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15 kVA, 11kV/400V Transformer Winding Fault Detection using Sweep Frequency Response Analysis (SFRA)

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Abstract: Power transformers offer safety to electrical systems as they have a weakness that not only reduces system efficiency but also results in unscheduled outages and other sudden failures even after routine maintenance. The ageing of the insulation as well as short circuit issues, might be the primary causes of failure in the transformer winding. The problem is solved by creating the frequency response analysis (FRA) technique which improved in the diagnosis and detection of power transformer failures. By applying a sweep frequency to the winding, this technique detects winding deformation. The sweep frequency response analysis (SFRA) is simulated using MATLAB/SIMULINK software and the results is used to determine if the transformer is in unfault or fault condition by evaluating the frequency variations in the transformer winding. According to the analysis, when a fault is added into the winding, the first resonance is greater than the unfault conditions. From the unfault condition, it can be concluded that the first resonance after transformer model simulation occurs at 414 Hz, while for the inter turn fault condition, the first resonance of 415 Hz occurs at the second winding. Furthermore, for turn to turn fault condition is concluded that 415 Hz of first resonance occurred between first and second winding. Lastly, after changing the ground capacitance to 52.6 pF due to changing the length between windings to 0.0209 meters, it is recorded that the first resonance were occurred at 189 Hz. Based on this condition, the lower capacitance value reflects the life span of the transformer spent due to the lower frequency resonance.

Keywords: Winding Fault Detection, Frequency Response Analysis, Power Transformers

1. Introduction

Transformer is a passive electrical system that converts energy from one electrical circuit to another without any modification in frequency [1].The transformers have two windings which are primary winding and also the secondary winding [2]. The primary winding is the coil which supplies electricity from the source, while the secondary winding is the coil which passes energy to the load at a transferred

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Corresponding author: dirman@uthm.edu.my or changed voltage [3]. The fault that usually happen at the winding is the inter turn fault where it occur due to winding flashovers caused by the line surges. When it is under normal operation, there is only few difference current value in each branch. Otherwise, the inter turn fault cause a high current in the short circuit loop which can damage the transformer.

Frequency response analysis (FRA) method is applied to know the state of 3-phase transformer rating which is 15 kVA, 11kV/400V, where it is obtained by using sweep frequency response analysis (SFRA) through the direct measurement in frequency domain [4]. The SFRA can trace fault in transformer winding that can shows resonances at several numbers of frequencies. The resonances are related to variations of inductances and capacitances in a complex network which can cover the series and parallel resonances between windings, between the layers within winding and between the winding and grounds of the transformer [5]. When applying SFRA to the transformer winding, it helps to detect winding deformation, minimize the rate of error detection besides has good reliability and high efficiencies [6]-[7].

This project aims to develop FRA by using MATLAB/SIMULINK software, to diagnose the transformer winding fault using FRA method by applying SFRA and compare the results of fault condition with reference to the unfault condition. Furthermore, the simulation of SFRA produces waveform of inter turn fault, turn to turn fault and change ground capacitance which shows significant waveform conditions are changing compared to the unfault condition waveform. The transformer assumed in healthy conditions when there is no changes in waveform to the reference of unfault waveform.

2. Materials and Methods

Generally, this section are explain briefly the project flow. Its function is to achieve the project objectives. The FRA and the SFRA are study in details and comprehensively. Besides that, the development of the SFRA using MATLAB/SIMULINK software by applying appropriate parameters to obtain desired results also studied in details. To simulate the result, first the circuit are designed like in figure 3 and then the bode plot window from Matlab library are added to the circuit. The next step is double click at the bode plot window and run the simulation and wait until the simulation is done. Finally, when the bode plot graph are shown, the result are analyze.

2.1 Sweep frequency response analysis (SFRA)

Figure 1 illustrated the steps how to simulate the SFRA using MATLAB software. It shows how the diagnosis method implemented in the simulation tools based on FRA step by step [8]. This proposed model provide proper information on the identification of the core movement and deformation of the winding.

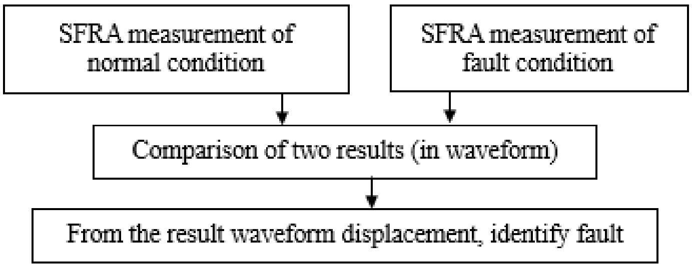


Figure 1: Proposed model of SFRA

Firstly, the measurement of SFRA is done in normal condition of transformer and followed on fault condition with similar transformer rating. Then, the characteristics of the waveform obtained between the normal and fault condition are compared and last but not least, identify the fault from the result waveform displacement. When there is different between both results, the simulations were considered success as the fault occur in the transformer winding.

2.2 Short Circuit Forces

The formula for the electromagnetic forces acting on current carrying conductor during short circuit is given as:

$$F = B \times I \times L \qquad Eq. 1$$

Where F is the electromagnetic force measured in newton, B is the magnetic field, I is the current and L is the length of conductor. The electromagnetic force higher due to the current increasing. These forces increase the conductor's current both radially and axially due to the mechanical changes in the transformer winding [9]. Partial core transformer shows the part of the full core transformer. The difference is the outer limb and the connecting yoke are absent from the partial core transformer as in Figure 2. This indicates that the magnetic circuit for a partial core transformer contains core and the ambient air, resulting in high magnetic resistance [10].

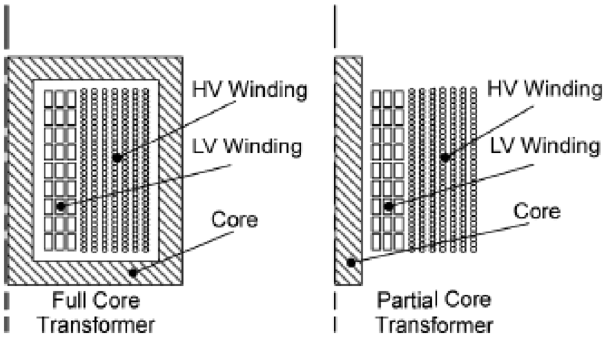


Figure 2: The cross-sectional view of the full core and partial core transformer

Generally, the FRA is applied into a complex network of passive elements. For the practical purposes, only the resistors, inductors and also capacitors is considered as passive circuit components and it assumed as ideal circuit. Besides, this SFRA of a transformer winding or known as SFRA response curve is quite complex and it consists of increasing and decreasing magnitude (in absolute) with respect to the frequency (in Hz) [11]. The parameters of the loads are listed in Table 1.

