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A NOVEL APPROACH TO SFRA (SWEEP FREQUENCY RESPONSE ANALYSIS) TEST ON ONLINE TRANSFORMER

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Abstract: In this paper, a study of 6.6kV transformer with continuous disc type winding is implemented. the deformations in winding are explored by frequency response analysis (FRA) method. Presented circuit is developed on the basis of lumped parameter model. Series inductance, ground capacitance (shunt capacitance) and series capacitance are elements considered for analyzing transformer. The calculations were performed using the data sheet for the 6.6kV transformer design specification. To simulate the risk of winding failure, the parameter values were altered, resulting in a varied frequency range spectrum. The FRA simulation has a frequency range of 10 kHz to 2MHz. Transfer function (Vout/Vin) and trans-impedance (Vin/Iout) simulations were performed.
The MATLAB/Simulink software program is utilized for simulation and analysis. The bode plot command used to plot the magnitude of the equivalent circuit of the transformer. Simulations used to develop faulty and healthy circuits for the purpose of analysis. For measuring minor deviations within specified frequency bands, linear frequency scale used (varies from 10Hz-2MHz). This paper includes sweep frequency response analysis in the FRA. A simple offline SFRA tests have performed on the transformer, along with a description of the various features of winding problems. A basic online SFRA test is performed using the same transformer and presented using MATLAB/Simulink tools and routines.

Keywords: SFRA, FRA, HV, LV, MATLAB/Simulink, winding fault of transformer

I. INTRODUCTION

Power is transmitted between the supply and the customer in power systems via necessary devices. Inspection of these devices is essential before usage for safety reasons. For increased efficiency and accuracy, it is mostly done by computer simulation. The power transformer is the most valuable asset in the power industry. Transformers step up or down the voltages for safe and efficient power transmission. Because transformers play such an essential role, their reliable performance is critical for providing a constant power supply to meet industrial and home demands. Fault detection and diagnosis are critical for increasing the dependability and safety of such complex dynamic systems. Short circuit failure of transformers is a major source of concern for transformer users. Short circuit defects in windings have piqued researchers' interest because they are considered the heart of a transformer.

Another intriguing field of research is the computation of short circuit forces, which can be used to improve the design of transformer windings' short circuit strength withstand capabilities. The reactance is calculated before and after the test using the traditional approach. If the change in reactance is greater than 1% for a transformer with a rating greater than 100MVA, the transformer has failed the test. Later, the transfer function method was found to be effective in demonstrating transformer winding structural integrity. Furthermore, it was demonstrated that the frequency response analysis (FRA) method is superior for establishing the mechanical integrity of transformer windings. Signal analysis methods play a key part in detecting and classifying winding deformation, and they're supported by a variety of signal modifications.

One of the most significant and difficult areas of transformer design is short circuit strength design. When a transformer fails, it may endure mechanical shock, which displaces and distorts the windings over time. During winding motions, the insulation between the turns might be abraded, resulting in a short circuit and winding damage. Mechanical vibrations caused by short circuit forces may cause the windings to lose their clamping pressure, resulting in winding collapse.

Extensive vibration during transformer shipment could also induce winding movement. Vibrations may cause the windings to slacken, making them unable to sustain the mechanical stress exerted during faults. Winding looseness is also a result of ageing. Winding and core vibration may also be caused by harmonics generated under normal operating conditions. Short circuit forces can be extremely damaging because if the clamping pressure is insufficient to restrict the pressures, permanent winding deformation or even collapse can occur practically instantly, often accompanied with shorted turns.

FREQUENCY RESPONSE ANALYSIS (FRA) METHOD

The FRA method is a frequently used methodology for evaluating transformer winding condition. The LVI (Low Voltage Impulse) excitation method and the sweep frequency approach using a sinusoidal signal source, often known as SFRA, are two methods for performing FRA. The impulse voltage signal is applied in the LVI method, and the current going through the winding can be detected, after which the signal is transformed to the frequency domain using the rapid Fourier Transform algorithm (FFT). The LVI has an issue with noise and poor resolution in the high frequency zone. Existing winding deformation analysis methods are mostly based on frequency domain transfer function determination using low voltage impulse excitation and frequency response analysis utilizing a sinusoidal sweep.

For monitoring transformer windings, SFRA is a fairly reliable technique. SFRA can detect a variety of mechanical and electrical fault states. SFRA's primary function is to detect mechanical flaws. When compared to finger print measurement, the SFRA test is performed on a regular basis to monitor the winding condition and frequency response. Due to changes in R, L, and C values, variations in frequency responses may show a physical change inside the transformer winding. For large power transformers, most utility providers have their own FRA data.

The sinusoidal voltage is applied at multiple frequencies with constant magnitude in the SFRA technique. The winding's response is measured. A master frequency response is comparable to this frequency response. The FRA testing is currently considered as offline mode test of transformer. Before testing can be carried out securely, a lot of preparation is required. Separating the transformer from the rest of the network is required. When the transformer is being serviced or maintained, then the FRA testing is recommended.

PROBLEM STATEMENT

Despite the fact that transformers are sturdy and can sustain numerous short circuit failures without total breakdown, significant winding deformation reduces transformer lifespan over time due to locally enhanced electromagnetic pressure [3]. As a result, it's vital to spot any winding distortion right away and take appropriate correction action.

Traditional methods for identifying internal problems and winding movements in transformers have proven ineffective. Frequency response analysis, on the other hand, has proven to be a powerful diagnostic tool for detecting transformer winding deformation. Since the invention of particular FRA test equipment, the testing process has become quite straightforward.
The interpretation of the results is still a murky concept, and experts are frequently called in to determine the nature and location of the fault. The SFRA technique has been evolving for years, with repeated proposals for industrial standards and criteria. However, SFRA is currently used in offline applications, and it is mainly used after a transformer failure, which is insufficient to avoid a transformer failure in real time. As a result, the aim is to conduct a theoretical examination of SFRA in an online environment.

PROBLEM FORMULATION

FRA signature obtained after simulation of transformer model –
FRA is the most often used sensitive method for detecting mechanical faults in power transformers, according to study. The purpose of this research is to develop a model that can be used in Simulink, a MATLAB software toolbox, to simulate the transformer model and obtain the transformer's FRA signature.

Winding deformation as interpreted by the FRA –
This study [3,2] shows how changing the model's parameter values can simulate deformation in transformer windings. The goal of this paper is to improve FRA. interpretations by modelling and evaluating transformer winding deformation. Winding distortion would be accurately represented by parameter approximations.

