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Evaluating the Inter-Resonance Characteristics of Various Power Transformer Winding Designs

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ABSTRACT Resonance is a very familiar phenomenon in electrical circuits that occurs when a frequency of incoming signal is similar to the natural frequency of the electrical circuit. When resonance occurs, excessive over-voltage may appear. Resonance over-voltage is one of the factors suspected as the cause of the power transformer failure, especially when the transformers are in good condition and also protected by arresters. In this study, inter-resonance phenomenon, namely the resonance that occurs inside the transformer windings, were investigated. The small-scale transformers were designed with four different type windings: continuous disc winding, shield disc winding, closing disc winding and layer winding with additional measurement points. The phenomenon of resonance was characterized by sweep frequency response using current SFRA technology. The resonance frequency in the inside winding shift several kHz from one in the full winding. This may lead to inter-resonance indicated by the voltage at a location cross over to the other location. Based on SFRA characteristics, it was found that the highly potential occurrence for inter-resonance is above 100 kHz. This may strongly influence the voltage distribution along the winding. Layer winding is less risk of inter-resonance than disc winding. In a homogeneous winding, the inductance curve can be used as a reference to predict the resonance frequency in the real transformer by extrapolating.

INDEX TERMS Arrester, power transformer, disc winding, layer winding, inter-resonance, SFRA, inductance.

I. INTRODUCTION

Resonance is a very familiar phenomenon in electrical circuits that occurs when a frequency of incoming waveform is similar to the natural frequency of the electrical circuit. When resonance occurs, excessive over-voltage may appear.

Transformer, the main equipment in the utility network, plays a very important role because the failure of the transformer can cause seriously power outages. Transformer failures could be caused by several phenomena, such as the temporary overvoltage. Temporary overvoltage may be caused by switching operation and lightning strike. The last one can be followed by high impulse voltage that be dangerous to the transformer.

Failure mode of the transformer failures can be grouped into dielectric, electrical, thermal, physical, chemical and mechanical. Based on [1], transformer failures caused by dielectric problem related to voltage stress is 37%, and the failures location is dominated in the winding 43%. Thus, the transformer failures are dominated by dielectric mode caused by voltage stress on the windings.

Based on the transformer failure data at Indonesia Electricity Company, PLN UID East Java, the transformer failures were dominated by breakdown insulation of the windings. Breakdown insulation may be caused by deterioration of the insulation material or excessive stress on the insulation.

The dominance of transformer failures which was indicated by breakdown insulation is a concern of the research. During operation, power transformers suffered various kinds of stresses. Over-voltage is the severest stress that the most probably occurred. Normally, the excessive over-voltage suffered by transformers is the impulse voltage. However, impulse voltage will suffer distortion and oscillation during travelling in the network. Even though transformers have been protected by arresters or surge protection, the excessive over voltage that occurs in the network still has a significant impact on the transformer winding, especially on the winding insulation. There is various report of transformer

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failures as a result of over voltage during operation, although there are no indication of defects or failures during testing and also protected by arresters. Under these conditions, one of the factors suspected to be the cause of transformer failures is the resonance effect on the transformer [2], [3].

Several studies have been conducted in [4]– [7] to investigate the effect of transformer design on resonance phenomena. Based on the reports, resonance over voltage is a phenomenon that is unique to each transformer and its connected network. Characteristics of a transformer could not be used in other transformers, either because of the design, the material used and the environment in which the transformer is installed. Although several studies investigated the phenomenon have been carried out, however there is no current standard and reference regarding how the phenomenon is avoided and what protection must be installed to prevent equipment damage due to the phenomenon.

The characteristics of resonance as the effect of transformer design such as winding design, core design, material, oil and others still need to be studied. Resonance characteristics of the existing transformers are also important for providing the preliminary data as a guidance. These preliminary data may be important for the transformer designer and transformer engineer to minimize equipment damage caused by these phenomena.

II. RESONANCE

The phenomenon of resonance exists when the system is affected by periodical excitation with a frequency similar to its natural frequency of oscillation. If the excitation source has the same frequency as the system's natural frequency, the system's response to that excitation can be very high [2]. Electrical resonance occurs in a circuit when the capacitive reactance equals to the inductive reactance at the natural frequency. Refer to (1), the natural frequency depends on the capacitance (C) and inductance (L).

$$f_n = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Figure 1 is an example of resonance circuit with L_1 1mH, L_2 50mH, C_1 1μF and C_2 0.02μF. Both circuits have equal natural frequency. Figure 2 is the time response simulating the resonance effect.