Table 1: The electrical load parameters

Parameter	Value
Series Resistance, R_s	0.01942 Ω
Series Inductance, L_s	0.3655 mH
Series Capacitance, C_s	0.914 pF
Ground Capacitance, C_g	0.011 nF

3. Results and Discussions

The results and analysis are briefly discussed based on the simulation development of the SFRA in MATLAB/SIMULINK software. The simulation result is used to analyze and differentiate SFRA in normal, inter turn fault, turn to turn fault and change in ground capacitance conditions.

3.1 Normal/unfault condition

The unfault condition results of transformer winding can be seen in Figure 3 below. For a wide range of frequencies, the equivalent winding circuit of the transformer consists of various inductance, resistance, and capacitance components. Mutual inductive and capacitive couplings are formed between the winding components which effectively evaluate the SFRA winding response including multiple resonance and anti-resonance response.

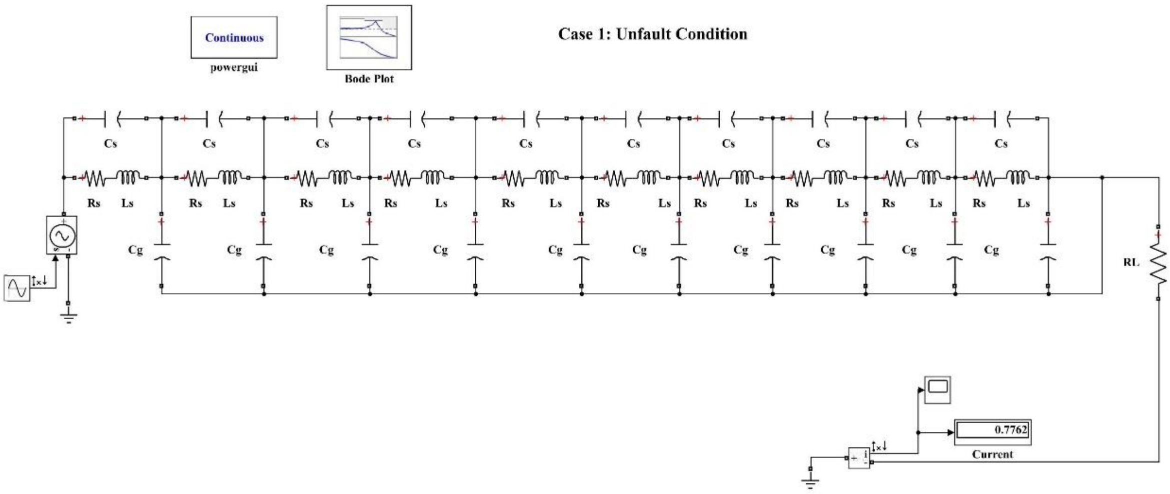


Figure 3: Transformer model for unfault condition

From the transformer model for normal conditions, the simulated SFRA plot is shown in Figure 4. The first resonance after the simulation of the transformer model is occurring at 414 Hz. Beyond this resonance point, the inductance of the transformer winding is dominating. The magnetic effect of the point begins to rise, but the winding inductance effect is monitored after the first resonance point. This method is continuously repeated several times so that the medium frequency range provides more resonance points. The current obtained from the waveform of the windings is 0.7762 A. From this first resonance point, further analysis can be considered.

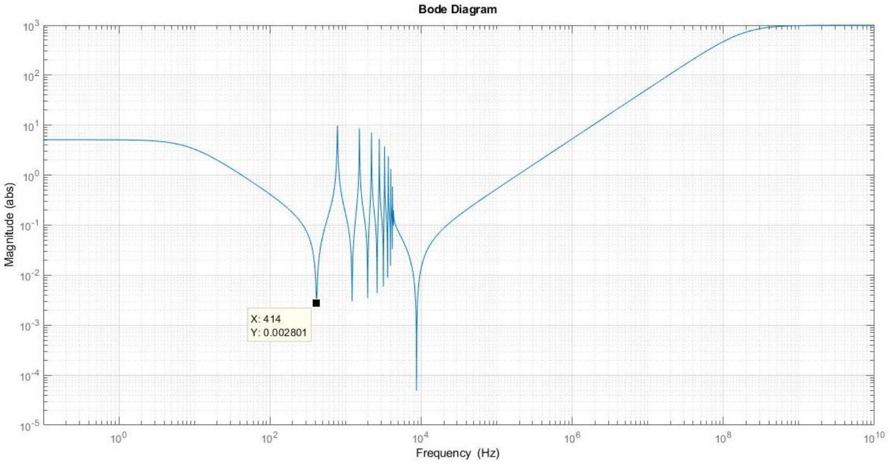


Figure 4: Simulated SFRA for unfault/normal condition

3.2 Inter turn fault conditions

Figure 5 until 8 show the transformer model for the inter turn fault conditions. The fault are created in second turn, fourth turn, sixth turn and ninth turn of the transformer winding respectively.

