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Research Original Article

Log-Spiral Sensor Design to Detect Partial Discharge in Transformer

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Abstract

The method of detecting electromagnetic signals generated by partial discharge is a method that is currently developing to detect early damage to Transformers. This method is done by utilizing an antenna that serves as a sensor to capture electromagnetic signals. This paper discusses the design of sensors to detect partial discharge in Transformers. The designed sensor is a planar type which has dual-arms log-spiral. Customized sensor dimensions inspection windows are commonly found on power transformers, with a diameter of 15 cm. With the specified dimensions attached sensor with an impedance of 160 Ohms. Because measuring instruments generally have an impedance of 50 ohms, it takes a balun as a transition from the sensor impedance of 160 Ohms. The designed Balun is a coplanar wave guide - coplanar strip line (cpw-cps) type with 6 of number of transition.

Keywords: Log-Spira Sensor, Partial Discharge, Electromagnetic Signals

Introduction

The distribution of electrical energy from the power plant center to the load is carried out using high-voltage transmission. Because the voltage level generated by the plant is generally a medium voltage level, a transformer is needed to raise the voltage generated by the power plant to a high voltage level used in the transmission system. The Rating of electrical energy that can be delivered by Transformers varies greatly from several hundred kVA for 220volt low voltage distribution transformers to hundreds of MVA for high voltage power transformers. Damage to transformers that are serving the load will not only result in very large replacement costs, but also can cause environmental damage due to oil spills, endanger people around the transformer and cut off the energy supply which leads to a decrease in service quality. So it is necessary to pay attention to periodic maintenance of the transformer so that it can operate at peak loads (Prastia et al., 2024), (Lukman et al., 2023).

On the other hand, the power provider in this case PLN usually wants the transformer to be operated at maximum power and continuously. Over time, this of course will cause stress on the transformer insulation that can trigger the deterioration of the transformer insulation system. Degraded parts of the insulation system will occur and can trigger damage to the transformer (Ismail et al., 2020), (Nisworo et al., 2022).

To prevent the breakdown of the transformer insulation, on-line detection plays a very vital role in the detection and determination of the condition of the insulation system. From the detection data, isolation conditions can be known so that preventive measures can be determined. In the event of very severe deterioration, follow-up measures such as regular checks and repairs can be planned to prevent fatal damage to the transformer. One type of transformer isolation condition monitoring system is to detect partial discharge.

Literature Review

Partial discharge (Partial discharge) is defined as partial electrical discharge that occurs only in part of the insulation between conductors and can occur in the area near the conductor or the middle of the insulation. If the discharge increases and causes the connection of the two conductors, the insulation will breakdown. Although there is no direct correlation between partial discharge and breakdown, sometimes breakdown occurs without being preceded by partial discharge, but partial discharge will result in a decrease in insulation strength and can trigger a breakdown if the discharge occurs in the long term (Alhazmi et al., 2023).

Partial discharge can be detected from the products it produces such as discharge currents, sounds, gases (due to chemical reactions), heat, light and electromagnetic signals. Detection of partial discharges by means of detecting electromagnetic signals is one of the newly developed methods in recent times to detect discharges in Transformers (Judd et al., 2005). Electromagnetic signals are captured using entenna which functions as an electromagnetic sensor.

Partial Discharge Electromagnetic Signal Detection Method

Electromagnetic signals generated during the partial discharge process will have a frequency spectrum that depends on the type/type of PD source and the medium in which the PD process takes place (Judd et al., 2005). The tapered Metal piercing insulation system produces a very fast pulse wave, with a wavefront time of less than ~0.9 ns on an oil insulating medium. Whereas imperfect isolation contacts produce pulses with an advance time reaching ~17 ns (Judd et al., 2005). The pulse with the slowest advance time is generated by the corona source (Sinaga, 2009) with advance time reaching ~50 ns. Thus, the frequency range of electromagnetic signals generated in the process of partial discharge is in the order of tens of MHz to above 0.5 Ghz.