Online SFRA approach –
It is seen that transformer can have different SFRA tests while the transformer is offline. But further improvement of SFRA technique can be done by online SFRA test. The another aim for this paper is to make a model of simulation of a healthy winding transformer to get the results of SFRA while the source (230v rms) is connected. Which is consider as online SFRA approach.

II. PROPOSED WORK

Creating a Winding Model for a Transformer

Various analytical methods have been used for transformer modelling in recent decades. Because of their simplicity, some of the approaches have been employed for deformed winding analysis despite their limitations in terms of detailed depiction of genuine transformer geometry. The methodologies discussed above are mostly concerned with inductances in the transformer model, which is a huge undertaking in transformer modelling. The lumped parameter model is most suitable for modelling 13 kV/ 275 kV/ 400 kV, 1000 MVA, continuous disc type transformer windings with continuous disc type high voltage, according to the literature review. The frequency range of interest for this paper is 10 kHz to 2MHz. Winding resonances (i.e., transfer function maxima and minima) are used to identify high frequency behavior. These characteristics will change when mechanical displacement is introduced. Fault type and location are significant operational requirements. These correlations can be determined via measurements on the power transformer or simulations using an appropriate transformer model.

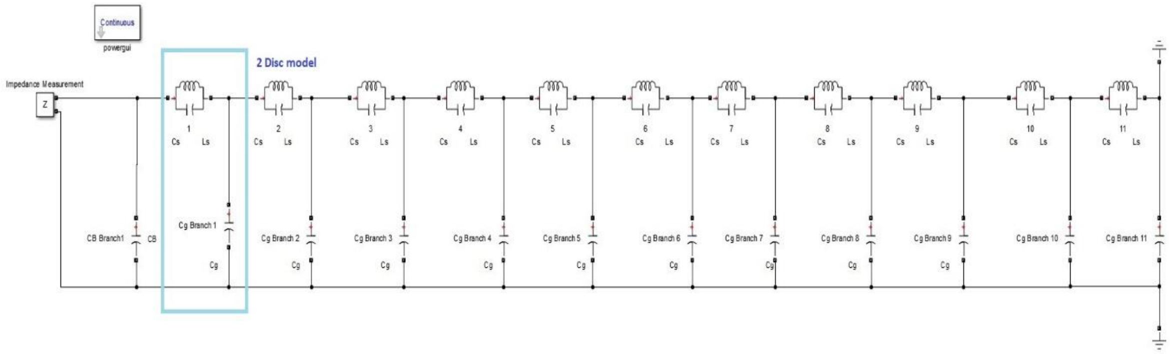
Model by Lumped Parameter

This chapter explains how to simulate a high frequency characteristic and modelling of a 6.6 kV continuous disc type transformer winding. The transformer data for modelling is given in Appendix A. The approach considers winding design as well as the frequency dependence of losses.

Scomplete lumped-element model of the transformer, as shown in Figure 1. The elements of the lumped units are connected in this equivalent circuit. A continuous disc winding was used to create this model.

Cs, Cg, and Ls are the series, ground, and self-inductance capacitances, respectively, per unit length, and on a turn-by-turn basis.

When running the simulation in SimPowerSystem, the 50Ω resistance is ignored in order to produce a totally undamped transient waveshape. The model is used to show how sensitive the impedance measurement and transfer function are as a monitoring tool for identifying transformer winding movement.



1 The equivalent electrical network of lumped parameter

Table 1 shows the final values of the computed series capacitance, inductance, and shunt capacitance.

Symbol of Parameter	Parameter Name	Value of parameter
C_g	Shunt Capacitance	13.92pF
C_s	Series Capacitance	7.909pF
L_s	Self-Inductance	532.958µH

Table 1 Two discs Calculated model parameter values

SFRA Measurand

In the application of the SFRA method, there are two alternative measurand potentials. The trans-impedance measurement (Vin/Iout) and the transfer function (Vout/Vin). The output voltage is Vout, the input voltage is Vin, and the output current is Iout. The impedance measurement has no link with the transfer function determined from the voltage ratio (Vout/Vin).

As a measurand transfer function, the voltage ratio (Vout/Vin) is the most often used. The goal of employing impedance or voltage ratio transfer functions has yet to be simply explained in the literature. Admittance measurements are less susceptible to minor geometric changes than voltage ratio measurements because the needed current transformers create a low-level output of the signal.

Analysis of Frequency Response

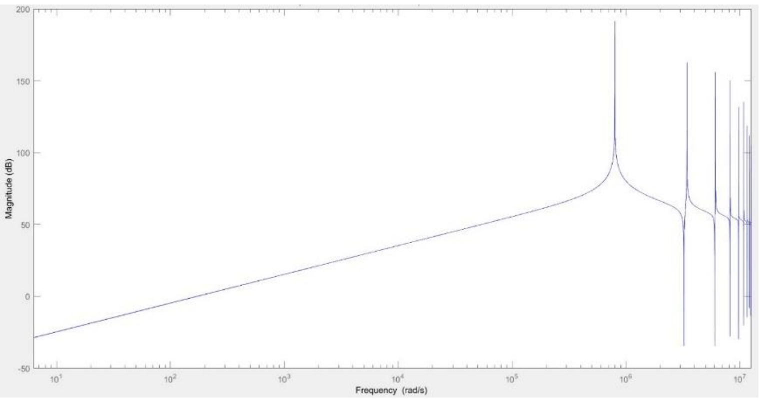
The following major elements have been identified in the literature regarding transformer winding deformation categories:

- Inductive components commonly found in the transformer winding response of impedance or transfer function have been linked to frequencies of [<20kHz] (or lower frequency).
- Capacitance and inductive parameter mixes produce multiple resonances in the [20-400kHz] (or mid frequency) range.
- The capacitance component leads the frequency response signature in the [>400kHz] (or higher frequency) frequency range.

III. CASE STUDY & RESULTS

The goal of this chapter was to plot discrete changes in series inductance, capacitance, and ground capacitance along the windings while maintaining the healthy transformer winding model. The element-by-element fault simulations for the case studies are listed below. The SFRA of a healthy transformer winding model is the first outcome. Two cases of winding fault were then demonstrated using terminal impedance analysis: disc to disc fault and comparison between two different disc to disc faults based on locations. Both analyses included the remaining three cases: terminal impedance analysis and transfer function analysis.