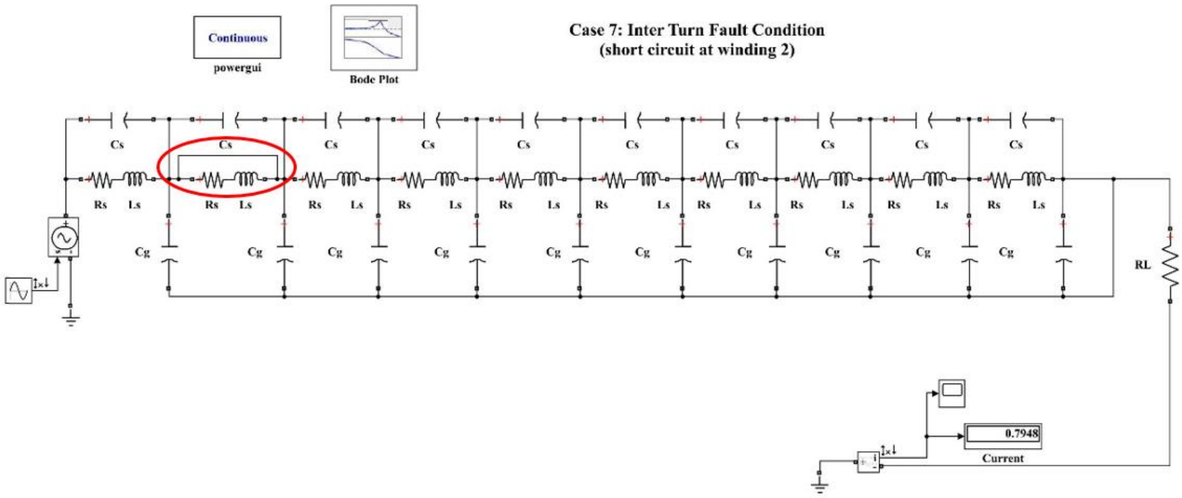


Figure 5: Transformer model for inter turn fault condition at winding 2

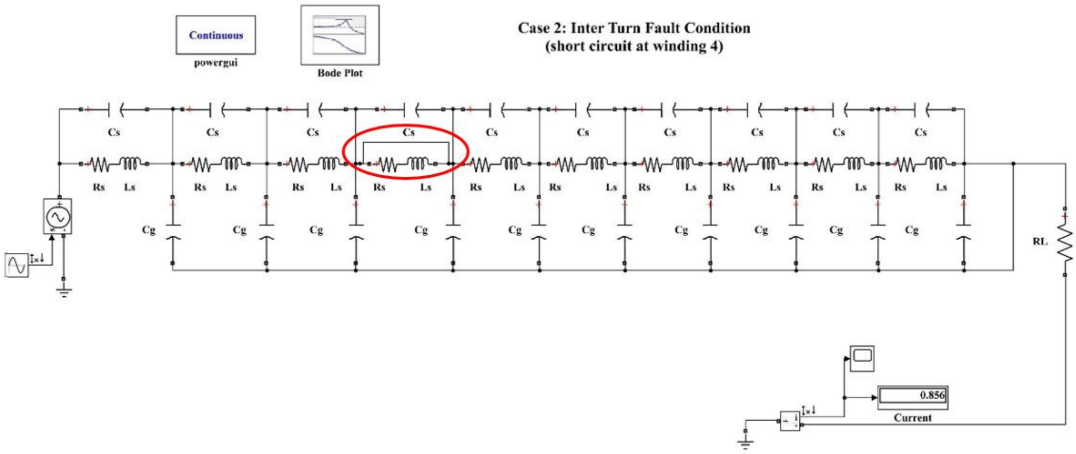


Figure 6: Transformer model for inter turn fault condition at winding 4

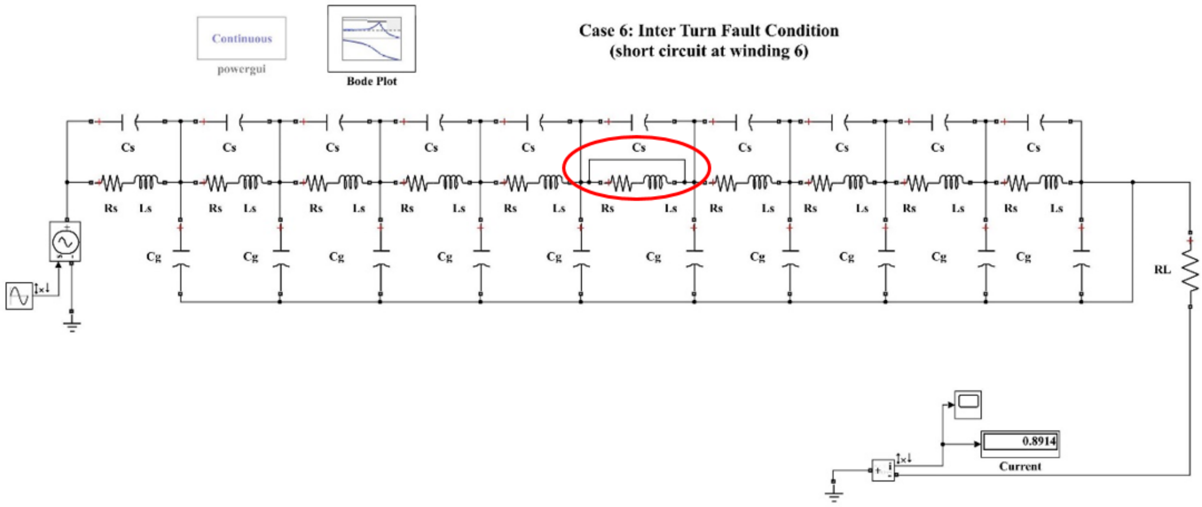


Figure 7: Transformer model for inter turn fault condition at winding 6

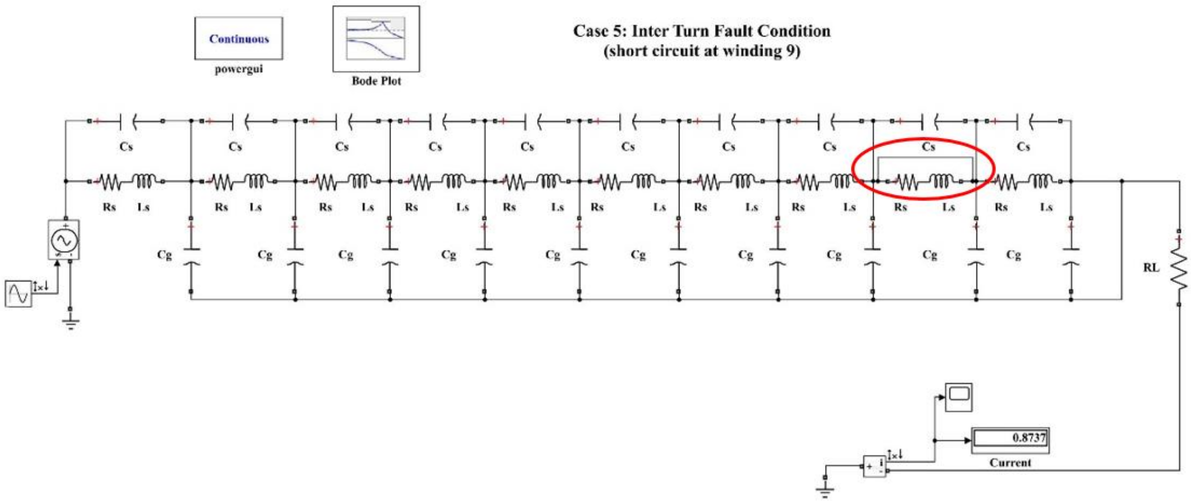


Figure 8: Transformer model for inter turn fault condition at winding 9

The waveform displacement found from the bode plot in Figure 9 is slightly increase compared to the unfault waveform which from the absolute 0.0028 to 0.00293. The first resonance occurred at 415 Hz and it has a relatively significant waveform displacement compared to the unfault condition waveform. From this simulation, 0.7948 A of current measured which is higher than the unfault condition. In this simulation, increased current released abnormal heat which affecting transformer insulation and causing the winding to burn out.