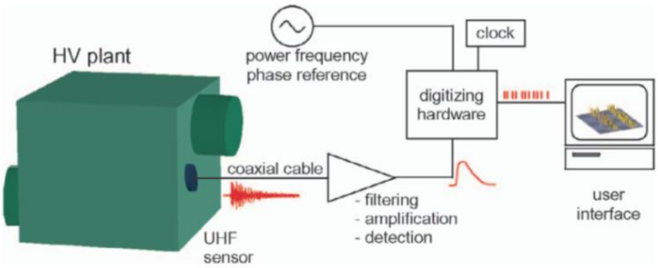


Figure 1. Partial Discharge Detection Diagram by Capturing Electromagnetic Signals

A large discharge detection diagram is shown in Figure 1. The main component for detecting electromagnetic signals is an antenna that serves as a sensor to capture electromagnetic signals emitted by a partial discharge source. The Sensor is connected with the measuring equipment to display the partial discharge signal. If the signal generated by the partial discharge source is too small, the amplifier can be placed between the sensor and the measuring instrument. The electromagnetic signal captured by the sensor can be recorded using an oscilloscope or digitizer. The captured electromagnetic wave will display the magnitude of the electromagnetic signal as a function of time.

Sensors to Detect Partial Discharge in the Transformer

The function of monitoring the isolation condition of the transformer includes the detection and identification of partial discharge to the determination of the location of the partial discharge (Nisworo et al., 2024). So that the partial discharge monitoring function on the transformer can be performed, it is necessary to have a sensor with the ability to detect the partial discharge signal. For transformer isolation monitoring, a sensor can be installed in the transformer tank to capture the electromagnetic signal generated by the partial discharge source. There are two possible placement of sensors on the transformer tank, namely: through the drain hole of insulating oil (Lopez-Roldan et al., 2008) or with dielectric Windows (Judd & Farish, 1998). The way of placement through the exhaust hole of the insulating oil will limit the size of the sensor that can be made. While the dielectric window can be made by following the size of the sensor to be designed. However, a sensor placed on a dielectric window will require a special window that must be made by perforating the transformer tank. This can be done when the transformer is in a routine inspection period or can be added If the transformer is not yet in production. This will not reduce the overall performance of the transformer.

The Sensor placed through the exhaust duct of the insulating oil is usually a sensor with a monopole type. The sensor size is very limited with respect to the limited duct size. Usually, the diameter of the exhaust duct of the transformer insulating oil does not exceed 5 cm with a length of less than 20 cm. The Shape of the sensor can be a short monopole (Pinpart & Judd, 2009), plate, zigzag or conical (Agoris et al., 2007) or any other form provided that it can be included on the channel. The deeper the sensor is inserted, magnitude the greater the magnitude of the suppressed discharge signal. But note, the placement of the sensor should not be too deep because it can trigger a breakdown due to high electric field pressure at the end of the sensor. The pressure of the electric field at the end of the sensor can be reduced by wrapping the sensor with a certain dielectric material (Cavallini et al., 2010).

Meanwhile, for sensors placed through a dielectric window usually has a planar shape (horizontal). The sensor can be a micro-stri sensor (Erentok & Ziolkowski, 2008), log-spiral, spiral (Roy et al., 2007) or fractal (Erentok & Ziolkowski, 2008). Sensors of this shape are usually printed on the surface of a dielectric material, in the same method as the manufacture of printed circuit panels (PCB-printed circuit board). The Sensor is printed on a PCB board with a size and design that matches the working frequency of the sensor. For high frequencies, the sensor size can be reduced to 5x5 cm (Marrocco, 2008). But this sensor has a very small working frequency spectrum bandwidth. To zoom in bandwidth, (Erentok & Ziolkowski, 2008) designing microstrip sensor use Layered PCB. As a result, a sensor with a very high working frequency range of 30 MHZ to 1000 MHZ is obtained. But such a design is very difficult and impractical to make.