In the real network, resonance occurs when the specific frequency of incoming waveform come to the circuit with equal natural frequency as shown in Fig. 3. The frequency response of this condition is shown in Fig. 4. This similar condition occurs when incoming waveform come to the inside transformer winding. Resonance will occur when the frequency of incoming waveform is equal to the natural frequency of the transformer winding.

III. METHODOLOGY

The research was performed to investigate the resonance characteristics as the effect of the winding design. Unlike in the previous studies that generally use rectangular

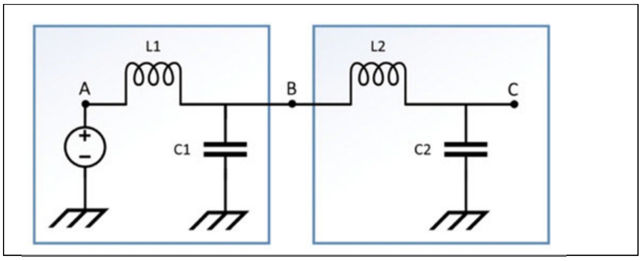


FIGURE 1. Resonance circuit.

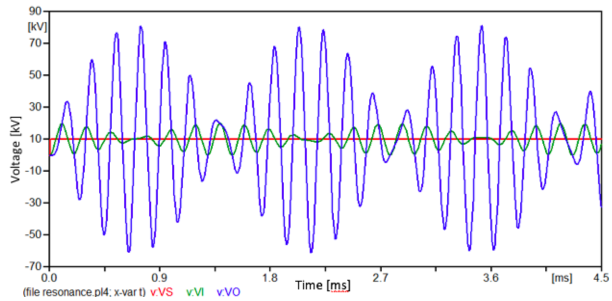


FIGURE 2. Resonance response in time domain.

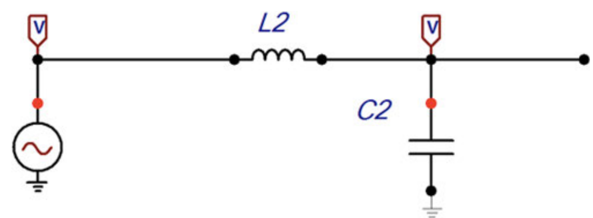


FIGURE 3. Resonance condition in the real network.

waveform as input surge waveform, this study was conducted using sinusoidal waveform with a frequency range up to 2MHz. This sinusoidal waveform is chosen because objective of this research is to obtain the comprehensive frequency characteristics.

The experiment that has been done in this study using two different miniature of 20 kV distribution transformer. The first one was 10 kVA distribution transformer with layer type winding. The second one was 10 kVA distribution transformer with three different type of disc type winding on high voltage winding. Phase A use continuous disc type winding, phase B use shield disc type winding and phase C use closing disc type winding. The transformer design that applied in this research is a special transformer design without oil, without bushings application and additional tapping point every 25% of the total turns. The measurement points of both transformers were located at position A (25% of full winding), B (50% of full winding), C (75% of full winding), and D (100% or full winding), for both low voltage winding and high voltage winding. Fig. 5 shows the photograph of the test object and Fig. 6 shows the winding design.

For transformer with shield disc winding, the winding has additional insulation material between turns in the same disc. Unlike the others, closing disc winding have no space

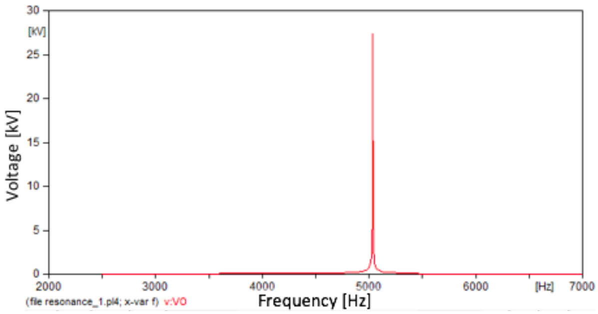


FIGURE 4. Frequency response in frequency domain.