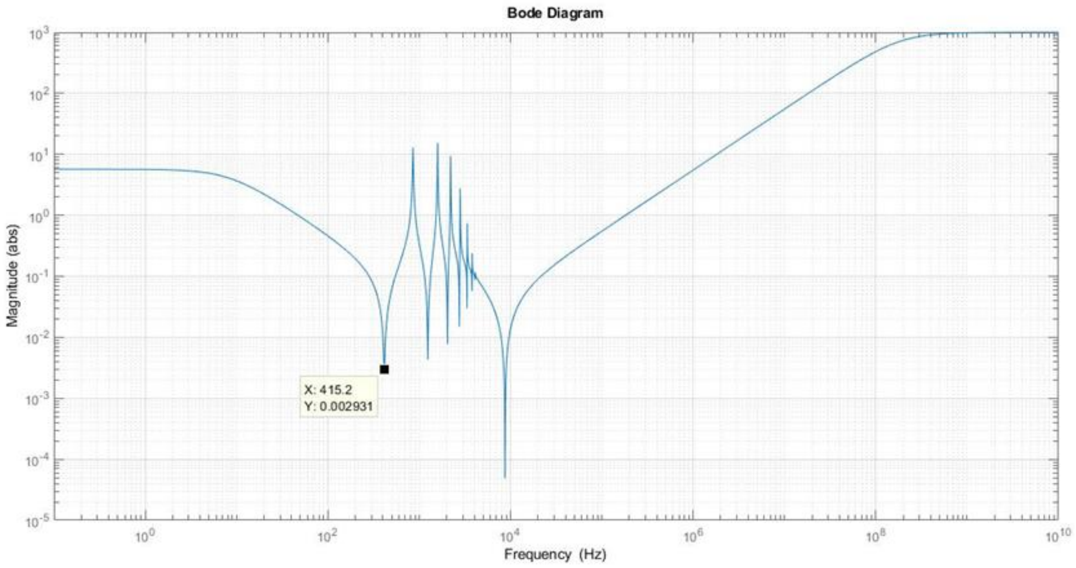


Figure 9: Simulated SFRA for inter turn fault condition at winding 2

The waveform displacement found from the bode plot in Figure 10 is slightly increase compared to the unfault waveform which from the absolute 0.0028 to 0.00293. The first resonance occurred at 415 Hz and it has a relatively significant waveform displacement compared to the unfault condition waveform. From this simulation, 0.7948 A of current measured which is higher than the unfault condition. In this simulation, increased current released abnormal heat which affecting transformer insulation and causing the winding to burn out.

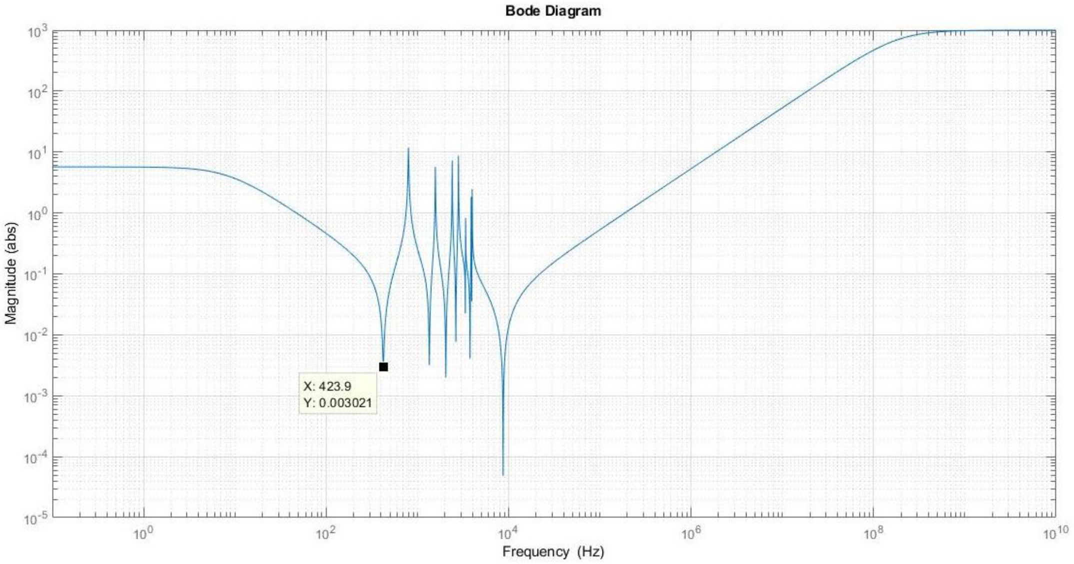


Figure 10: Simulated SFRA for inter turn fault condition at winding 4

This process repeated for the inter turn fault condition at fourth winding as shown in Figure 11, where it also shows the slightly increase waveform displacement occurred compared to unfault condition which is from absolute 0.0028 to 0.00302. Besides that, the first resonance of the fourth winding also give a relatively significant waveform displacement which is 424 Hz. The current also increases to 0.8560 A that can lead the transformer winding to burn out.

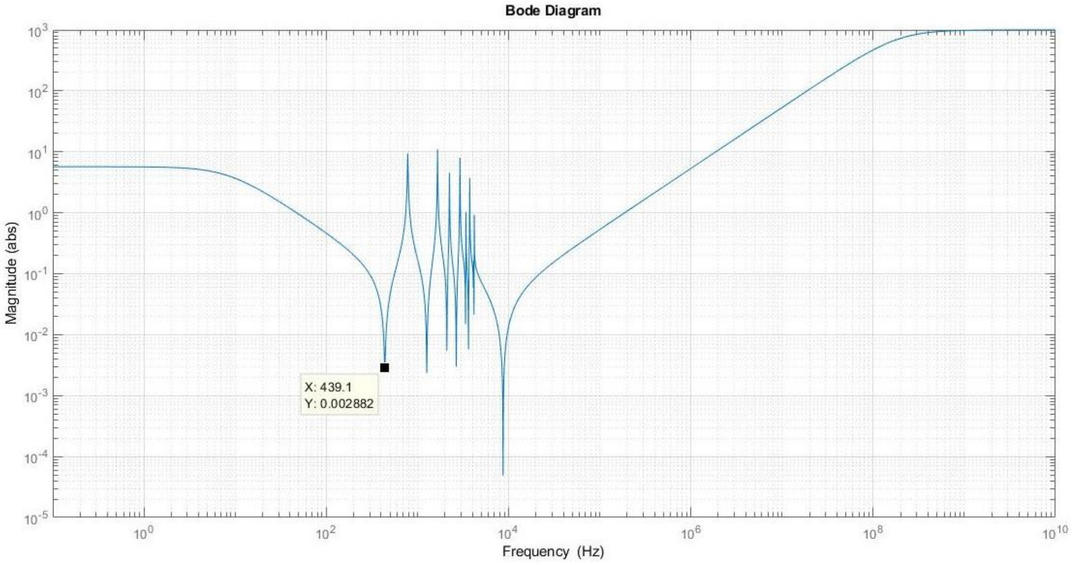


Figure 11: Simulated SFRA for inter turn fault condition at winding 6

Furthermore, this process repeated for the inter turn fault condition at sixth winding as shown in Figure 12, where it also shows the slightly increase waveform displacement occurred compared to unfault condition which is from absolute 0.0028 to 0.0029. Besides that, the first resonance of the fourth winding also give a relatively significant waveform displacement which is 439 Hz. The current also increases to 0.8914 A that also lead the transformer winding to burn out due to presence of the abnormal heat.

