence of PDs, and it also provides additional and extra diagnostic information. Different levels of each of the gases can refer to a specific type of fault within the HVT using extremely and widely developed tables. Even though this test is frequently used, a few debates regarding whether or not the levels of dissolved gases truly correlate to a specific type of fault exist. Experts argue that the rate of increase of these gases is more important than the absolute measure of their concentrations [5].

HPLC is another test that measures the byproducts of transformer wall insulation breakdown because paper is the material used for insulating the wall of the transformer. Glucose and degraded forms of glucose are the breakdown products. Even though the test is administered by evaluating oil samples from the transformer in an offsite lab, there are still some problems with this test as well [5].

The glucose levels in the oil are low because glucose is not highly soluble in mineral oil, and the degraded forms of glucose are unstable. Moreover, this test is uncertain just like DGA because there are no standard values for glucose concentration and their correlations to HVT faults.

Chemical testing faces a few limitations that stop it from being the only method used for PD detection. The first problem is that information regarding the position of the
PD and the extent of the insulation damage is not provided in the chemical testing. Nevertheless, researchers are working on adding chemical “tags” for transformer insulation that would be released and dissolved into the oil in the incident of a PD. If these tags could be made and successfully included with new transformer insulations, valuable information could be provided about the type of PD fault that has taken place within the transformer. However, this ability still does not satisfy the need to extract position information from chemical PD detection.

The second problem is that online chemical testing cannot be performed. Usually, the transformers must be taken out of operation to obtain the oil sample. In the case of HPLC, the oil sample has to be taken away from the site to be analyzed. Moreover, the test results take a long time to obtain. These problems limit the usefulness of chemical detection and rule it out as a single solution to PD recognition and positioning only [5].

**Electrical Detection**

This method usually concentrates on the electrical pulses created by the current streamer in the void and captures them. These electrical pulses have a small duration time of nanoseconds and measured frequencies in the range of a few kHz to GHz, just like the values used later on in this experiment. The shape of the pulse, its relative phase location within the AC cycle of the high voltage transformer and the signal force all will indicate the type of PD fault and the insulation damage. Electrical measurements are categorized into two different groups: direct probing and RF emission testing. The first group requires that capacitive couplers be connected to the phase terminals of the transformer, while the second group is conducted and joined using antennas in the transformer area. Both methods require a time domain recording device (for example, a data storage oscilloscope) to confine and detect the PD signal. Later, the PD is identified using many digital processing methods. The above mentioned processing methods make PD detection very useful because they allow real-time monitoring of high-voltage systems [5].

Electrical detection also has some limitations. One of its primary limitations is its weakness to noise. The HV transformer environment includes high levels of electrical noise (narrowband and broadband). In certain cases, it is almost impossible to tell the difference between a PD and noise because of the short PD pulse width and
noise, causing a false detection in online electrical PD systems. One way to solve this problem is to take the transformer offline and connect it to an external power source to test it and in order to get rid of some of the noise. However, this technique is expensive and may cost the company thousands of dollars per day [13]. Moreover, the characteristics of the received pulse depend on the geometry of the HV transformer that causes another problem within the electrical detection. Different components within the transformer can be deformed and change the pulse shape needed to characterize the type of PD fault. Even though electrical detection has many problems, these systems are extensively used in power plants globally and supply equipment managers with valuable information about the condition of the HVT [12].
2.3 Lumped Parameter Model

2.3.1 The model

The lumped parameter model is a model that divides the windings into a number of segments, discs or groups of turns. For example, the model that would be used in this thesis would be that every two discs of windings were equal to a single circuit. The lumped parameter model is composed of inductance, series capacitance and a shunt capacitance.

2.3.2 Inductance

When all materials are linear, the current applied into the winding segment is proportional to the total magnetic flux of the windings. Usually there is a self inductance for segment L and a mutual inductance between the two segments that indicates the magnetic flux from the energizing segment that is linked to the other segment. If both the self inductance and the mutual inductance are equal, then the linkage connection between the two winding parts is strong[18].

2.3.3 Capacitance

There are two capacitors used in the model, and they will be discussed briefly below.

2.3.3.1 Series capacitance

This capacitor consists of several capacitances between turns inside the disc and adjacent to the turns in the next disc. These series capacitances have to be calculated, which requires the use of some assumptions for the voltage distribution between and inside the discs.