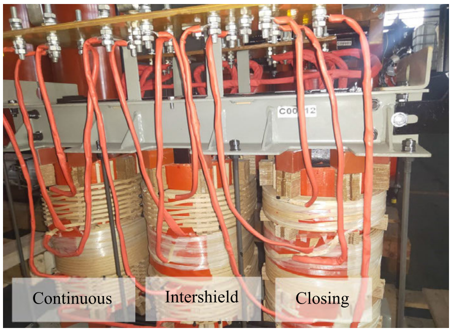


FIGURE 5. Transformer with disc type winding.

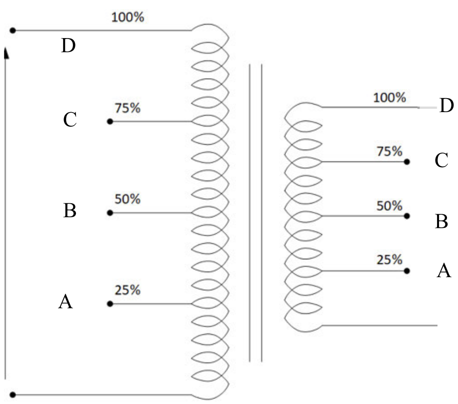


FIGURE 6. Winding design.

between disc. Hence, series capacitance of closing disc and shield disc winding are expected to be higher than continuous disc winding.

To analyze the frequency characteristics of the winding, the current SFRA technology will be used. Experimental setup using SFRA equipment as shown in Fig. 7. During the experiment, the other non-tested winding and neutral terminal were connected to ground. These will eliminate the effect of other non-tested windings. Utilization of the SFRA characteristics will be used to analyze the resonance characteristics of transformer, including the inter-resonance characteristics.

IV. RESULTS AND DISCUSSION

A. SFRA CHARACTERISTICS

In the previous study, SFRA characteristics of layer winding has been investigated in [8], while the SFRA characteristics

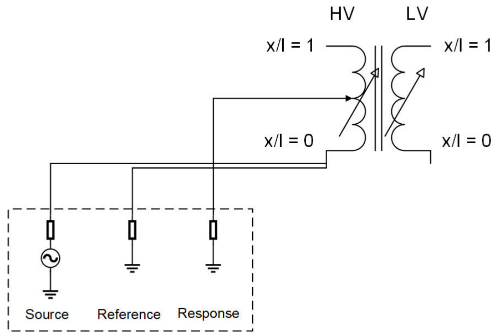


FIGURE 7. Experimental setup.

of disc winding has been investigated in [9]. In this study, investigation of the SFRA characteristics was done on internal winding of both winding designs. SFRA characteristics were obtained using SFRA measurement. SFRA characteristics of layer type winding and disc type winding was shown in Fig. 8.

The SFRA characteristic of layer winding shows that the first resonance occurs at 40-45 kHz. The first resonance tend to shift several kHz when the number of turns increase. The second resonance occurs at several different frequency depends on the number of turns/layers. The second resonance at position A and C occurs at 120-140 kHz, at position B and C at 270 kHz.

The SFRA characteristic of disc winding shows that the first resonance occurs at 40-45 kHz, similar to the layer winding. The first resonance tend to shift several kHz when the number of turns increase. The second resonance occurs at several different frequency depends on the number of turns/disc. The second resonance at position A occurs at 70 kHz, at position B, C and D at 130-150 kHz.

Figure 8 shows a comparison of SFRA characteristics at frequencies up to 2 MHz. The straight black line shows the first resonance point that occurs in the four types of windings, namely at a frequency of approximately 40 kHz. This point of resonance is similar between the four types of windings with a difference of less than 5 kHz. The straight yellow line shows that the SFRA characteristics of the three types of disc windings show a similar pattern up to 280 kHz so that the frequency range up to 280 kHz is not significantly affected by the winding types. On the other hand, there are a difference SFRA characteristics for frequencies above 280 kHz which means that the SFRA characteristics of these frequencies are greatly influenced by the series capacitance.

Based on the interpretation of SFRA characteristics on transformers [10]– [13], SFRA characteristics in the high frequency section (above 200 kHz) are dominant influenced by series winding capacitance. Based on the results of the above research, the phenomenon of SFRA characteristics are indicated to be strongly influenced by the series winding capacitance parameter for frequency above 280 kHz.