Most measuring instruments, including oscilloscopes, use an unbalanced system at the input, where the input to the bias oscilloscope is a coaxial cable consisting of a tensioned conductor core and a protective sheath connected to the ground. Meanwhile, the sensor printed on the PCB is usually a balanced system (Note: unbalanced systems are also possible using single-arm spiral and log-spiral models). Thus, to connect the sensor to the measuring device, a converter from a balanced system to an unbalanced system is needed. This component is usually connected directly to the sensor panel and is made in a single unit with the sensor. So basically, the sensor consists of two parts, namely the sensor component itself and the converter. These converters are known as balun (balanced-unbalanced).

Antennas and measuring equipment usually have different impedances. The most common equipment impedance is 50 ohms, although sometimes it can also be found with impedances of 75 and 100 ohms. While the impedance of the sensor is usually on the order of hundreds or even thousands of Ohms (Thaysen et al., 2000). So that the balun, in addition to being a balanced to unbalanced converter, also serves as a switching impedance between two different impedances (Duncan & Minerva, 2007).

With the advancement of microstrip technology today, baluns can be made using the same materials as sensors, namely using PCB boards. The Balun is printed on the PCB board so as to form a certain pattern that can bridge two different impedances with a certain working frequency. Jesper, et.al (2000) designed baluns for 0.1 to 3.8 GHz working frequency using PCB board. The total length of balun by using standard PCB board is 46 mm. Impedance transition is obtained by making a certain mold pattern.

Balun

Most measurement equipment is an unbalanced system. For example, the coaxial cable in Figure 2 is an unbalanced system. The ground plane below the coaxial cable becomes the third conductor in a three-wire system. The sheath conductor of coaxial cable has capacitance to ground while the inner conductor has no capacitance to ground. So that the current flowing through the ground can cause the current in the coaxial to be unbalanced. When an unbalance system is connected to a balance system such as a dipole sensor, a two-arm log-spiral, a transition component is required. This transitional component is referred to as a balun. In addition to bridging the balanced system with an unbalanced system, the balun also serves as an impedance transition due to the difference in the impedance of the sensor with the measurement equipment. There are several types of balun types such as: folded balun, sheath, split coaxial, transformer, sliced or balun microstrip. Sliced type (J. W. Duncan, 1960) and microstrip baluns (Choi et al., 2004) have high bandwidth capabilities making them suitable for large frequency ranges.

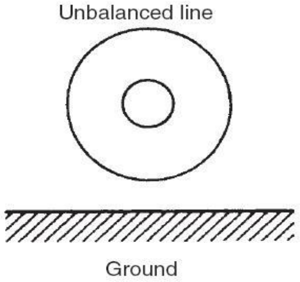


Figure 2. Cross-Section of Coaxial Cable

Balun Microstrip

Microstrip Balun has advantages compared to other types of balun. The size of the microstrip balun is relatively small and also has much smaller additional losses. An example of a microstrip balun is shown in Figure 3. This balun is a form of coplanar-waveguide to coplanar-stripline (CPW-to-CPS) balun. The figure shows the transformation from an unbalanced CPW supply line to an unbalanced CPS supply line. The number of sections depends on the impedance of the sensor and coaxial cable used and also the desired reflection coefficient.

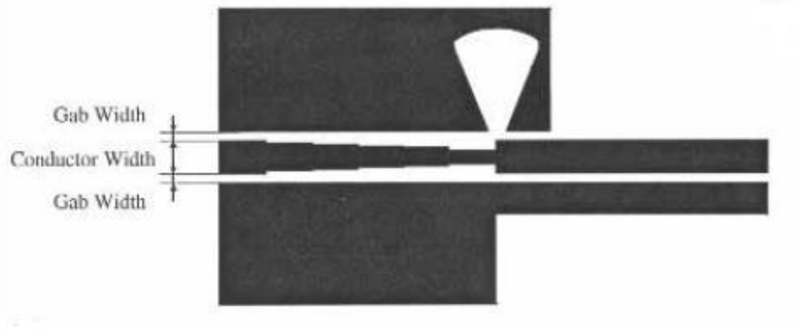


Figure 3. A 4-Level Microstrip Balun

Research Methods

The sensor is designed using CST Microwave Studio software. The sensor is configured as a two-arm log-spiral structure. To evaluate the performance of the sensor, the following parameters are used:

1. Voltage Standing Wave Ratio (VSWR):

This parameter represents the ratio between the transmitted and reflected signals at the sensor. An ideal (lossless) sensor exhibits a VSWR value of 1.

2. Bandwidth:

The desired operating frequency range is from 300 MHz to 3000 MHz.

3. Substrate Material Selection:

The sensor with the optimal design is fabricated using a printed circuit board (PCB). An FR4 PCB substrate is selected because it has lower capacitance compared to other materials. Lower capacitance results in a sensor with smaller physical dimensions, making it easier to fabricate and install on the transformer tank.

The Sensor designed is a balance sensor, so it requires a balun. The Balun is planned to be made of the same material as the sensor, namely PCB board. Balun dimensions are calculated using MATLAB software. Then the calculation results are plotted using CST microwave studio and combined with the sensor to determine the final performance of the sensor.

Results And Discussion

The following are discussed the simulation results and calculations obtained for Log-spiral and Balun Sensor components.

Sensor

Sensors to detect partial discharge using metal materials that are designed and made to capture electromagnetic wave signals. The Sensor serves as a link between testing equipment such as digitizer signals and the environment around the sensor. The following discusses the basic amount of sensors to be designed. The type of sensor chosen is log-spiral type. The log-spiral sensor arm can be calculated using the following equation:

$$r_1 = r_0 e^{a\phi}$$

$$r_2 = r_0 e^{a(\phi-\phi_0)}$$

where: r_1 = Outer Radius of the Spiral Arm
$R2_2$ = Radius In Spiral Arms
r_0 = Darius begins the spiral arms
a = Spiral Magnification Level
ϕ = Angular Position

The number of arms usually uses 2 or 4, and in this study 2 Arms were chosen for reasons of simplicity (Figure 5). The number of windings is 1.5 times because this number of windings is sufficient to produce a good radiation pattern for the sensor (Dyson, 2003). The end of the spiral arm is made circular truncated because it will produce a more stable impedance (Kaiser, 1960). The Sensor is designed using commercially available FR4 PCB media and the sensor diameter is limited to 15 cm for reasons of placement in the most ideal transformer.

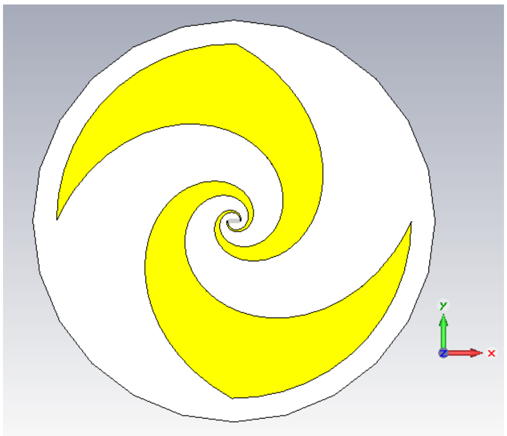
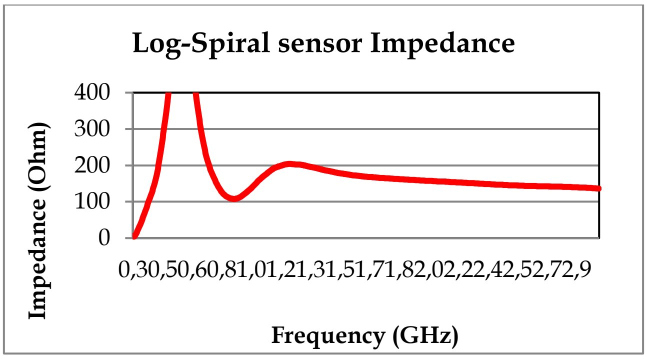
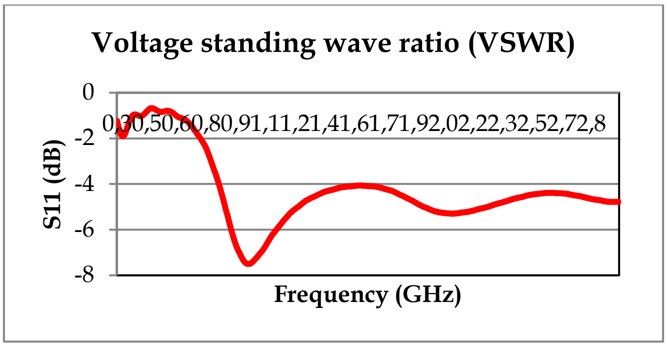