2.3.3.2 Shunt capacitance

These kinds of capacitors usually represent the capacitance from the winding to the earth or between windings and also between outer windings.
Chapter 3

3.1 Matlab

Matlab stands for Matrix Laboratory; the vectors and matrices are handled in a natural way without having to explicitly dimension them, which is unlike other programming languages. Therefore, the user can have a matrix that is dimensioned automatically depending on how he wants to define it, and he can change the dimension of the matrix dynamically by finding it in the work space and using the tutorial. Matlab is an interactive environment, which means that whenever the user types a command in Matlab, it will immediately act on it and show him the results on screen, so its response is immediate. There is no need for separate compilation and execution steps, and that makes it easy to use in a learning environment, especially at universities, because of its powerful state-of-the-art algorithms for linear algebra. Many built-in functions are included in Matlab for different applications in process control, image processing, optimization, power engineering, etc. Matlab is also an extensible program so that one can write new functions developed to be used in Matlab and toolboxes for new areas. It also offers much more in the form of compilers, the ability to interface with other programming languages. Learning how to start using Matlab is very easy and can be done by going through the program’s tutorial [8].

3.2 Simulink and Powerlib

Simulink, an add-on product to Matlab, provides an interactive, graphical environment for modelling, simulating and analysing dynamic systems [8] enables the user to build, design and test an electrical network. All the electrical parameters and components that the user might need to build his electrical network are already inserted in the program as blocks. These blocks can be found in the Powerlib library. More information about these blocks and how to use them to build the model used in this study will be explained in the Appendix. Simulink is integrated with Matlab, so data can be easily shared between these two programs by two.
3.3 Winding modelling

The winding model is the basis for the lumped parameter model. It was assumed that every two discs of the winding in a transformer are equal to a circuit (shown below) consisting of a capacitor ($C_k$) and an inductor (L) connected in parallel with a capacitor (C) connected between the LC block and the ground. This study also assumed that the resistance (R) was negligible. Each of these parameters indicated that the $C_k$ indicates the capacitance between each disc and another indicates the inductance of the windings; the (C) indicates the capacitance between the windings and the core.

Figure 3.1 represents a single disc of the simulated winding.

The parameter values of the winding model that were used are the following:

$R = 1 \, \mu \text{ohm}$

$C_k = 1 \, \text{nF}$

$L = 1 \, \text{mH}$

$C = 0.1 \, \mu \text{F}$

These values were calculated and taken from a previous study.

After simulating a single circuit using Simulink, I expanded the system by adding more circuits and connecting them to each other to end up with a complete winding model of a power transformer with a different number of discs. Later on, I calculated...
their impedance by including an AC voltage source with each of these different models (that had a different number of discs) at different frequency ranges and adding a neutral ground at the end of the model. The result of the impedance calculations will show whether the model is valid or not. Figures (3.2-3.6) shows the different models of winding that have been simulated by Simulink depending on the number of discs (10, 20, 30, 40, or 50).

Figure 3.2 A model consist of 10 discs

Figure 3.3 A model consist of 20 discs
Figure 3.4 A model consist of 30 discs

Figure 3.5 A model consist of 40 discs
Figure 3.6 A model consist of 50 discs

Where:

The AC voltage source: 1V

Range of frequency: 10 Hz - 1 MHz

Sample time: 50 µs

3.4 Partial discharge pulse modelling:

In this section, I modeled a partial discharge pulse on Simulink with one ampere magnitude and a width or duration of 1.02 microseconds. This section was divided into two steps: the first one was by creating the step or the pulse shape and values individually using ramps and time steps by simulink. The second step was changing this time step into a current single pulse and that was by including a block called “Controlled Current Source” (see figure 3.7).
3.5 Placing a bushing capacitance:

In this section, a bushing capacitance was placed instead of the voltage source in the model. Later on, the output response of the partial discharge that was injected at different sections along the model will be obtained through this capacitance. This bushing capacitance represents the real bushings that are shown in Figure (3.8B) while Figure (3.8A) shows the simulated model by simulink, which usually allow the safe passageway of electrical energy.
3.6 Obtaining the results

In this section, a block called “to workspace” in Simulink was involved in the simulation model. This block connected Simulink with Matlab by transferring the Simulink data into Matlab in an array format. This block called “to workspace” will be renamed as “i” so that later on the data will be found as a file called “i” shown figure 3.10.
3.7 Time Domain

In this section, after the data have been transferred from Simulink into Matlab, a function can be implemented in Matlab to obtain the time domain plot of the output.

The function is as follows:

```matlab
%filename.m
Fs=10e6;
T=1/Fs;
L=10e6;
t=(0:L-1)*T;
plot(t(1:5000),i(1:5000));
grid on;
xlabel('seconds')
ylabel('A')
xlim([0 0.0005]);
```
Chapter 4

4.1 After completing the model

This section shows the different results for different models with different numbers of discs discussed in Chapter 4 shown in the figures below as the second graph.

Figure 4.1 Impedance vs phase (20 discs)
Figure 4.2 Impedance vs phase (30 discs)

Figure 4.3 Impedance vs phase (40 discs)
Figure 4.4 Impedance vs phase (50 discs)

The winding impedance is usually inductive at low frequencies and capacitive at high frequencies. The phase angle vs frequency characteristics in figures 4.1 to 4.4 show that, the winding is inductive at low frequencies (90 degree phase) and capacitive at high frequencies (-90 degree phase). This finding confirms the validity of our high-frequency model for the winding.