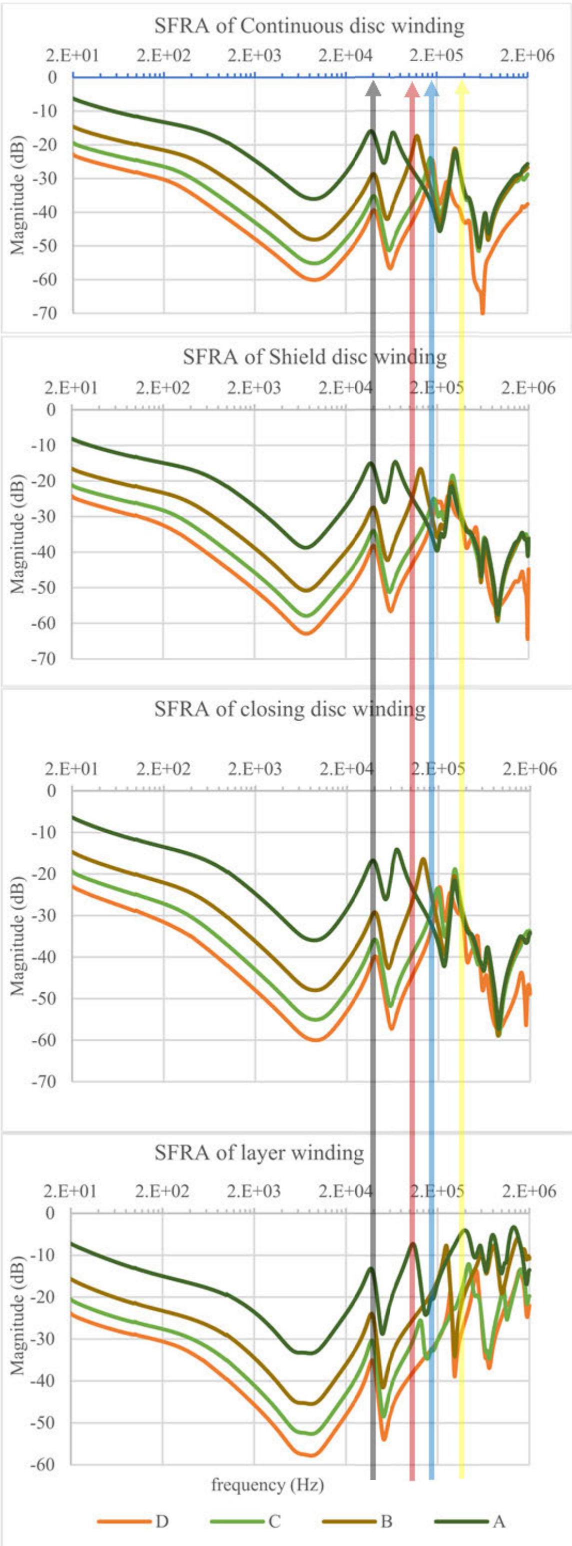


FIGURE 8. Comparison of SFRA Characteristics.

B. INTER-RESONANCE

Inter-resonance are indicated to occur when the voltage at a location cross over to the other location. The straight red line shows the first inter-resonance point, which occurs in the disc type winding, which is at a frequency of approximately 100 kHz, while the layer winding has not occurred. The straight blue line shows the first inter-resonance point of the layer winding at a frequency of 140 kHz. There is a shift in the starting point of the inter-resonance by about 40 kHz between the layer winding and the disc winding. A straight yellow line indicates that the inter-resonance characteristics of the disc windings to be different at a frequency of 280 kHz. Shield and closing disc winding have similar inter-resonance characteristics, whereas continuous disc winding has different inter-resonance characteristics. Based on the results of the above research, the phenomenon of inter-resonance is indicated to be strongly influenced by the series capacitance parameter of the winding.

The SFRA characteristic of continuous disc winding at a frequency of 100 - 350 kHz indicates a tendency for inter-resonance to occur. At this frequency, inter-resonance tends to occur as indicated by the voltage intersecting the tapping points of the windings. The SFRA characteristics of the shield disc type windings at a frequency of 100 - 700 kHz indicate a tendency for inter-resonance to occur. At this frequency, resonance tends to occur as indicated by the voltage intersecting the tapping points of the windings. The SFRA characteristics of the closing disc type winding have a frequency of 100 - 700 kHz indicating a tendency for inter-resonance to occur. At this frequency, resonance tends to occur as indicated by the voltage intersecting the tapping points of the windings.