Figure 5. Log-Spiral Sensor Design

Figure 6 shows the log-spiral sensor simulation result of its impedance and voltage standing wave ratio. From Figure 6.a it is seen that the sensor has an impedance that fluctuates with the impedance value at the center frequency of 1500 MHz is 160 Ohms. This value is used as a reference impedance sensor and will be use as a basis for designing the balun. While in Figure 6.a visible sensor has a VSWR value smaller than -4 db and is relatively flat for frequencies in the range of 750 MHz s to 3000 MHz.



(a)



(b)

Figure 6. Log-Spiral Sensor Parameter (a) Impedance, (b) Voltage Standing Wave Ratio (VSWR)

Balun

Because the log-spiral sensor is a balanced system (balance), while measuring equipment such as an oscilloscope is an unbalanced system (unbalance), the sensor must be given an additional transition from a balanced to unbalanced system known as balun (balance-unbalance). The Balun is planned to be made with FR4 PCB material as well.

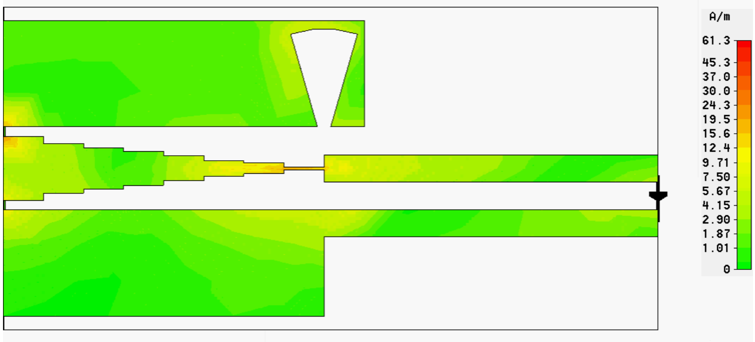


Figure 7. Distribution of current on the surface of the balun with the number of levels 6, the end of the balanced section is loaded with an impedance of 160 Ohms,At Afrequency Of 1500 Mhz

The length of each part of the balun should be in accordance with the 4 of the optimum frequency. With the target optimum frequency of 1500 Mhz, the 1/4 is 15 mm (Figure 7). With each section of 15 mm, then the length of the balun to 135 mm, the balun may make the overall length of the sensor becomes too long. By using the reduction factor (2n+1) with n = 7, the overall length becomes 48 mm.

Table 1. Log-Spiral Balun Parameter

Parts	Designed Impedance (ohms)	S (mm)	W (mm)	S+W (mm)	Calculated Impedance (ohm)
Coaxial	50	4.8	0.7	6.2	49
CPW 1	65.06	3.7	1.25	6.2	65
2	73.24	3.1	1.55	6.2	73.7
3	83.54	2.5	1.85	6.2	83
4	95.75	1.8	2.2	6.2	95.5
5	109.23	1.2	2.5	6.2	109.6
6	122.9	0.8	2.7	6.2	122.5
	160	0.5	2.2	6.2	159.3
CPS	160	3	2.7	8.4	160.6

CPS = coplanar strip-line

The balun values are calculated using Chebyshev multi-section transformer formula. The Balun is designed so that the VSWR does not exceed 0.2. The calculation results are shown in Table 1.

