Investigating the Capacitive Inter-Winding Response of Power Transformer

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Abstract. This paper presents an investigation on the occurrence of oscillation in the frequency response of transformer due to aging process. The frequency response was obtained using frequency response analysis (FRA) test and capacitive inter-winding test configuration. It has been reported that, there is abnormal occurrence to the frequency response after some period of operating time. The response shows a small oscillation at the mid-frequency region. Although, this oscillation was not there at first measured response. Therefore, three case studies are presented to investigate this occurrence, the measurement, the transfer function mathematical equation and the developed circuit. The case studies of the transfer function and the developed circuit are simulated using MATLAB and being compared with the actual measured response. The parameters that control the mid–frequency oscillation are also studied. The oscillation occurred at mid-frequency region is related with the actual condition of the transformer experiencing aging process. The new finding provides an understanding on the factors that affecting transformer aging. It is believed that, thermal, moisture and oil degradation are the main contributors of transformer aging process. Therefore, the significance of this study is to present the relationship between occurrence of mid-frequency oscillation and transformer aging condition.

1. Introduction
Power transformer is an important equipment in the power system network. Operating at very high loading condition to meet the demands can accelerate the deterioration of power transformer. This is due to the increase of mechanical, electric, and thermal stresses during the operation. All these stresses are called transformer aging process. In this study, the main concern is regarding the aging of power transformer. It is important to understand the factors that cause acceleration of transformer aging. Transformer may still be working as usual despite the aging process. However, its health condition is deteriorating thus need to be continuously monitored. By observing the transformer’s condition and performing appropriate maintenance, its lifespan can be maximized and the power system reliability can be achieved.

In general, there are several tests available to diagnose the transformer’s condition such as Dissolved Gas Analysis (DGA), Frequency Domain Spectroscopy (FDS) and Partial Discharge test. However, it has been proposed in the literature that for detecting mechanical changes, frequency response analysis (FRA) is the best method to be used. Beside mechanical or physical changes, it was

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also mentioned that FRA is sensitive towards moisture content, temperature and oil condition [1][2][3][4].

There are four different test configurations to conduct FRA measurement. The first two are the end to end open circuit test and end to end short circuit test which were demonstrated in [5] and [6]. In this paper, we propose an investigation of using different FRA test configuration which is the capacitive inter-winding test. Although this test was mentioned in the CIGRE, IEC, and IEEE standards, it has not been further investigated for its application and potential in examining the transformer condition. This is probably due to the fact that main reason of FRA test is to assess winding damage which can be determined from the end to end test. For this reason, the capacitive inter-winding test is rarely discussed in the literature.

In this paper demonstrates actual FRA measurement on a transformer which is subjected to an accelerated aging process in the laboratory. These measurements are taken before the aging, after 14 days and after 28 days of aging. From the measurement, an oscillation was occurred in the response due to the aging process. Beside the measurement, frequency responses are also simulated using transfer function and RLC circuit. Both transfer function and RLC circuit are for the first time being proposed in this paper. Comparison between three case studies (measurement, transfer function and circuit) are conducted in order to understand the occurrence of the oscillation in mid-frequency region of the capacitive inter-winding response. Although the equation and the circuit have been modelled, it is important to compare the simulated FRA traces with the actual measured response. This methodology is conducted to investigate the factors which affecting the mid-frequency oscillation in the response.

2. Frequency response analysis of power transformer

2.1. Frequency response analysis

There is a general agreement that, frequency response analysis (FRA) is a well technique to diagnosis transformer winding damage. The main function of FRA is to determine the damage on the active parts (winding, leads, and core). Another application of FRA is to verify the mechanical integrity of the transformer after relocation [2][7]. Also, it has been reported that, FRA is sensitive to non-mechanical parameters such as temperature and moisture content of the winding insulation [3]. FRA is a comparative test which requires two measurements to be compared (before and after faulty conditions). Any differences between two measured responses suggests mechanical change has been occurred.

2.2. Capacitive inter-winding measurement

![FRA measurement configuration](image)

**Figure 1.** FRA measurement configuration for (a) end to end open circuit (b) end to end short circuit (c) capacitive inter-winding (d) inductive inter-winding [8].
Measurement configuration refers to the connection between winding terminals and FRA equipment. There are four test configurations as shown in Figure 1. \( V_R \) and \( V_M \) in the figure are the reference voltage and measured voltage respectively. Many previous literatures only focus on end to end open and short circuit tests. In this study, capacitive inter-winding test is presented. As presented in Figure 1(c), the signal is applied to one end of a winding and the response is measured at one end of another winding of the same phase [2]. This test configuration is applied to measure the response due to the influence of the insulation between two windings.

3. Methodology

In this paper, three case studies are presented to investigate the occurrence of oscillation in mid-frequency region of transformer response. These studies are from the actual FRA measurement, the transfer function equation, and the developed circuit. The simulated result from the transfer function and the developed circuit are compared with the result from the actual FRA measurement. Then, the parameters and their values that have effect on the mid-oscillation of the frequency response are determined. By using MATLAB, the proposed mathematical equation of the transfer function is constructed. The resonant frequency and damping effect of the transfer function can influence the frequency response. On the other hand, a RLC circuit is also proposed and has been developed using Simulink to represent the frequency response. The three cases are discussed in details in relation with the aging process of the transformer.