Another important thing regarding the inter-resonance is the effect on the voltage distribution inside winding. Transformer designer has only considered the voltage distribution only for standard lightning impulse voltage with low frequency i.e. impulse voltage distribution (IVD). According to fig. 8, voltage distribution for frequency above 40 kHz is not linear, especially in the frequency of above 140 kHz for layer winding and frequency above 100 kHz for disc winding, where inter-resonance occurs. Because of the nonlinearity characteristics of inter-resonance, the current impulse distribution voltage that already have been performed during transformer design is no longer enough to characterize the voltage distribution because not yet consider the resonance phenomenon at high frequency section. It is strongly recommended for considering the distribution voltage caused by higher frequency component.

Similar investigations with different method and different goal were have already conducted in [14]– [16] to investigate the impulse voltage distribution. These previous researches were only focused on the impulse voltage so these results were valid only for testing where the impulse voltage waveform is still pure and not distorted. Therefore, it still need further investigation and research to determine the effect of series winding capacitance on the resonance phenomenon.

Evaluation of the characteristics of the transformer resonance and the inter-resonance of the windings in the four types of windings that have been carried out can illustrate how different the characteristics of the four types of windings are. These differences can be used as initial guidelines in determining direction and mitigation plans to minimize the impact of resonance.

Table 1 summarizes the resonance and inter-resonance point of the winding. As shown in table 1, the inter-resonance characteristics of the layer winding indicate that the inter-resonance of the winding starts at a frequency of 140 kHz. The probability of this frequency occurring in the power system is small. This is considered that the layer winding is not at high risk of inter-resonance of the windings. Whereas in the disc winding, the three types of windings indicate that the inter-resonance of the winding begins at a frequency of 100 kHz. This frequency is likely to be found in electric power systems as research results from [17]. It can be concluded that layer winding can be used without any design modification or optimization. While in the disc winding, it need design optimization to overcome the risk of resonance and inter-resonance. Especially when the system condition are undefined.

TABLE 1. Resonance frequency [kHz].

Winding type	Resonance		Inter-resonance		Mitigation
	I	II	I	II	
Layer	40	120	140	260	System condition
Disc	40	70	100	130	System condition and design optimization
Closing disc	40	70	100	130	
Shield disc	40	70	100	130	

C. WINDING PARAMETER INFLUENCE

Effect of winding parameter on resonance characteristics are performed by evaluating the winding parameter including resistance (R), capacitance (C) and inductance (L). By evaluating the SFRA characteristics on Fig. 8, we obtain the impedance characteristics. The resonance frequency of impedance characteristics are shown in table 2. The RLC parameter can be estimated by minimizing the error function with least square method from the difference between the actual admittance value Y_R and the admittance value of the model Y_M.

$$E\left(R_x, C_x, L_x\right)=\sum_{i=1}^{m}\left|Y_R\left(\omega_i\right)-Y_M\left(\omega_i, R_x, C_x, L_x\right)\right|^2 \quad (2)$$

where $Y_R\left(\omega_i\right)=G_R\left(\omega_i\right)+jB_R\left(\omega_i\right)$

The error function is minimal when the slope of the error function is zero and the Hessian of the error function is positive.

$$\nabla E\left(R_x, C_x, L_x\right)=0 \quad (3)$$

$$\nabla^2 E\left(R_x, C_x, L_x\right)>0 \quad (4)$$

The error function of the model with parallel RLC as follows:

$$E\left(R_x, C_x, L_x\right)=\sum_{i=1}^{m}\left|Y_R\left(\omega_i\right)-\left(\frac{1}{R_2}+j\omega C_2+\frac{1}{j\omega L_2}\right)\right|^2 \quad (5)$$

To calculate the R/L/C parameter, the gradient of the error function of equation (5) to the R/L/C parameter must be zero. By evaluating the equation, the following equation is obtained [18]:

$$R_2=\frac{m}{\sum_{i=1}^{m} G_R\left(\omega_i\right)} \quad (6)$$

$$L_2=\frac{m\sum_{i=1}^{m}\frac{1}{\omega_i^2}\sum_{i=1}^{m}\omega_i^2-m}{m^2\sum_{i=1}^{m}\omega_i B_i-\sum_{i=1}^{m}\frac{B_i}{\omega_i}\sum_{i=1}^{m}\omega_i^2} \quad (7)$$

$$C_2=\frac{\sum_{i=1}^{m}\frac{B_i}{\omega_i}-m\sum_{i=1}^{m}\frac{1}{\omega_i^2}\sum_{i=1}^{m}\omega_i B_i}{m-m\sum_{i=1}^{m}\frac{1}{\omega_i^2}\sum_{i=1}^{m}\omega_i^2} \quad (8)$$