4.2 Partial discharge pulse

This section shows a graph of the PD pulse injected into the model.
From this graph, we see that the PD pulse starts with a ramp that rises at zero seconds and reaches the final value of 0.01 us. Next, it reached one ampere then stayed in a steady state of one ampere from 0.01 us to 1.01 us then decreased from one ampere to zero ampere in a time of 0.01 us. Therefore, we ended up with a step of one ampere with a duration time of 1.02 us.

4.3 Obtaining the results

After injecting the PD pulse at different places or at different numbers of discs along the winding model, the data of the PD current response was calculated or obtained after the bushing capacitance block and transferred into Matlab by the “to workspace” block. These data were then used to obtain the time domain signals shown in figures (4.6 to 4.10) using the function in section 3.6.
Figure 4.6 The time domain graph of 10 discs

Figure 4.7 The time domain graph of 20 discs

Figure 4.8 The time domain graph of 30 discs
From these graphs, we see that the wave shifted to the right every time with the PD pulse moving down the winding. (That is increasing disc number).
4.4 Finding the frequency domain:

The method used here to obtain the frequency domain of the model (which later on will be used to indicate and localize the PD at the winding) calculated the time duration between the peaks, as shown in Table 1.

-T1 in table 2 equals to the first peak in the waveform and T2 refers to the second peak, T3 to the third peak, etc.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Disc_5</th>
<th>Disc_10</th>
<th>Disc_15</th>
<th>Disc_20</th>
<th>Disc_25</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2-T1 (s)</td>
<td>0.000045</td>
<td>0.0000511</td>
<td>0.0000571</td>
<td>0.0000603</td>
<td>0.0000654</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 2</th>
<th>Disc_5</th>
<th>Disc_10</th>
<th>Disc_15</th>
<th>Disc_20</th>
<th>Disc_25</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3-T2 (s)</td>
<td>0.0000354</td>
<td>0.000039</td>
<td>0.0000422</td>
<td>0.0000445</td>
<td>0.0000456</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 3</th>
<th>Disc_5</th>
<th>Disc_10</th>
<th>Disc_15</th>
<th>Disc_20</th>
<th>Disc_25</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4-T3 (s)</td>
<td>0.0000341</td>
<td>0.0000366</td>
<td>0.0000382</td>
<td>0.0000407</td>
<td>0.0000408</td>
</tr>
</tbody>
</table>

To find the frequency domain of the model, the reciprocal of the value of these time differences were determined; the time difference between the peaks had been divided into stages (Table 2).

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Disc_5</th>
<th>Disc_10</th>
<th>Disc_15</th>
<th>Disc_20</th>
<th>Disc_25</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1 (Hz)</td>
<td>22222.222</td>
<td>19569.472</td>
<td>17513.135</td>
<td>16583.748</td>
<td>15290.5199</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 2</th>
<th>Disc_5</th>
<th>Disc_10</th>
<th>Disc_15</th>
<th>Disc_20</th>
<th>Disc_25</th>
</tr>
</thead>
<tbody>
<tr>
<td>f2 (Hz)</td>
<td>28248.588</td>
<td>25641.026</td>
<td>23696.682</td>
<td>22471.91</td>
<td>21929.8246</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 3</th>
<th>Disc_5</th>
<th>Disc_10</th>
<th>Disc_15</th>
<th>Disc_20</th>
<th>Disc_25</th>
</tr>
</thead>
<tbody>
<tr>
<td>f3 (Hz)</td>
<td>29325.513</td>
<td>27322.404</td>
<td>26178.01</td>
<td>24570.025</td>
<td>24509.8039</td>
</tr>
</tbody>
</table>

Therefore, from table 3, we can localize PD at the winding, as follows:

Example 1: At stage 1, which stands for the time duration differences between the second peak at T2 and the first peak at T1, if PD appeared at a frequency of 22.2 kHz, then PD is at Disc 5.

Example 2: At stage 2, if PD appeared at a frequency of 23.7 kHz, then PD is at Disc 15.
Chapter 5

5.1 Conclusion

Partial discharge detection and location is a very important tool for monitoring the healthiness of the insulators within high-voltage transformers. Electrical and mechanical stresses are the main causes of any breakdown over time for the insulators of a high-voltage transformer. If they were allowed to be developed, these breakdowns in the insulators could lead to an ultimate failure in the power transformers. Partial discharge is one of the indications of insulation breakdowns because developing faults at the insulation can cause a local build up of electrical charge, which later dissipates in a form of an electrical pulse of energy. Therefore, detection and awareness of the position of the PD within the transformers is required to maintain these transformers and limit breakdowns inside them.