3.1. Actual measurement of response from the transformer

The first case is based on the actual measurement of the response from 5 kVA oil filled transformer as shown in Figure 2. The measurement was taken in three different occasions to determine the transformer aging process. The first measurement was taken before the aging process started (in new condition), second was taken after 14 days and the third was taken after 28 days of operating under accelerated aging condition. This work is a continuation of the previous study which has been presented in [3]. The study investigated transformer aging process using FRA and FDS. However, it did not include further investigation on circuit simulation to transformer aging process. Therefore in this paper, the measured results are compared with the simulated responses from transfer function and developed circuit.

![Figure 2. Single phase transformer 5 kVA used in this study.](image)

3.2. Simulation of response from transfer function equation

In the second case study, a transfer function which is a mathematical equation representing the response is constructed. This is required to understand the behaviour of the mid-frequency oscillation which occurred in the actual transformer measurement. The value of parameters of the transfer function are defined in the results section.

3.3. Simulation of response from lumped circuit
In the third case study, it shows the methodology to obtain frequency response using the proposed 
RLC lumped circuit. The circuit is constructed in MATLAB Simulink to simulate the response. After 
that, the capacitance, resistance and inductance are adjusted to produce the response which is similar 
to the actual measured response. Then, examination on the capacitance and inductance values which 
effect the mid-frequency oscillation is performed.

4. Results and discussions
The measurement of FRA using capacitive inter-winding test configuration was conducted on a single 
phase transformer. After 14 days of aging, there was an unusual variation occurred on the frequency 
response. It was absorbed that an oscillation has appeared in the middle region of the frequency 
response. The oscillation was not seen on the initial response before the transformer experiences the 
aging process (in the first measurement). It is believed in this occurrence might be due to the aging of 
isolation.

4.1. Actual FRA measurement
The actual FRA results of the tested transformer are shown in Figure 3 and Figure 4. The 
measurements were taken before the aging, after 14 days and 28 days of aging process. Based on the 
results, it shows an oscillation has occurred at about 2 kHz and -80 dB. It can be seen in Figure 3 that 
the oscillation amplitude has increased from 14 days to 28 days of aging. The phase plot in Figure 4 
also presented an oscillation at frequency of about 2 kHz. Due to aging, it causes the drop in phase 
plot from about 80° to 20° after 28 days.

The main concern now is to investigate how the mid-frequency oscillation occur and what aspect 
influence it. It is believed that temperature and moisture content increasing the insulation permittivity 
as mentioned in [3] and [9]. Additionally, the oscillation could possibly also be due to core 
magnetization as the core influence is usually dominant in low frequency response. Besides that, a 
change of inter-winding capacitance and insulation resistance may also have trigged the response 
oscillation. According to [1] and [10], FRA can be influenced by paper insulation of the winding 
which is subjected to the transformer operating temperatures. The higher the operating temperature is, 
the more degradation it can cause on the paper. FRA measurement is also sensitive to several other 
factors as stated in [1][11][12] such as temperature, moisture content, core magnetizing and 
measurement leads. Further study in [4] investigate on the influence of temperature and moisture on 
FRA trace. It is concluded that this significant movement is due to changes on the transformer shunt 
capacitance.

![Figure 3](image-url)  
Figure 3. Magnitude plot of frequency response measurement on a single phase transformer.

![Figure 4](image-url)  
Figure 4. Phase plot of frequency response measurement on a single phase transformer.

4.2. Transfer function equation
To simulate the capacitive inter-winding response, we are proposing the transfer function as in (1). It 
consist of the combination of three terms. The first term controls the overall positive slope of the 
response. The other two terms control the peak and valley of the oscillation in the mid-frequency 
region.
\[ H(s) = \left( \frac{s+35}{100000000} \right) \cdot \left( \frac{\omega_{na}}{s^2+2\zeta_a\omega_{na}s+\omega_{na}^2} \right) \cdot \left( \frac{\omega_{nb}}{s^2+2\zeta_b\omega_{nb}s+\omega_{nb}^2} \right) \]  

(1)

The simulated responses from (1) are shown in Figure 5 and Figure 6. These are relatively similar with the measured responses especially on the oscillation in the magnitude plot and the phase drop in the phase plot. The parameter values for obtaining the frequency response from the transfer function is shown in Table 1.