Using the equation (6), (7) and (8), RLC parameter were calculated based on the impedance characteristics of each winding type. Cell-1 refer to the first resonance frequency, cell-2 refer to the second resonance frequency, and cell-3 refer to the third resonance frequency. The estimated value of RLC parameters were shown in fig. 9.

The inductance and resistance parameters are dominant in cell-1 and show similar characteristic where the greatest value is in the shield disc winding and the lowest value is in the layer winding. This similarity of describing inductance and resistance says that the value of the two parameters is strongly depended on the conductor length. Thus, the length of conductor greatly influences the resonance characteristics in cell-1. The longer the conductor, the greater the inductance and resistance values, and the greater the resonance frequency. In a homogeneous winding design, the data on the miniature transformer can be used as a reference to predict the resonance frequency in the windings by extrapolating the inductance factor curve. Meanwhile, the inductance and resistance parameters in cell-2 showed similar but much smaller than cell-1.

The capacitance parameter in the four types of windings shows a similar characteristic where the highest value is in cell-2 and inversely proportional to the number of turns. The larger the winding, the smaller the capacitance value. The largest value of capacitance is in the layer winding while the lowest capacitance is in the continuous disc winding. The capacitance on the closing disc and shield disc windings shows almost the same value.

Inductance in cell-1 is highly more dominant than capacitance, the effect of capacitance in cell-2 is highly more dominant than inductance. However, the effect on the resonance characteristic is combination of the two parameters. Comparison of the L/C ratio was carried out to see which parameter is more dominant in each cell. Based on Table 3, the effect of inductance was highly dominant on cell-1, while in cells-2 the effect of inductance was lower. In other words,