Sensor Response to Rapid Pulses

The generated pulse waveform time is about 1 us with tail time adjustable. Figure 8 shows the designed sensor response to a given pulse input. It is noticeable that the sensor gives a fairly high response, with oscillations in the tail. Oscillations are generated by the construction of an elliptical sensor. With this shape, the overall length of the sensor will increase. So the signal received at the sensor end will take a greater time to arrive at the feed point to the oscilloscope.

The magnitude of the oscillation is influenced by the number of windings. The more windings, the more oscillations will be. This is not desirable because the resulting electromagnetic signal will undergo a large deformation. In this study used two arms and many windings of 1.5 windings.

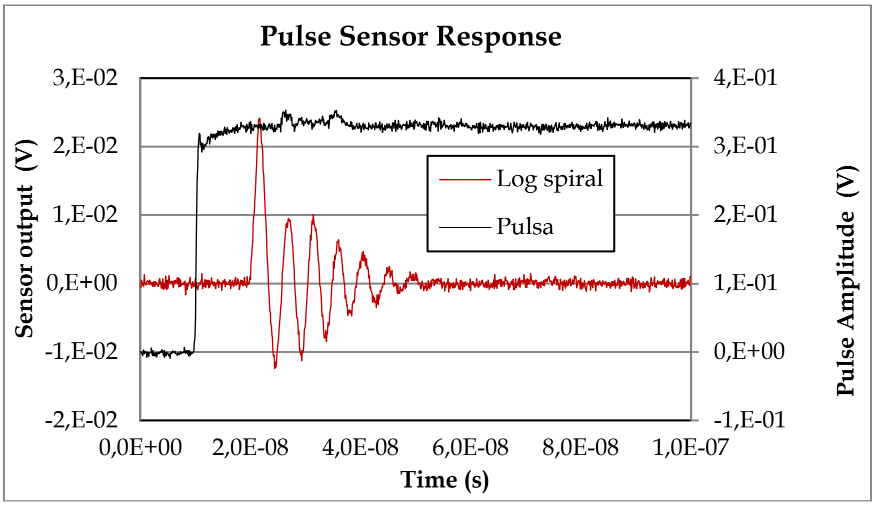


Figure 8. Step-Pulse Response of Log-Spiral Sensor

From testing the sensor response to this pulse, it can be determined the sensor response to the signal with a very short time as in the partial discharge signal. Sensors with a large energy response will be very useful for capturing a small partial discharge signal, also the oscillation should be as small as possible to reduce the amount of error that may occur when the sensor is used for partial discharge location determination applications. From Figure 8 can be seen with the input of 330 mV obtained sensor output of 25 MV, so that the sensitivity of the log-spiral sensor is designed around -11.21 dB.

Conclusions

Based on the results of this study, it can be concluded that a dual-arm log-spiral sensor can be successfully designed and simulated using CST Microwave Studio. With a sensor size constraint of 15 cm, the designed sensor achieves a characteristic impedance of approximately 160 Ω at the center frequency of 1500 MHz and exhibits a Voltage Standing Wave Ratio close to −4 dB within the frequency range of 300 MHz to 750 MHz. To enable compatibility between the log-spiral sensor and a standard 50 Ω measurement system, a balun is designed to function as an impedance-matching transition from 160 Ω to 50 Ω. The optimal balun configuration consists of six tiers, resulting in a total balun length of 48 mm. Furthermore, the designed log-spiral sensor demonstrates a good transient response to step pulse excitation, characterized by minimal oscillations and sufficient energy capture. The sensor sensitivity reaches −11.12 dB, indicating that the proposed design is suitable for high-frequency pulse detection applications.

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