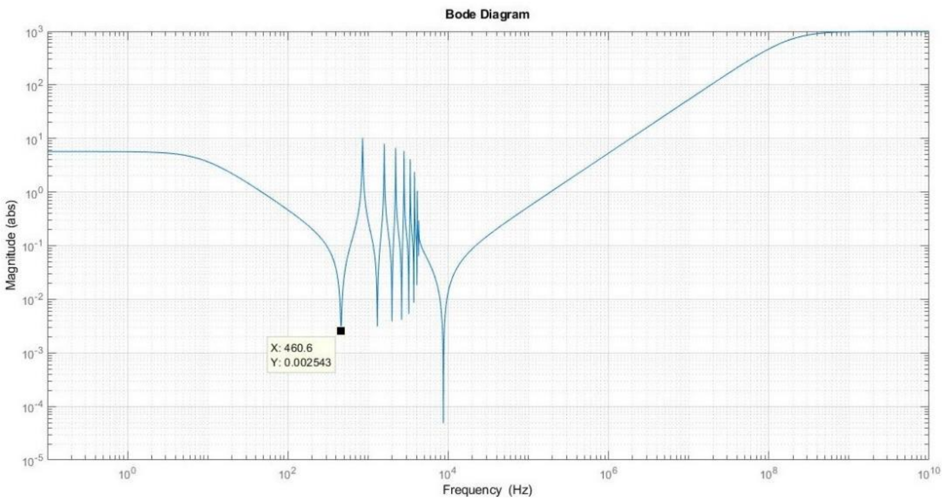


Figure 12: Simulated SFRA for inter turn fault condition at winding 9

3.3 Turn to turn fault conditions

Figure 13 until 16 show the transformer model for the turn to turn fault conditions. The fault are created between first and second turn, third and fourth turn, fifth and sixth turn and ninth and tenth turn of the transformer winding respectively