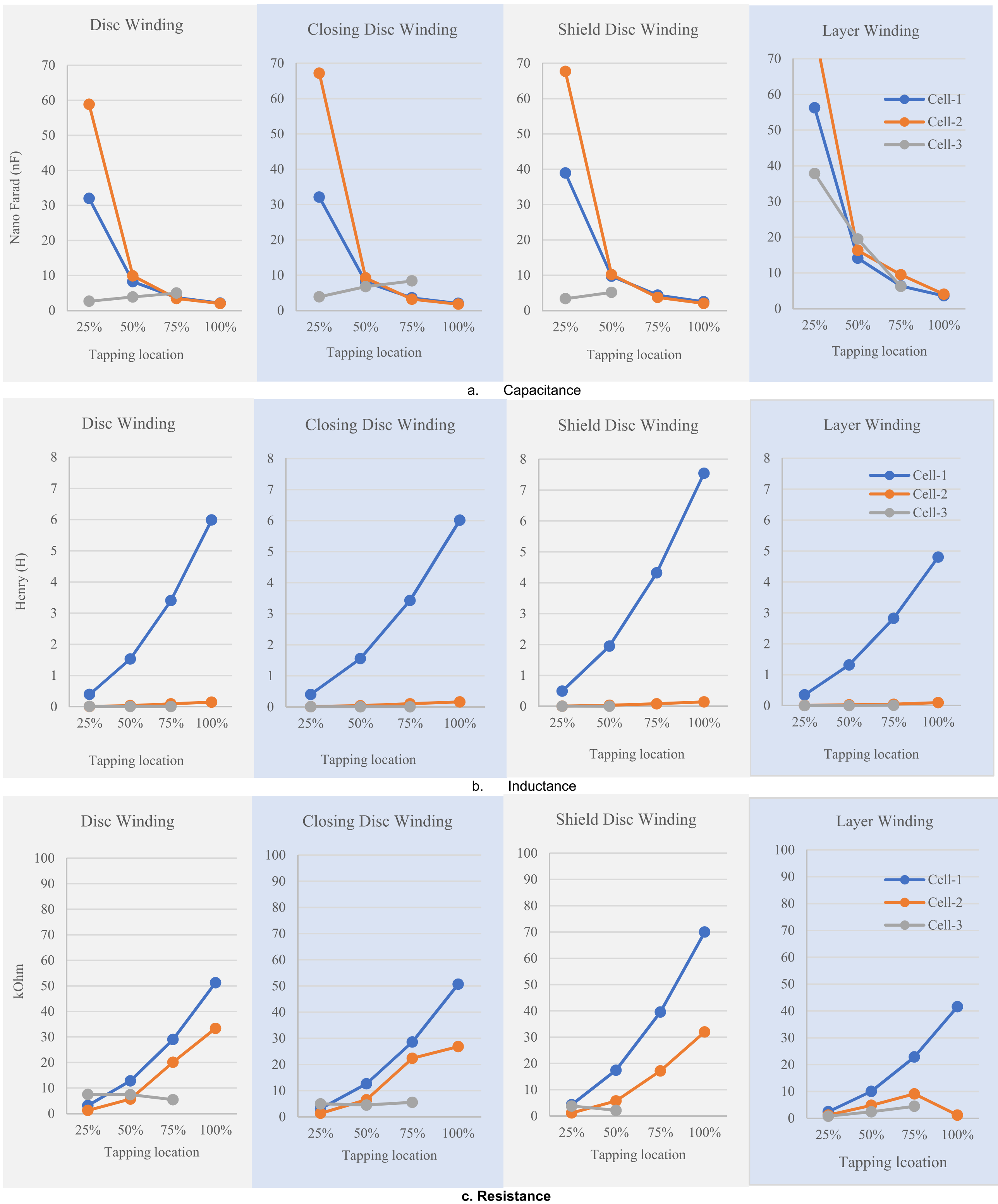


FIGURE 9. **Transformer winding parameter (Resistance, Inductance and Capacitance).**

the parameter that has more dominant effect on cells-2 is parameter C.

The evaluation of the effect of the parameters on cell-3 was somewhat different than for cell-1 and cell-2. Because the estimated parameter in cell-3 is only valid for 25% and 50% winding, while in 75% and 100% winding some data shows a very poor level of accuracy. Based on Table 4., the effect of capacitance in cell-3 for disc winding is highly dominant

TABLE 2. Resonance frequency of impedance [kHz].

Winding type	Cell number	Winding section			
		25%	50%	75%	100%
Layer	Cell-1	7.28	7.77	7.44	8.3
	Cell-2	49.57	50.67	51.23	51.79
	Cell-3	148.4	319.5	167.4	-
Continuous disc	Cell-1	8.67	8.96	9.26	8.77
	Cell-2	52.37	55.93	59.73	60.39
	Cell-3	215.4	217.8	217.8	220.2
Closing disc	Cell-1	8.77	8.77	9.16	9.16
	Cell-2	52.37	55.9	59.73	61.7
	Cell-3	230	235.2	235.17	434.6
Shield disc	Cell-1	7.36	7.36	7.36	7.36
	Cell-2	51.79	56.54	59.08	61.05
	Cell-3	199.5	199.5	235.2	-

TABLE 3. L/C ratio of cell-1 to cell-2.

Winding type	Winding section			
	25%	50%	75%	100%
Layer	87.81	60.07	98.73	56.28
Disc	124.81	51.71	34.64	38.84
Closing disc	152.17	46.19	30.88	33.13
Shield disc	161.75	59.77	44.35	42.73

compared to cell-2, while in the layer winding, the effect of capacitance on cell-3 is almost the same as that of in cell-2. In the four types of windings, the more turns, the effect of capacitance is lower.

In the next research, the effect of series winding capacitance on inter-resonance should be investigated more detail in order to get way to optimize the winding design. Research can be carried out on transformer with combination winding type including continuous disc, disc with interleaved and disc with inter sheath.