Result of Healthy Condition of Transformer



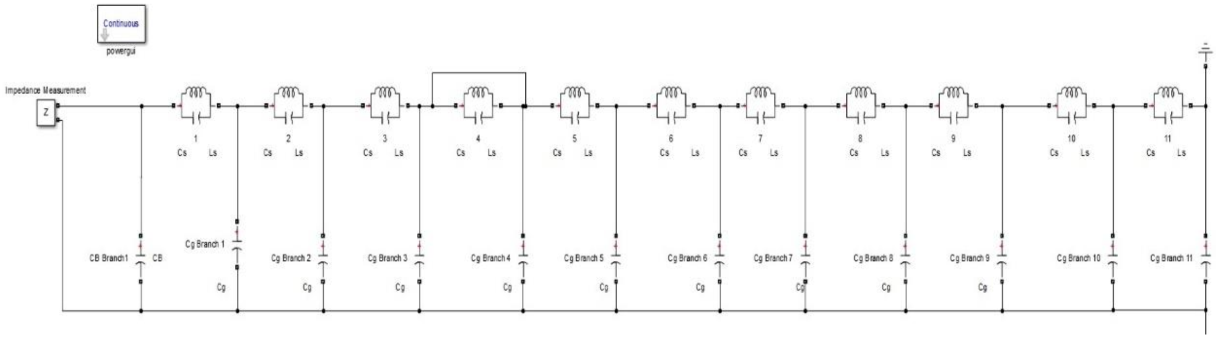
1 SFRA of healthy transformer using impedance measurement

Figure 2 shows the first result, the SFRA of a healthy transformer winding model of figure 1.

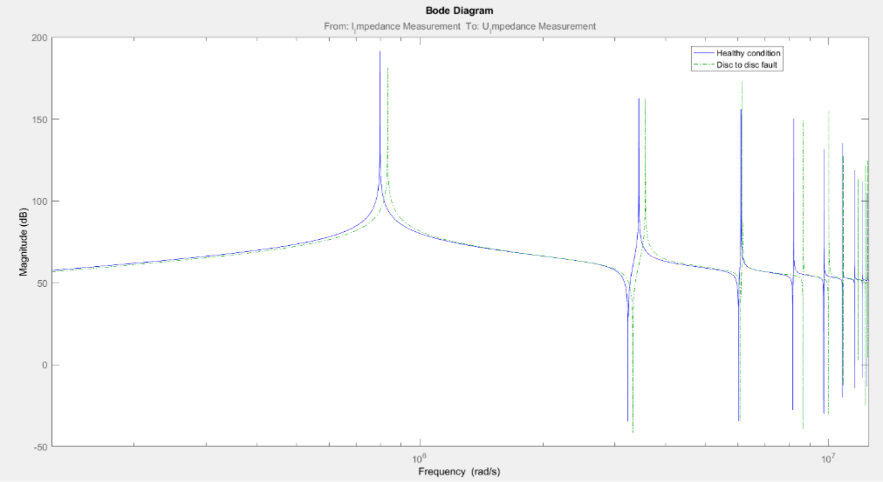
The equivalent circuit of a transformer winding includes various inductance, resistance, and capacitance elements for a wide variety of frequencies. The winding elements have mutual inductive and capacitive coupling, which effectively determines the SFRA response of the winding, including numerous resonances and anti-resonances.
Around 120kHz, the first resonance occurs. The inductance of the transformer winding dominates beyond this resonance threshold. The magnetic effect of the point tries to increase after the first resonance point, but the winding inductance effect is screened. This process is repeated numerous times, increasing the number of resonance spots in the medium frequency band.
The frequency is varied from 0Hz to 2MHz. The graph shows the value of frequency in rad/s which can be converted in Hz and vice versa by,
1 Hz = 2π rad/s = 6.2831853 rad/s
Or
1 rad/s = 1/2π Hz = 0.1591549 Hz
In this analysis magnitude is due to trans-impedance (Vin/Iout) and it’s unit is in dB.

Case 1: Disc to Disc Fault

Figure 3 depicts the transformer model for a disc to disc failure. Model is designed such that the fault created between 7th and 8th discs of the transformer winding. Figure 4 depicts the disc to disc fault plot derived from this model.



3 Transformer model for disc to disc fault

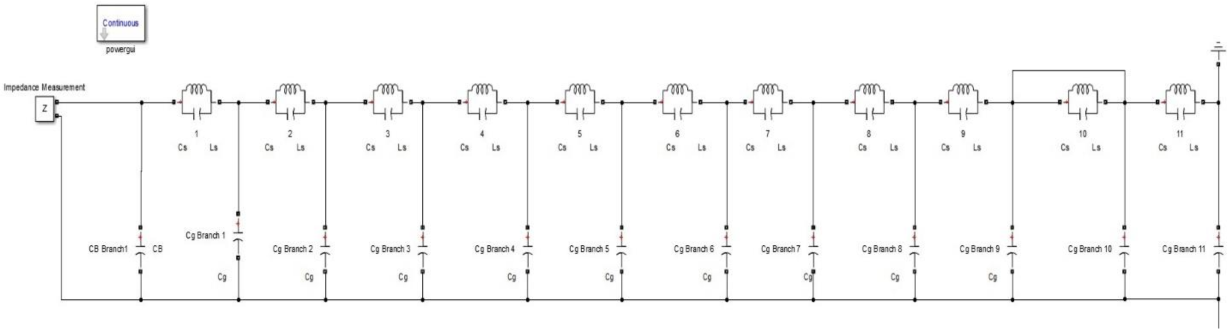


2 SFRA of disc to disc fault

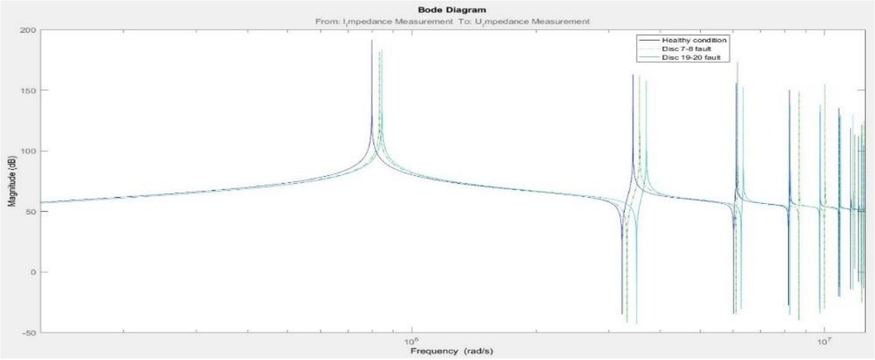
Figure 4 shows that significant waveform displacement occurs when compared to a waveform with no fault. At 127kHz (799krad/sec), the first resonance point occurs for unfaulty condition. While for faulty condition the first resonance is shifted to right at 132kHz. There is also a little waveform displacement in the middle frequency band when compared to the unfaulty condition waveform.