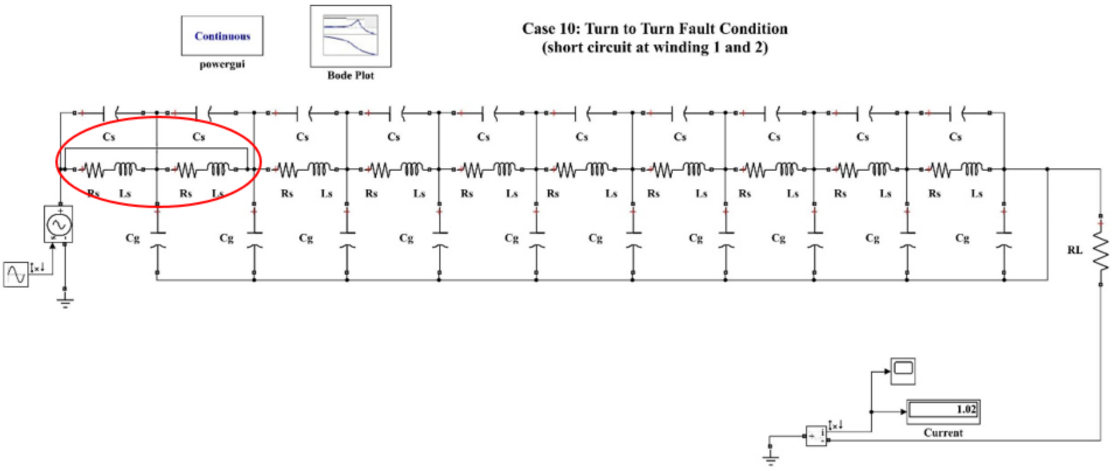


Figure 13: Transformer model for turn to turn fault condition at winding 1 and 2

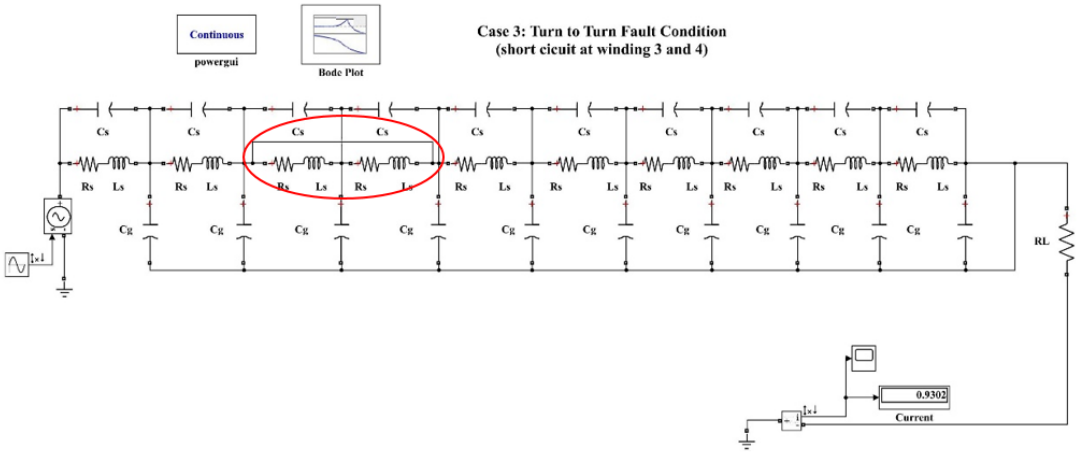


Figure 14: Transformer model for turn to turn fault condition at winding 3 and 4

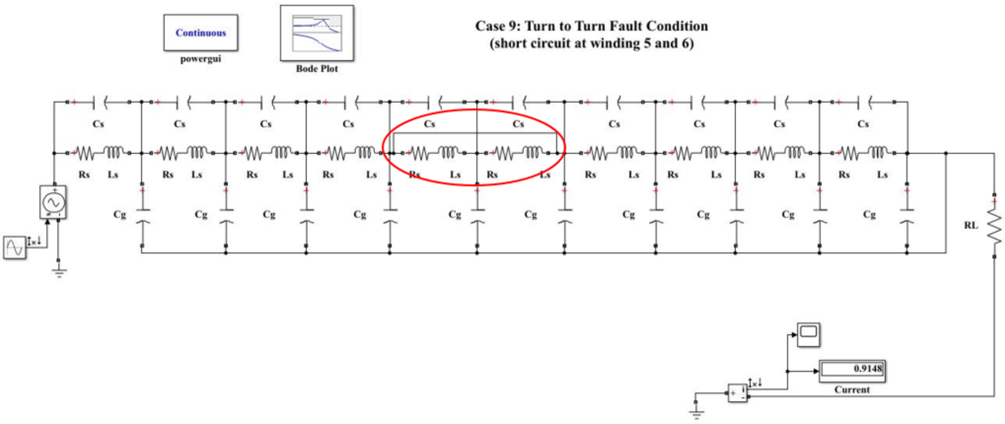


Figure 15: Transformer model for turn to turn fault condition at winding 5 and 6

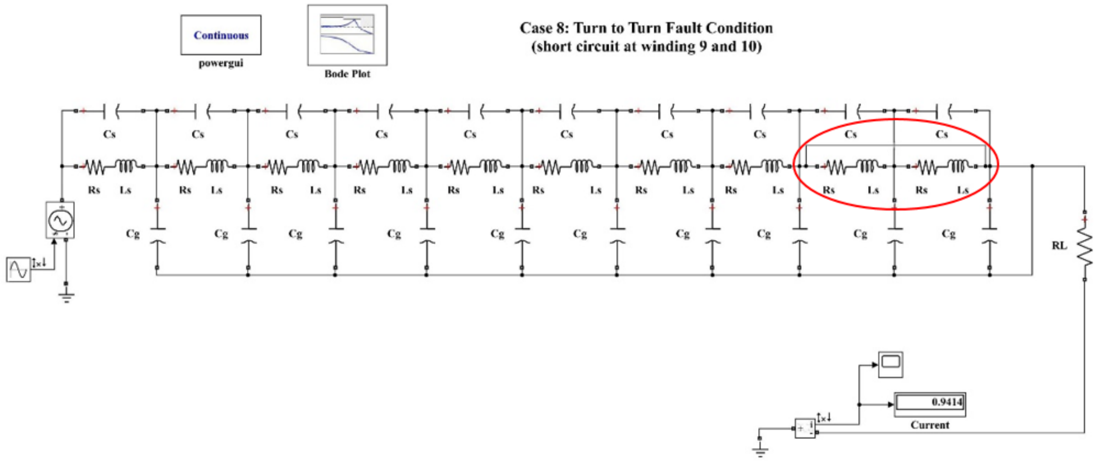


Figure 16: Transformer model for turn to turn fault condition at winding 9 and 10

The bode diagram obtained from all model for turn to turn fault are shown in Figure 17 until 20. Firstly, the bode diagram for Figure 17 shows the slightly increase waveform displacement occurred compared to the unfault conditions which from the absolute 0.0028 to 0.00295. In addition, the first resonance point is observed at 415 Hz as it is completely displaced compared to the unfault condition. At this stage, the measured current is 1.02 A, where it is increased by 0.2438 A from unfault current condition which thermally stress the insulation. The insulation were degraded due to this unexpected thermal stress used in the transformer winding.

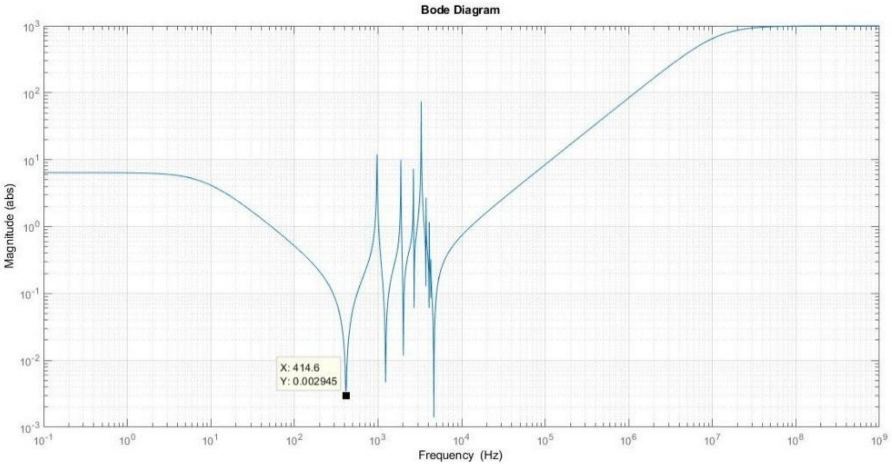


Figure 17: Simulated SFRA for turn to turn fault condition at winding 1 and 2

This method is continue for the turn to turn fault between third and fourth winding at Figure 18. Slightly increased waveform displacement also occurred after compared it to the unfault condition which is from absolute 0.0028 to 0.00328. The first resonance of each winding also give slightly increase waveform displacement of 428 Hz while the current also increases to 0.9302 A. At this condition, the occurred fault in transformers caused the interruption of the power supply due to high thermal stress.

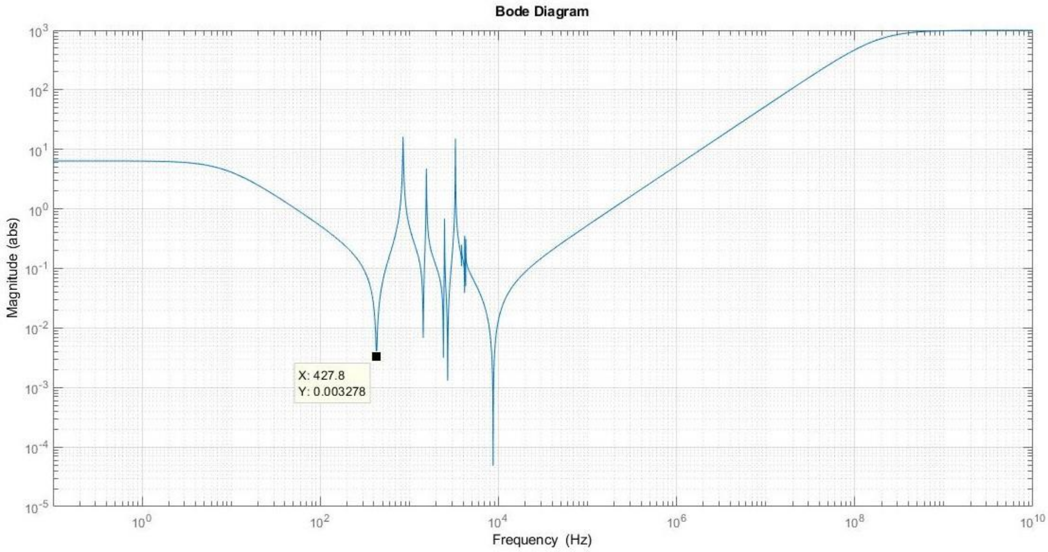


Figure 18: Simulated SFRA for turn to turn fault condition at winding 3 and 4

Next, Figure 19 shows the slightly increase waveform displacement occurred compared to the unfault conditions which from the absolute 0.0028 to 0.00313. Also, the first resonance point is observed at 458 Hz as it is completely displaced compared to the unfault condition. At this condition, the measured current is 0.9148 A, where it is increased by 0.1386 A from unfault current condition. The insulation were degraded due to this unexpected thermal stress used in the transformer winding.