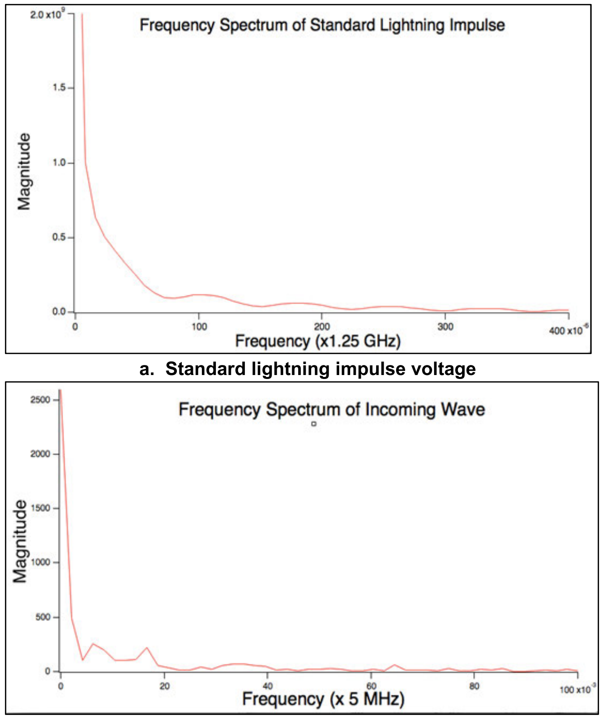
D. WINDING VOLTAGE DISTRIBUTION

Another important thing regarding the inter-resonance is the effect on the voltage distribution inside winding. Transformer designer has only considered the voltage distribution only for standard lightning impulse [15], [16], [14] as shown in fig. 10.a. According to fig. 8, voltage distribution for frequency above 40 kHz is not linear, especially in the range frequency of above 100 kHz where inter-resonance occurs. Because of the nonlinearity characteristics of inter-resonance, the current impulse distribution voltage that already be performed during transformer design was no longer enough to characterize the voltage distribution because not yet consider the resonance phenomenon at high frequency section.

In the electricity network, the frequency spectrum of the incoming waveform at transformer terminal is no longer similar to Fig. 10.a. Fig. 10.b. is the frequency spectrum of incoming waveform at transformer terminal in Katamayasu

TABLE 4. L/C ratio of cell-2 to cell-3.

Winding type	Winding section			
	25%	50%	75%	100%
Layer	2.43	59.41	2.95	-
Disc	0.03	2.57	30.08	-
Closing disc	0.07	10.40	112.55	-
Shield disc	0.04	4.11	-	-



a. Standard lightning impulse voltage

b. Katamayasu substation incoming waveform

FIGURE 10. Frequency spectrum.

substation [17]. Frequency spectrum of the incoming waveform at transformer terminal is still exist up to 500 kHz, while in the standard lightning impulse voltage is almost disappear at 200 kHz.

Hence, it is strongly recommended to perform sinusoidal voltage distribution for range frequency up top 500 kHz for considering the higher frequency component. By performing sinusoidal voltage distribution, a comprehensive voltage distribution for full range frequencies are obtained. Unfortunately, unlike impulse voltage distribution where the frequencies are superposition from several frequencies, the sinusoidal voltage distribution are only single frequency at the same time. By performing both sinusoidal voltage distribution and impulse voltage distribution, a comprehensive voltage distribution for full range frequencies and impulse voltage distribution are obtained.

V. CONCLUSION

Resonance occurred in the internal winding or winding section may shift several kHz compare to resonance in the full winding. This may lead to phenomenon such as inter-resonance indicated by the voltage at a location cross over to the other location. Based on that SFRA characteristics, it was found that the highly potential occurrence for inter-resonance that needs to be considered is the inter-resonance occur at the frequencies above 100 kHz. This may strongly influence the voltage distribution inside winding.

Regarding the voltage distribution inside the winding, it is highly recommended to analyze the voltage distribution using sinusoidal waveform, in addition to the impulse voltage distribution for considering the effect of resonance at higher frequency.

Based on the estimation value of resistance, inductance and capacitance, the longer the conductor, the greater the inductance and resistance values, and the greater the resonance frequency. In a homogeneous winding design, the data on the miniature transformer can be used as a reference to predict the resonance frequency in the windings of real transformer by extrapolating the inductance curve.

Based on comparison of capacitance-inductance ratio, the effect of inductance was highly dominant on cell-1, while in cells-2 the effect of inductance was lower. The effect of capacitance in cell-3 for disc winding is highly dominant compared to cell-2, while in the layer winding, the effect of capacitance on cell-3 is almost the same as that of in cell-2.

This research is the first research that investigate the resonance characteristics inside winding using the current SFRA technology. This SFRA method could analyze the characteristic of inter-resonance to get the frequency characteristics inside winding.

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