Case 2: Disc to Disc Fault Comparison

Figure 5 shows the transformer model for disc to disc faults in the 19th and 20th discs. Figure 6 shows the disc to disc fault plot derived from this model. The storyline also includes a previous record of unfaulty transformer condition and a disc to disc failure between the 7-8th discs. Figure 6 shows that significant waveform displacement occurs when compared to a waveform with no fault. While for faulty condition in disc-disc fault at 19-20 discs the first resonance is shifted to right at 134kHz. Which is little right shifted compare to the previous fault between discs 7-8.



5 Transformer model for disc to disc fault in between 19-20th disc



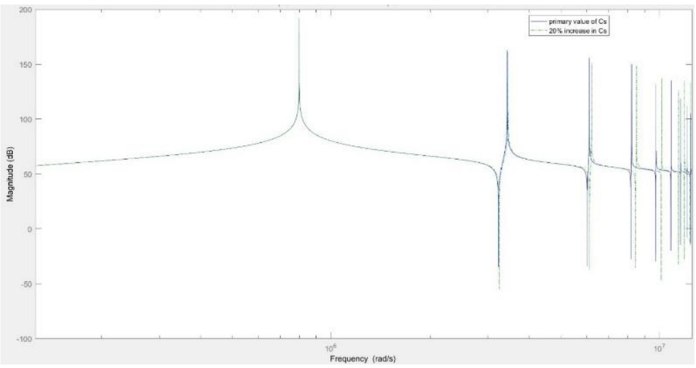
3 SFRA of disc to disc fault comparison

In comparing both the faults with considering different location of fault in mind, the fault which occurred near the source terminal of transformer (7-8 discs) and fault at far location from the input terminal (19-20 discs), showing different behavior at different band of frequencies. So, it can be concluded that based on location change of same fault the SFRA is different for different location and its do not have same behavior in different frequencies.

Case 3: Trans-Impedance measurement of different faults

case 3.1: Increase in Series Capacitance (Cs) by 20%

This example relates to a situation in which the series capacitance is altered. The series capacitances on discs 1-2, 9-10, and 17-18 are increased to achieve this.

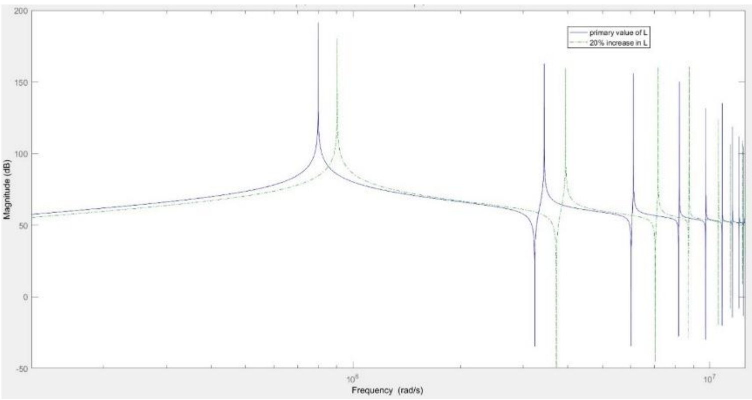


4 Comparison of Series capacitance

While the inductance and ground capacitances stay unchanged, the series capacitance has been increased by 20%. This flaw is disguised as series capacitance fluctuations caused by insulation ageing, which reduces insulation dielectric strength and thus affects series capacitance. Figure 7 depicts the effect of increasing series capacitance.

case 3.2: Increase in Series Inductance (Ls) by 20%

In this example, the defect is disc deformation caused by local breakdown, and the parameter impacted is inductance. At positions L2, L6, and L11, the windings are simulated, and the inductance values are increased by 20% at these locations. Other aspects of the original transformer remain unchanged.



5 Comparison of Series inductance

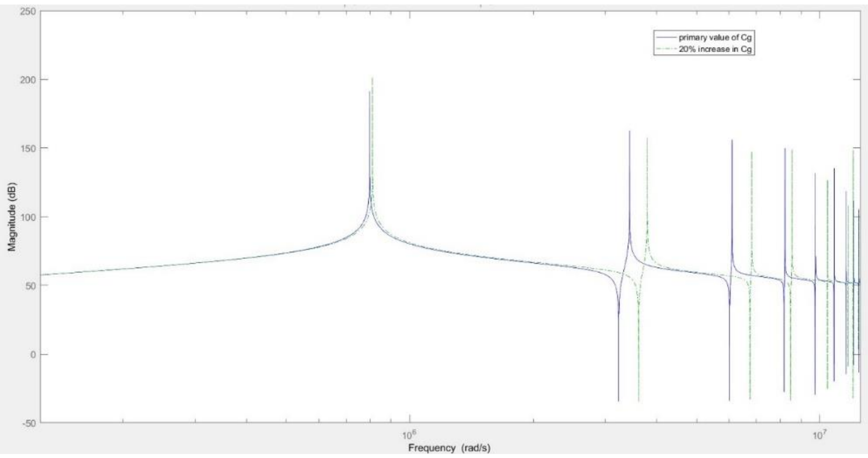
Figure 8 depicts the effect of inductance on terminal impedance. Figure 8 shows a typical bode plot of the healthy (blue) and damaged (red) transformer signatures. (Green slashes).

As the green dashed lines shift leftward, increased inductance has a similar effect to series capacitance, resulting in a reduction in all frequencies at the relevant discs. Changes in L, like changes in Cs, have an impact on lower frequencies (from 400kHz upwards).

Here the change in Ls affects much more in whole SFRA compare to previous fault.

case 3.3: Increase in Ground Capacitance (Cg) by 20%

The ability to detect and locate disc movements, buckling due to significant mechanical stresses, and moisture intrusion anywhere along the winding will all have an impact on shunt capacitances. Shunt capacitances were increased by 20% at the Cg3, Cg7, and Cg10 winding positions to investigate this.