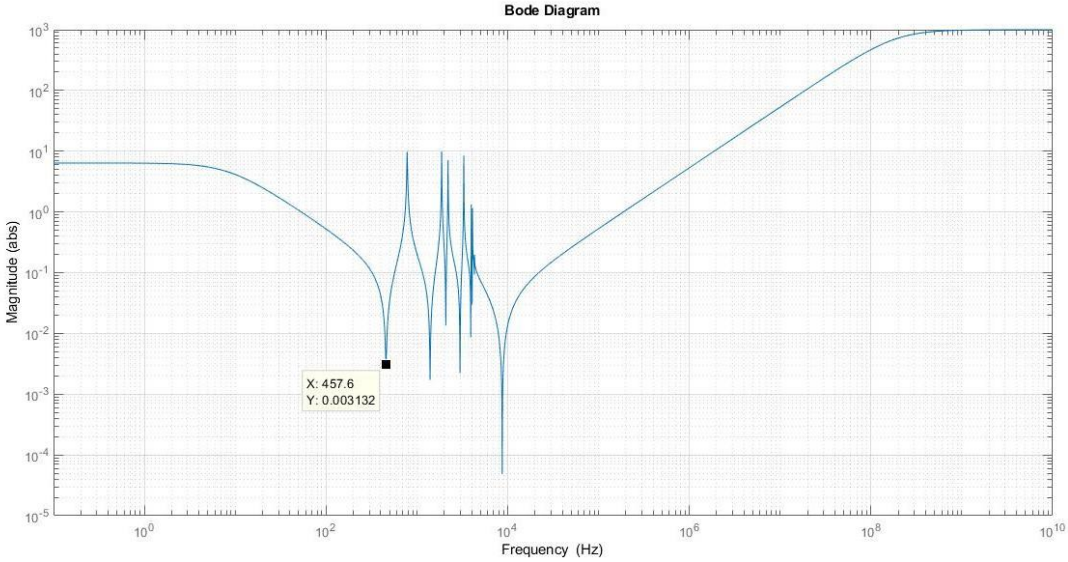


Figure 19: Simulated SFRA for turn to turn fault condition at winding 5 and 6

Figure 20 also shows the significant waveform displacement occurred compared to the unfault conditions which is from the absolute 0.0028 to 0.00222. The first resonance point is observed at 524 Hz as it is completely displaced while the measured current is 0.9414 A, where it is increased by 0.1652

A from the unfault condition. The insulation also corrupted due to this unexpected thermal stress used in the transformer winding.

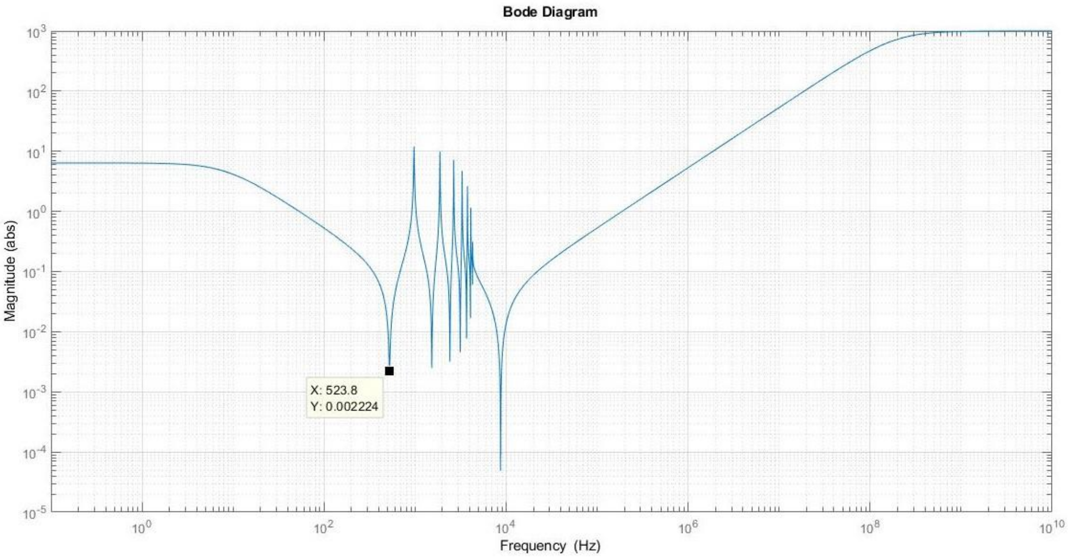


Figure 20: Simulated SFRA for turn to turn fault condition at winding 9 and 10

3.4 Change of ground capacitance

The transformer model for the ground capacitance condition is shown in Figure 21 where the ground capacitance (Cg) is changed from 0.011 nF to 52.6 pF. The calculation of the new Cg is shown in appendix B. This condition happen due to the length between windings, l is changed from 1 meter to 0.0209 meter to see the first resonance of the transformer winding. The ground capacitance for each winding is depend on the distance between windings. Thus, each of the Cg has the same value of 0.011 nF as the capacitor for each winding are connected in series. The new capacitance depend on the length between windings as it is equal to the total of series capacitor for each winding. The new ground capacitance value calculated after changing the length between windings is 52.6 pF.

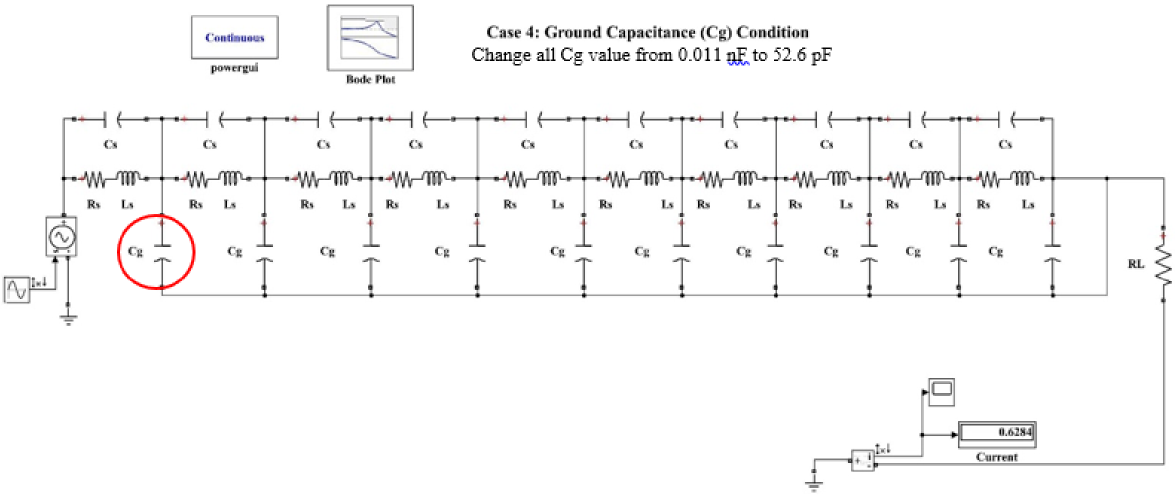


Figure 21: Transformer model for changing ground capacitance condition

The change of turn to ground capacitance observed due to the radial displacement of the transformer winding as shown Figure 22 below. The value of capacitance for normal condition is 0.011 nF. The comparison of Figure 21**Error! Reference source not found.** and Figure 22 observed that there is significant waveform displacement occur after the value of capacitance is changed from absolute 0.0028 to 0.0134. The waveform from the bode plot is completely collapse due to the capacitance is inversely proportional to frequency. The first resonance point is appeared at 189 Hz while the simulated current is limited to 0.6284 A which is lower than the reference condition. Therefore, the lower capacitance value reflects the life span of the transformer spent due to the lower frequency resonance.