This thesis presented a developed, high-frequency model of power transformer winding, which can identify the propagation of high-frequency partial discharges in a continuous disc type of high-voltage transformer winding. The lumped parameter model was used to simulate the windings of the power transformer using Simulink. This lumped parameter model was represented as if every two discs of windings were equal to a single circuit consisting of a capacitor and an inductor connected in parallel with another capacitor in shunt to ground. PD was injected at a different number of locations along the model. Using the time domain signals and their frequency components the position of the partial discharge on the winding could be obtained as shown.

5.2 Suggestions for future work

I would like to suggest adding and developing new blocks for Simulink, which could calculate the time domain of the data obtained as the response of PD at the model instead of transferring them into Matlab. It also would be much better if an Fast Fourier Transform (FFT) analysis block can be developed in Simulink, which will allow us to find the frequency domain of the model instantaneously from Simulink; Through this block, we can locate the position of the PD in the windings. These two steps would save time and effort when determining the position of the PDs in high-voltage transformer windings.
Chapter 6

References


[16] “Transformer Theory”.


Appendix

This section lists some elements used in the Simulink program.

1) The Series RLC Branch

-Using this block The user can include a resistor, a capacitor and an inductor connected all together in serious and include the value that he need in each one of them. Also he can create either a resistor, a capacitor or an inductor by them self by changing the branch type from the block parameters. Like what have been done in this project as the branch type been changed into C to implement a single capacitor.

“R” stands for the resistor while “L” for the inductor and “C” for the capacitor.


**Branch type**

Select the elements you want to include in the branch. The R letter defines the resistor, the L letter defines the inductor, and the C letter defines the capacitor. Select Open circuit to define an open circuit (R=0, L=0, C=inf).

**Resistance**

The branch resistance, in ohms (Ω). The Resistance parameter is not visible if the resistor element is not specified in the Branch type parameter.

**Inductance L**

The branch inductance, in henries (H). The Inductance parameter is not visible if the inductor element is not specified in the Branch type parameter.

**Set the initial inductor current**

If selected, the initial inductor current is defined by the Inductor initial current parameter. If not selected, the software calculates the initial inductor current in order to start the simulation steady-state.

The Set the initial inductor current parameter is not visible and have no effect on the block if the inductor element is not specified in the Branch type parameter.

**Inductor initial current (A)**

The initial inductor current used at the start of the simulation. The Inductor initial current parameter is not visible and have no effect on the block if the inductor is not modeled and if the Set the initial inductor current parameter is not selected.

**Capacitance C**

The branch capacitance, in farads (F). The Capacitance parameter is not visible if the capacitance element is not specified in the Branch type parameter.

**Set the initial capacitor voltage**

If selected, the initial capacitor voltage is defined by the Capacitor initial voltage parameter. If not selected, the software calculates the initial capacitor voltage in order to start the simulation in steady-state.

The Set the initial capacitor voltage parameter is not visible and have no effect on the block if the capacitor element is not specified in the Branch type parameter.

**Capacitor initial voltage (V)**

The initial capacitor voltage used at the start of the simulation. The Capacitor initial voltage parameter is not visible and have no effect on the block if the capacitor is not modeled and if the Set the initial capacitor voltage parameter is not selected.

---

**Figure 7.2 : The series pRLC parameters description (Matlab help)**

2) **The Parallel RLC Branch**

Using this block the user can include a resistor, a capacitor and an inductor connected all together in parallel and include the value that he need in each one of them. Also he can
create either a resistor, a capacitor or an inductor by them self by changing the branch type from the block parameters. In this project there was a need to implement an inductor and a capacitor in parallel so the branch type been changed into LC either than RLC.

3) The AC voltage source

![AC Voltage Source](image)

Figure 7.4 AC Voltage Source

-Using this block the user can implement an ideal Ac voltage source.

4) Controlled Current Source:

![Controlled Current Source](image)

Figure 7.5 Controlled Current Source

-This block converts the simulink input signal into an equivalent current sourse. Just like been shown in this thesis when a PD pulse was created at section 3.3.
Figure 7.6 Controlled Current Source parameter

- These parameters which are the initial amplitude, initial phase and initial frequency can only appear if initialize was selected.

5) Powergui
-This block is necessary for simulation of any Simulink model containing SimPowerSystems blocks (which can be found by typing “Powerlib” in the dash page of Matlab) it store the equivalent Simulink circuit that been represents the state-space equations of the model the rules of using the block can be found at Simulink help. This block also allows the user to choose either continuous method, Ideal switching, Discretization of the electrical system and a phasor solution method and that's by changing the configure parameters of the block.

![Image](image.png)

**Figure 7.8 Powergui parameter block**

-Also from the parameter block we can see that the impedance of the model at a range of frequencies can be found from this block and that's after injecting the impedance measurement block to the model.
Figure 7.9 Impedance Measurement block