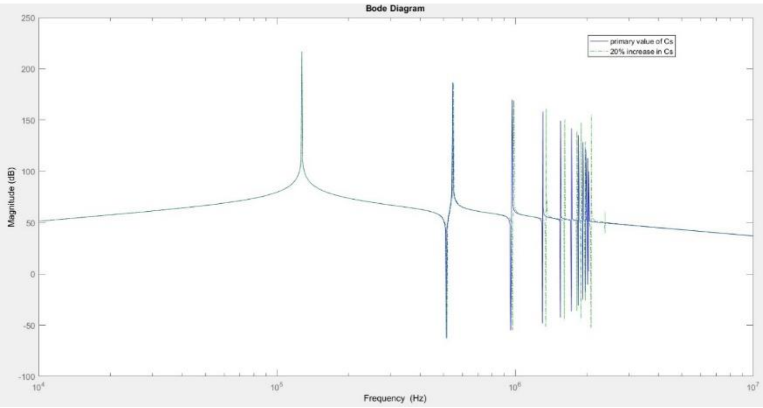


6 Comparison of ground capacitance

Figure 9 illustrates a bode plot comparison of the primary Cg value (blue) and a 20% increase in Cg values at specific points (green). Figure 5.8 shows how a 20% rise in Cg causes the magnitude to shift leftward. The impedance's resonant frequencies have been changed by a change in Cg. At 400kHz, the effect is hardly discernible, but as the frequency rises, so does the visibility.

Case 4: Transfer Function Measurement of different faults

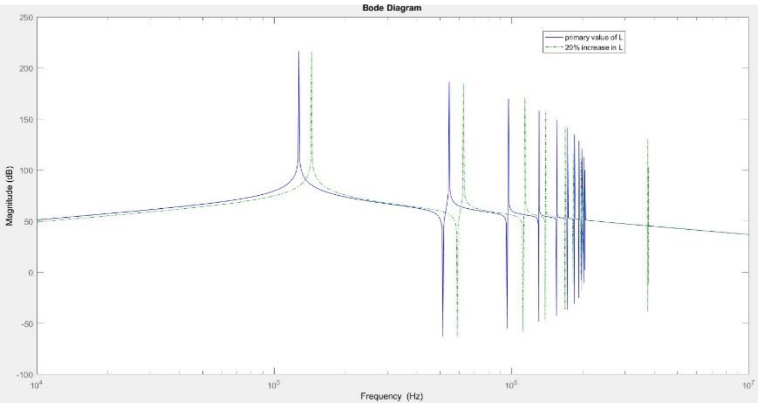
Case 4.1: Increase in Series Capacitance (Cs) by 20%



7 Comparison of Series capacitance using tf

The technique for Case 3.1 was then repeated, but this time with transfer function measurements has taken instead of impedance measurements and varying series capacitance values. Figure 10 depicts the results of a healthy measurement and the defect insertion, which are identical to Case 3.1.

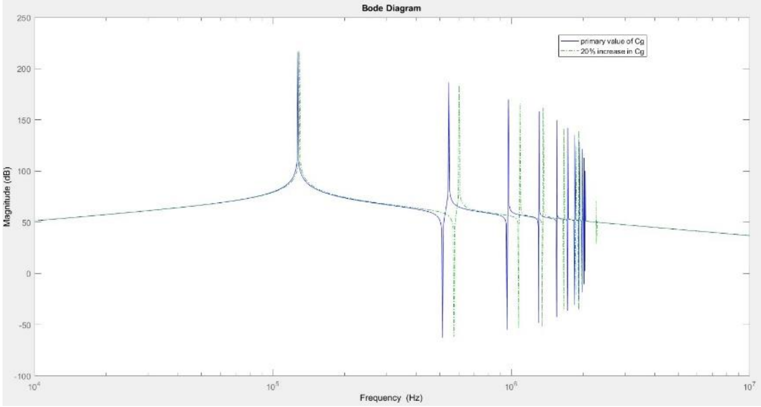
Case 4.2: Increase Series Inductance (Ls) by 20%



8 Comparison of Series inductance using tf

Inductance values L2, L6, and L11 are increased by 20%, as in Case 3.2, and the transfer function command is used. Figure 11 depicts the bode plot analysis. The resonance frequencies alter with the existence of the fault, as can be seen. The amplitude diminishes with increasing frequency.

Case 4.3: Increase in Ground Capacitance (Cg) by 20%



9 Comparison of ground capacitance using tf

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Cg values at Cg3, Cg7, and Cg10 have been increased by 20% in winding positions to explore the impacts of ground capacitance. Figure 12 depicts the bode plot analysis. Case 4.3 yielded the same findings as 3.3.

IV. ONLINE SFRA APPROACH

Researchers all over the world have proposed and developed many ways for detecting mechanical winding distortion. Frequency response analysis (FRA) is known to be an accurate, economical, reliable, rapid, and non-destructive procedure among all the methodologies. The SFRA method has been evolving for years, with consecutive proposals of industry standards and criteria, and these works have made significant contributions to the advancement of winding mechanical fault diagnostics.

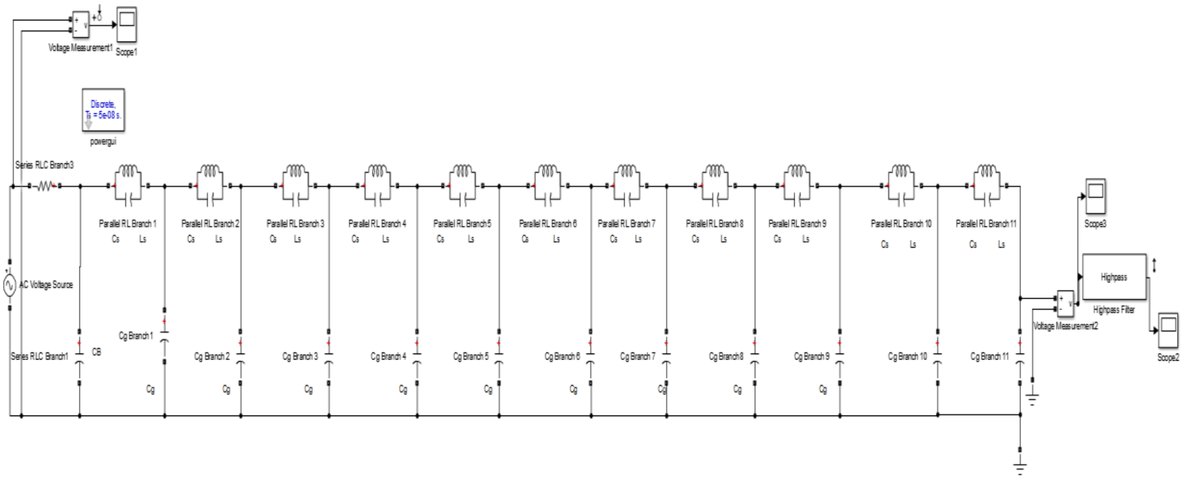
However, SFRA is currently used in offline applications, and it is mainly used after a transformer failure, which is insufficient to avoid a transformer failure in real time. As a result, the goal is to conduct a theoretical examination of SFRA in an online environment.