Based on the transfer function, the damping factor, \( \zeta \) controls the mid-frequency oscillation. To explain the relationship of the aging process and the damping factor, the damping is adjusted to a certain value that produces oscillation which similar in terms of its magnitude and frequency compared with the actual frequency measurement. Data in Table 1 shows that the decrease of damping value, \( \zeta \) cause an increase of oscillation’s magnitude. This indicates that \( \zeta_a \) and \( \zeta_b \) control the resonance and anti-resonance of the mid-frequency oscillation. In general, this study suggests that the damping factor might have relationship with the moisture content, temperature and oil quality which are the contributors to the aging of transformer as has been discussed in the previous section.

| Table 1. Value of parameters used for the transfer function |
|----------------------------------------------------------|
| Natural frequency(\( \omega_{na} \)) | Natural frequency(\( \omega_{nb} \)) | Damping(\( \zeta_a \)) | Damping(\( \zeta_b \)) |
|--------------------------|--------------------------|--------------------------|--------------------------|
| Before ageing            | 100\times10^6            | 110\times10^6            | 11,200                    | 11,200                    |
| 14 days ageing           | 100\times10^6            | 110\times10^6            | 2,600                     | 2,600                     |
| 28 days ageing           | 100\times10^6            | 110\times10^6            | 800                       | 800                       |

4.3. Developed circuit

A circuit model describing the electrical behaviour of the transformer’s capacitive inter-winding frequency response is proposed. It is a combination of RLC parameter connected in parallel and series. It is developed to simulate the response which is similar to the actual measured frequency response. This was achieved by adjusting the value of circuit components. With this approach, the effect of capacitance on the mid-frequency oscillation can be investigated. The circuit parameters may have real and imagery values. Figure 7 shows the proposed combination of RLC circuit that can produce similar response which contains the mid-frequency oscillation. In the circuit, reference voltage, Vref is measured across a 50\( \Omega \) resistor and the output voltage, Vout is measured across another 50\( \Omega \) resistor. Besides the RLC circuit, other components such as the 50\( \Omega \) resistor are the equivalent circuit of FRA test equipment.

![Figure 5](image1.png) Transfer function magnitude plot.  

![Figure 6](image2.png) Transfer function phase plot.
The simulated responses obtained from the circuit are shown in Figure 8 and Figure 9. The best values used in the circuit to obtain these responses are given in Table 2. The parameters are series capacitance, Cs, series inductance, Ls, parallel capacitance, Cp and parallel inductance, Lp. Each of the parameters controls different factor in the simulated frequency response. In this case, both capacitances (Cp and Cs) are a complex value which contains real and imaginary part. This is mainly due to the complex permittivity ($\varepsilon = \varepsilon' + i\varepsilon''$) of the insulation system as capacitance is dependent of the permittivity ($C= \varepsilon A/d$). The use of complex capacitance is actually important to achieve the mid-frequency oscillation. The values of complex capacitance which can provide response similar to the actual frequency measurement are shown in Table 3.

### Table 2. Value of parameters used for the circuit

| Component | Cs (F) | Ls (H) | Cp (F) | Lp (H) |
|-----------|--------|--------|--------|--------|
| value     | $4.444 e^{-10} - i 9.0909 e^{-18}$ | $2e^{-7}$ | $4.65 e^{-9} - i 5.5e^{-9}$ | 0.1 |

### Table 3. Complex capacitance for all three aging conditions

| Cp                  | Before aging | 14 days aging | 28 days aging |
|---------------------|--------------|---------------|---------------|
| Imaginary Capacitance (F) | $i x 5.5e^{-9}$ | $i x 0.77e^{-9}$ | $i x 0.333e^{-9}$ |
| Real Capacitance (F)   | $4.65e^{-9}$   | $5.71e^{-9}$   | $5.71e^{-9}$   |

**Figure 7.** Developed circuit presents the Frequency Response

**Figure 8.** Magnitude response from the developed circuit

**Figure 9.** Phase plot from the developed circuit
Figure 8 and Figure 9 present the magnitude and phase frequency responses which contain the same oscillation as in the measured response. As in typical FRA measurement of the capacitive inter-winding test, a continuous positive slope can be seen in the simulated magnitude response. Regarding the oscillation in the mid-frequency region, the simulated responses showed almost similar trend as in the measured response. This is mainly possible by changing the imaginary part of the complex capacitance. This is actually can be supported by studies presented in [3] and [9] where both mentioned that the imaginary part of complex permittivity basically corresponds to the aging of insulation material. Therefore in general, this finding suggest that the aging process in transformer can be modelled by this proposed circuit.

5. Conclusion
This paper investigate the transformer aging process using the capacitive inter-winding configuration of FRA test. The FRA measurement was taken from an actual 5 kVA single phase transformer. This study demonstrated two simulations using transfer function and RLC lumped circuit for further understanding the effect of transformer aging on its frequency response. In order to better interpret the changes on the FRA response, it is useful to understand which elements are responsible for the frequency region and the shapes of the response curve. This can be realized by examining the character’s response of the various elements and their combination. The proposed techniques presented are used to evaluate the mid-frequency oscillation by using MATLAB simulation. The frequency response of actual measured was being compared with two simulated techniques from the transfer function and the developed RLC circuit. The obtain results from frequency response of both simulated techniques show a relatively similar with the frequency response from actual measurement.

Findings show damping, $\zeta$ in transfer function and complex capacitance in the developed circuit are controlling the oscillation which occurred in the mid-frequency region. It is believed that, these parameters are representing the changes in winding capacitance mainly the insulation. According to the theory, the change of winding capacitance is due to increasing of moisture content and temperature which are the main contributors of transformer aging. Further investigation is recommended on the transformer aging process using FRA and capacitive inter-winding.

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7. References
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