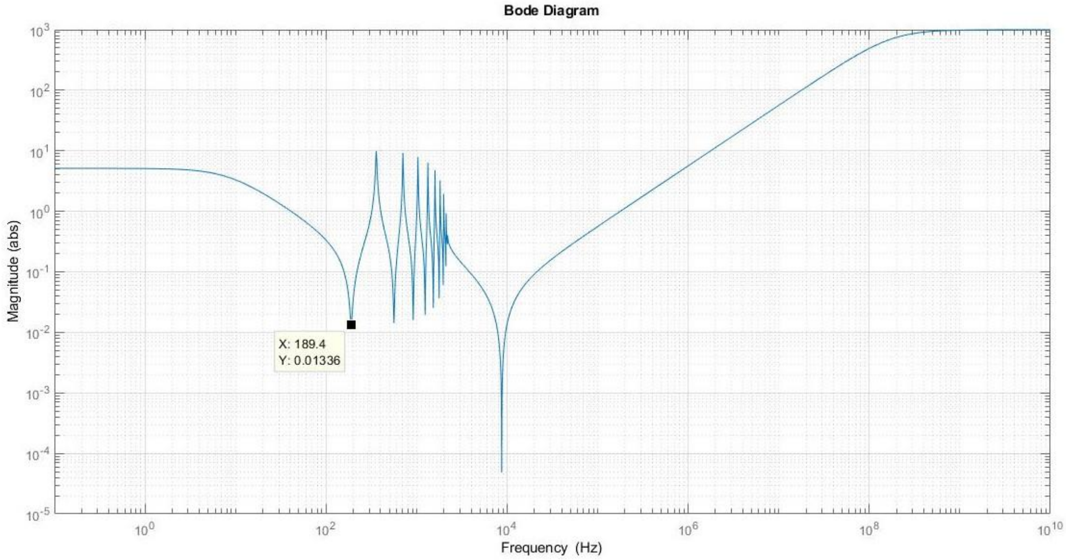


Figure 22: Simulated SFRA for changing ground capacitance condition

4. Conclusion

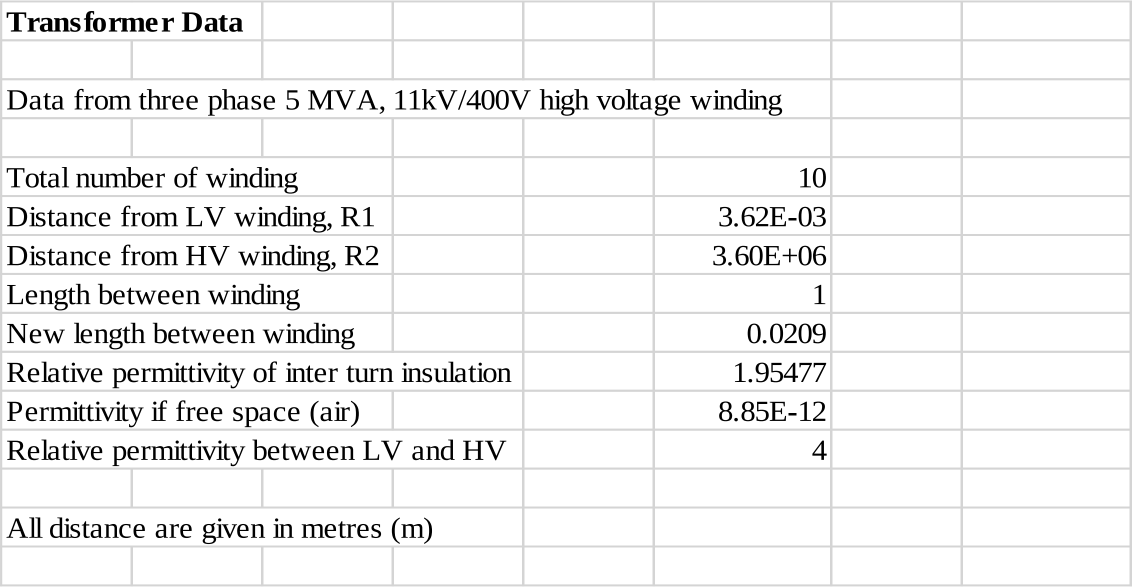
In the process of completing this project, the simulation of the transformer winding fault detection using SFRA was simulated. At the end of this study, the objectives of this project is achieved and compared with the result obtained from the simulation. By using MATLAB/SIMULINK software, the FRA can be developed by applying sweep frequency to the transformer winding. Besides, the transformer winding fault are diagnosed using FRA method by applying SFRA. This method is shown by created a short circuit in the winding and also between two windings for the fault conditions. Last but not least, there are three fault conditions like inter turn fault, turn to turn fault and change in ground capacitance are simulated and compared with the reference to the unfault conditions. There are several recommendations for future works suggested in this project, for improving its performances. Firstly, the rating of the voltage source from the transformer model can be changed into larger value to get the bigger current value as well as its resonance point and also magnitude and adding and developing new blocks for Simulink software such as using a Fast Fourier Transform (FFT) analysis block as it is easy to find the frequency domain of the transformer winding model instantaneously

Acknowledgement

The authors would like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

Appendix A

Transformer data



Transformer Data	
Data from three phase 5 MVA, 11kV/400V high voltage winding	
Total number of winding	10
Distance from LV winding, R1	3.62E-03
Distance from HV winding, R2	3.60E+06
Length between winding	1
New length between winding	0.0209
Relative permittivity of inter turn insulation	1.95477
Permittivity if free space (air)	8.85E-12
Relative permittivity between LV and HV	4
All distance are given in metres (m)	

Appendix B

Ground capacitance calculation

The general equation for the capacitance is

$$\frac{C}{l} = \frac{2\pi\varepsilon}{\ln\frac{b}{a}}$$

To find the ground capacitance for each winding,

$$C = \frac{\varepsilon_0\varepsilon_1 2\pi}{\ln\frac{R2}{R1}} \times l$$

Where R1 and R2 are the distance between the low voltage and high voltage winding respectively.

$$C = \frac{8.85 \times 10^{-12} \times 4 \times 2\pi}{\ln\frac{3.6 \times 10^{6}}{3.62 \times 10^{-3}}} \times 1$$

$$C = 0.011 \times 10^{-9}\, F$$

We know that,

$$C = C_1 = C_2 = C_3 = C_4 = C_5 = C_6 = C_7 = C_8 = C_9 = C_{10}$$

Therefore,

$$C_1 = C_2 = C_3 = C_4 = C_5 = C_6 = C_7 = C_8 = C_9 = C_{10} = 0.011\, nF$$

To find the new ground capacitance, C_g

$$\frac{1}{l \times C_g} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} + \frac{1}{C_5} + \frac{1}{C_6} + \frac{1}{C_7} + \frac{1}{C_8} + \frac{1}{C_9} + \frac{1}{C_{10}}$$

Where l_{new} is the new length between winding = 0.0209 m.

$$\frac{1}{0.0209 \times C_g} = 10 \times \frac{1}{0.011 \times 10^{-9}}$$

$$0.0209 \times C_g \times 10 = 0.011 \times 10^{-9}$$

$$C_g = 52.6 \times 10^{-12}\,F$$

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