Lumped Parameter Model for Online SFRA and Result

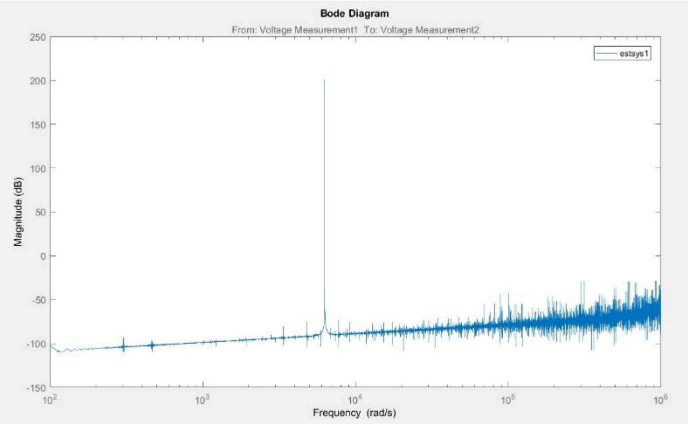
The requirement for the online SFRA is that the transformer must be connected to the source, and we need to provide sweep frequency to the input terminal, so modulation must be performed such that the source voltage signal has a base frequency of 50/60Hz, and the sweep signal (frequency varies from 10Hz to 2MHz) is converted into modulated signal and sent to the transformer input.

At the output terminal of transformer is then connected to a filter, to filter out the unwanted source frequency of 50/60Hz, which can be called as demodulation. Here high-pass filter is used whose cut out frequency is 70 Hz. Which gives at output only frequency above 70Hz that is varied from 70-2MHz.

The model is developed in MATLAB/Simulink environment which shown in figure 13. The linear analysis and frequency estimation tool is utilised to get chirp signal and modulated input signal.



13 Lumped parameter model for online SFRA



10 Online SFRA plot

The plot of an online SFRA is shown in figure 14. As the modulation and filter concept involves in the signal, at the higher frequencies behaviour of capacitance and inductance is changes alongside it. And as shown in the figure 14 the output of the online SFRA contains much more noise compare to the offline SFRA. Such that further model improvement is needed and the detailed study have to be carried out to verify different faults at different frequencies.

V. CONCLUSION & FUTURE SCOPE

Change in Electrical Parameter	Related Types of faults
Inductance	Disc Deformation, Local Degradation, Winding short circuits
Shunt or Geometrical Capacitance	Disc breakdown, disc movements, Buckling due to large mechanical forces, moisture ingress, loss of Clamping pressure
Series Capacitance	Aging of Insulation

Table 2 Electrical parameter of transformer and relationship with different faults

Currently, Sweep frequency response analysis (SFRA) is currently gaining popularity due to its high sensitivity in identifying mechanical deformation in power transformers. Furthermore, the bulk of transformers deployed around the world are nearing or have passed their useful life. As a result, it's critical to spot any winding issues and take appropriate action. In this paper, an offline and online technique was used to examine frequency response analysis (FRA) which includes SFRA using a continuous 6.6kV disc type transformer simulation model. The circuit elements of series capacitance, inductance, and ground capacitance were used in the model, which was based on lumped parameters. Changes in series capacitance, inductance, and ground capacitance were used to simulate faults, and a disc to disc fault was created by short circuiting two discs. The location of the problem in a disc to disc fault is discovered to affect the FRA graph. Furthermore, at different frequencies, these graphs have different behavior.

According to impedance testing and transfer function sensitivity analysis, a 20% increase in inductance, which corresponds to disc deformation and local breakdown faults, modifies the FRA signature over the entire frequency range. A shift in series and ground capacitance that correlates to disc movement problems, on the other hand, occurs exclusively at frequencies above 400 kHz.

A table was created that included parameter elements, fault correlations, and the change in FRA signature that accompanied them. This information can be used to create standard codes for interpreting power transformer FRA signatures. The impedance and transfer function charts show identical patterns, demonstrating that both techniques are quite sensitive in detecting winding movement in transformers.

Some of the expectations can be enhanced further, such as a detailed investigation of inductance's contribution to the core of the transformer, model enhancement, and effective use of software packages for computing. It is clear that offline SFRA is insufficient to eliminate transformer sudden failures, and that online SFRA is the one of the ways to solve the problem. The online SFRA requires more research into bushing and winding defects, as well as the effect of capacitor and inductor in each frequency band. More case studies on the deployment of online SFRA on a theoretical and practical basis are needed to extend the transformer's life.

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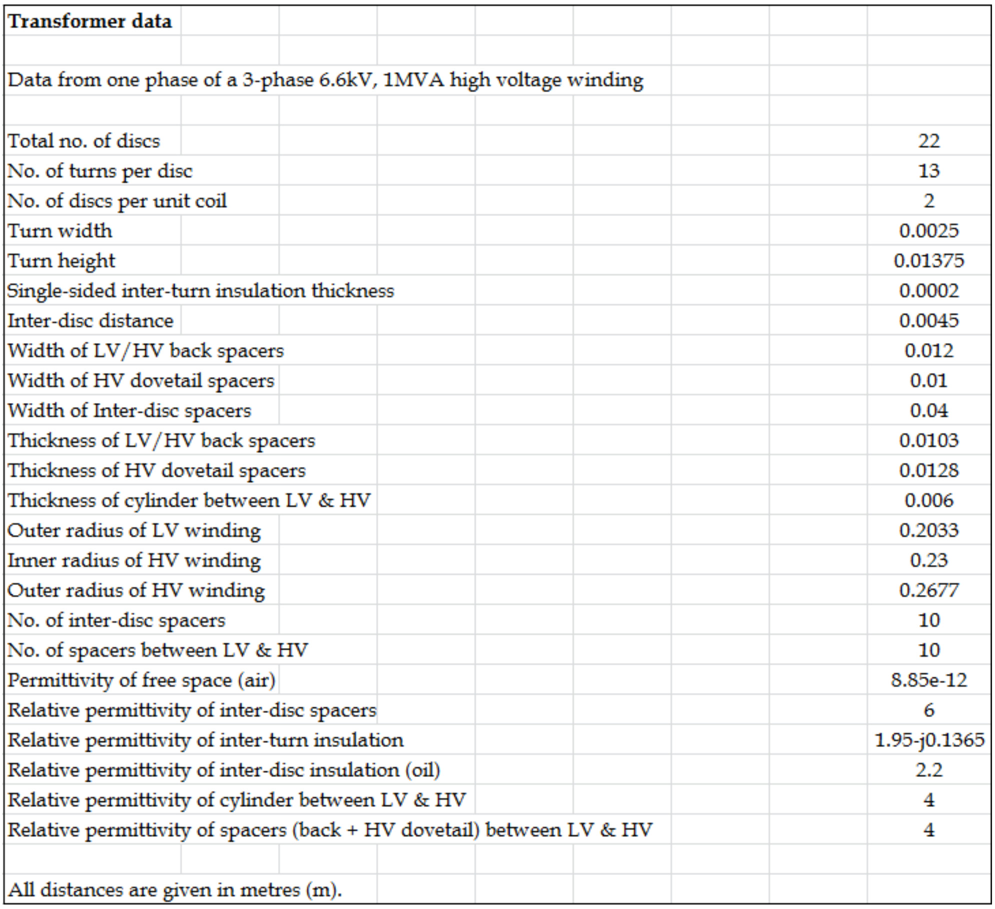
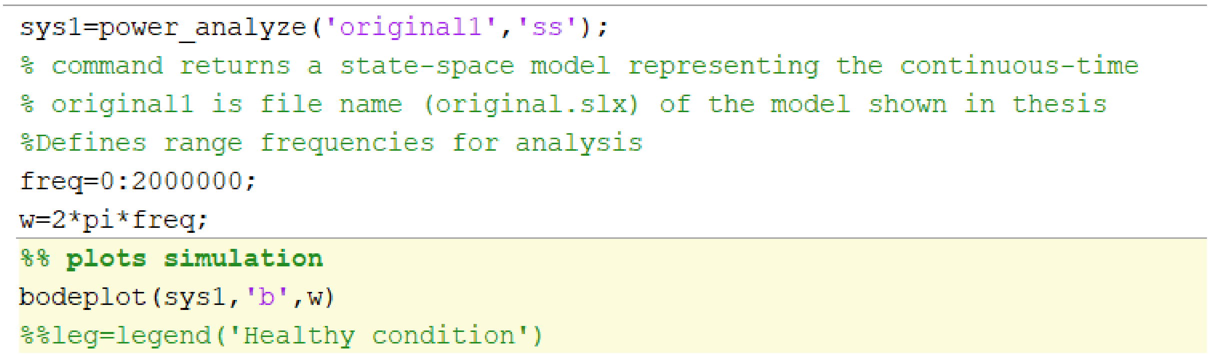
Appendix A – Transformer Data



Transformer data	
Data from one phase of a 3-phase 6.6kV, 1MVA high voltage winding	
Total no. of discs	22
No. of turns per disc	13
No. of discs per unit coil	2
Turn width	0.0025
Turn height	0.01375
Single-sided inter-turn insulation thickness	0.0002
Inter-disc distance	0.0045
Width of LV/HV back spacers	0.012
Width of HV dovetail spacers	0.01
Width of Inter-disc spacers	0.04
Thickness of LV/HV back spacers	0.0103
Thickness of HV dovetail spacers	0.0128
Thickness of cylinder between LV & HV	0.006
Outer radius of LV winding	0.2033
Inner radius of HV winding	0.23
Outer radius of HV winding	0.2677
No. of inter-disc spacers	10
No. of spacers between LV & HV	10
Permittivity of free space (air)	8.85e-12
Relative permittivity of inter-disc spacers	6
Relative permittivity of inter-turn insulation	1.95-j0.1365
Relative permittivity of inter-disc insulation (oil)	2.2
Relative permittivity of cylinder between LV & HV	4
Relative permittivity of spacers (back + HV dovetail) between LV & HV	4
All distances are given in metres (m).	

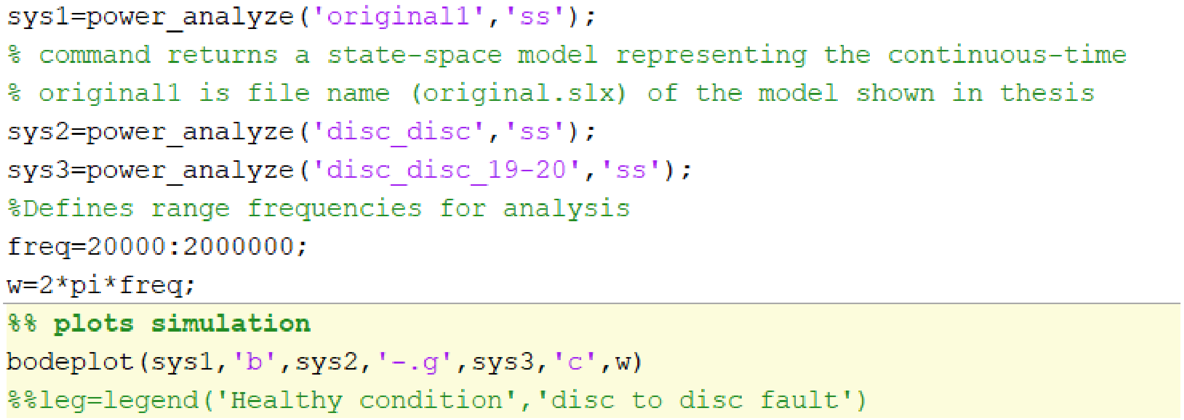
11 Transformer data

Appendix B – MATLAB CODE FOR OFFLINE SFRA TEST



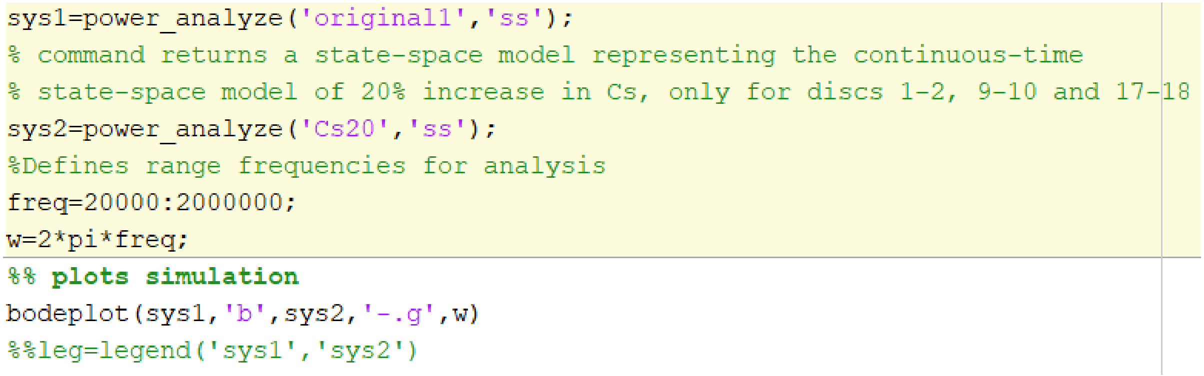
```
sys1=power_analyze('original1','ss');
% command returns a state-space model representing the continuous-time
% original1 is file name (original.slx) of the model shown in thesis
%Defines range frequencies for analysis
freq=0:2000000;
w=2*pi*freq;
%% plots simulation
bodeplot(sys1,'b',w)
%%leg=legend('Healthy condition')
```

16 Coding in MALAB for healthy condition model



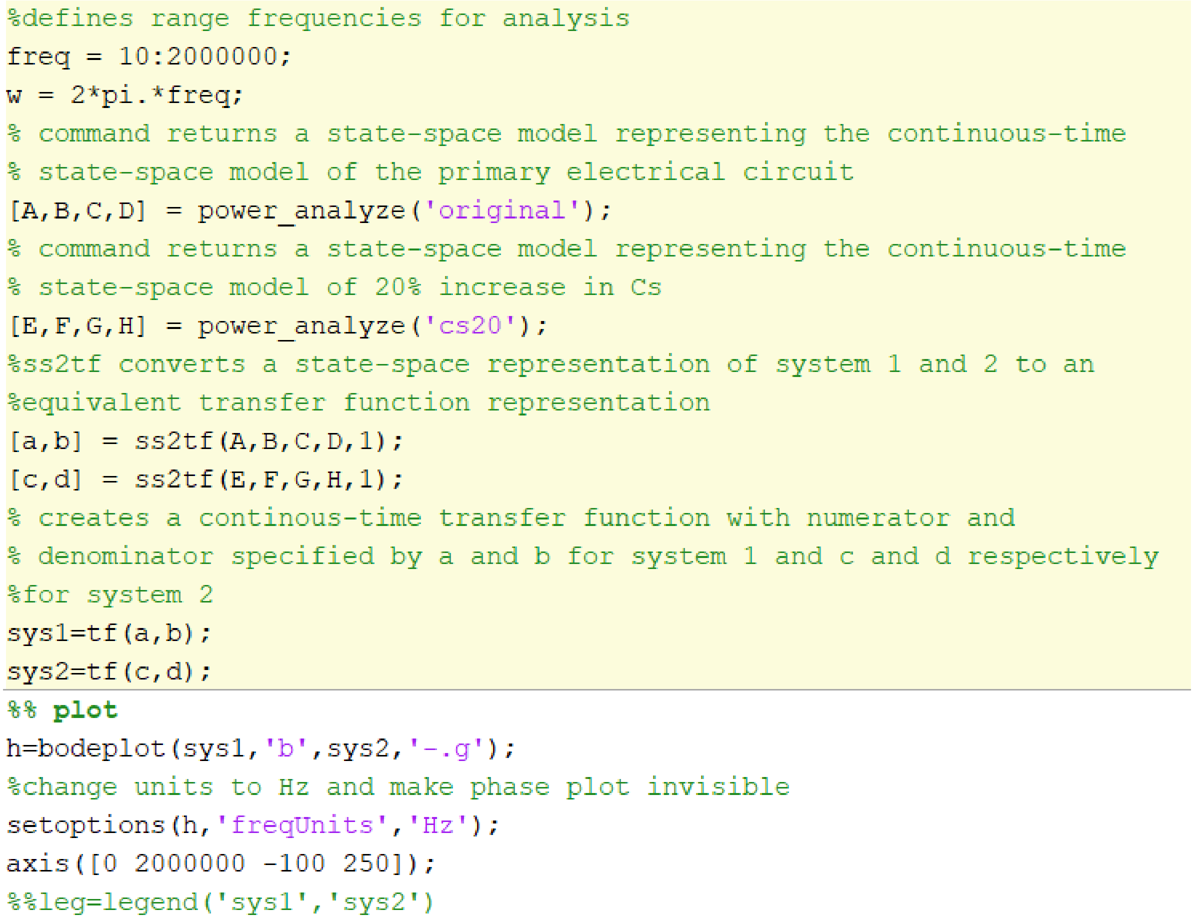
```
sys1=power_analyze('original1','ss');
% command returns a state-space model representing the continuous-time
% original1 is file name (original.slx) of the model shown in thesis
sys2=power_analyze('disc_disc','ss');
sys3=power_analyze('disc_disc_19-20','ss');
%Defines range frequencies for analysis
freq=20000:2000000;
w=2*pi*freq;
%% plots simulation
bodeplot(sys1,'b',sys2,'-.g',sys3,'c',w)
%%leg=legend('Healthy condition','disc to disc fault')
```

17 Coding in MATLAB for Case 2



```
sys1=power_analyze('original1','ss');
% command returns a state-space model representing the continuous-time
% state-space model of 20% increase in Cs, only for discs 1-2, 9-10 and 17-18
sys2=power_analyze('Cs20','ss');
%Defines range frequencies for analysis
freq=20000:2000000;
w=2*pi*freq;
%% plots simulation
bodeplot(sys1,'b',sys2,'-.g',w)
%%leg=legend('sys1','sys2')
```

18 Coding in MATLAB for Case 3.1



```
%defines range frequencies for analysis
freq = 10:2000000;
w = 2*pi.*freq;
% command returns a state-space model representing the continuous-time
% state-space model of the primary electrical circuit
[A,B,C,D] = power_analyze('original');
% command returns a state-space model representing the continuous-time
% state-space model of 20% increase in Cs
[E,F,G,H] = power_analyze('cs20');
%ss2tf converts a state-space representation of system 1 and 2 to an
%equivalent transfer function representation
[a,b] = ss2tf(A,B,C,D,1);
[c,d] = ss2tf(E,F,G,H,1);
% creates a continous-time transfer function with numerator and
% denominator specified by a and b for system 1 and c and d respectively
%for system 2
sys1=tf(a,b);
sys2=tf(c,d);
%% plot
h=bodeplot(sys1,'b',sys2,'-.g');
%change units to Hz and make phase plot invisible
setoptions(h,'freqUnits','Hz');
axis([0 2000000 -100 250]);
%%leg=legend('sys1','sys2')
```

19 Coding in MATLAB for Case 4.1