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DESIGN OF TEM CELL TO TEST THE ELECTROMAGNETIC SENSOR

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ABSTRACT

Partial discharge in transformer insulation can be detected by the product produced during the PD event. Electromagnetic signal is one kind of the product that produces by the PD event. By using appropriate sensor, the electromagnetic signal can be captured thus detect the PD event in the transformer insulation. The method capturing the electromagnetic signals to detect PD event in transformer has advantage compare to other PD detection methods. The advantage mainly due the electromagnetic signal prone to the disturbance noise around the transformer. To be able to capture the electromagnetic signals, a sensor with capability to detect the electromagnetic signals is needed. The capability of a sensor can be tested using a TEM cell. In this paper discussed the design of TEM cell (Transverse Electromagnetic cell) which able to test a sensor such the sensor which use to detect the PD event in transformer. The TEM cell is an open cell type and construct using alumina as the material. The TEM cell has length of 1200 mm and height 105 mm. The TEM cell shown has a good capability to test the sensor which designed to detect the PD in transformer.

Keywords: electromagnetic signals, log-spiral sensor, TEM cell.

INTRODUCTION

In every measurement system, calibration which compares the output of a piece of measuring equipment to a standard value is required. The calibration establishes with certainty the amount being measured. However, this is not the case for the UHF detection method. The output of the UHF sensors cannot be calibrated as per IEC 60270 as they do not directly quantify the amount of charge of the PD pulses [1].

The reason is that a PD can occur at almost any location inside the transformer tank. The path of the electromagnetic signals from the PD source to the sensor is affected by the structure inside the transformer. The PD signal propagation can be obstructed by some solid material parts inside the transformer. The active parts of the transformer also affect the attenuation of the electromagnetic signals which caused the attenuation not linear to the distance. Thus without knowing the exact location of the PD, it is difficult to convert the amount of PD detected by the UHF sensor to an equivalent pC level [2].

To provide information about the sensor capabilities, it is important to set up tests which are repeatable and can be used to test various sensors. In [3, 113] sensor calibration is introduced and information is provided about the sensor frequency response. A µ-TEM cell was used in [5] to test antenna response. In [113, 6], a TEM cell was built to test the sensor frequency response in an attempt to calibrate the sensor for PD detection. The TEM cell can also be used to test the sensor response for specific pulses such as the step pulse [7, 8] in order to find the most suitable sensor for application of PD diagnostic and monitoring. Using a step pulse to determine the frequency response of the sensors has an advantage over the sweep frequency generator [8]. This is because the step pulse contains all necessary frequency components so only one measurement is needed. Also, the cost of the test can be reduced as the frequency generator can be eliminated. However, the sweep frequency generator will provide real frequency response where input and output can be compared directly, unlike the step pulse where the pulse signals must be converted to frequency response.

As the UHF sensors cannot be calibrated based on a pC value, CIGRE WG 15.03 [9] has recommended a method for its sensitivity verification which can be used to determine on-site the minimum sensitivity of this measuring method in GIS. The sensitivity test will show the amount of PD which can be measured by the UHF method. The sensitivity of the UHF method is very dependent on the type of sensor, types of PD source and the surrounding structure [2, 10, 11, 12].

In this paper, design of open type TEM cell is discussed. A TEM cell was used to simulate the transverse mode of the PD electromagnetic waves in the transformer tank.

PLANAR TRANSMISSION LINES

An open type of TEM cell is chosen to be designed and use to test the electromagnetic sensor. This is due to simplicity of the open type TEM cell. As the TEM cell intended to be used to test the electromagnetic sensor that applied to detect PD inside transformer tank, the TEM cell dimension thus must accommodate the sensor size. To design the TEM cell, software named Maxwell electromagnetic field is used to determine the uniformity of the space inside the TEM cell. The TEM cells itself follow the strip line theory.

Coplanar strip line (CPS)

The coplanar strip line consists of two parallel strip conductors separated by a narrow gap. Similar to the CPW, the CPS is also built above or between dielectric layers. The CPS is a balanced transmission line which is made suitable to connect to printed balanced antennas such as spiral, bowtie and log-spiral ones.

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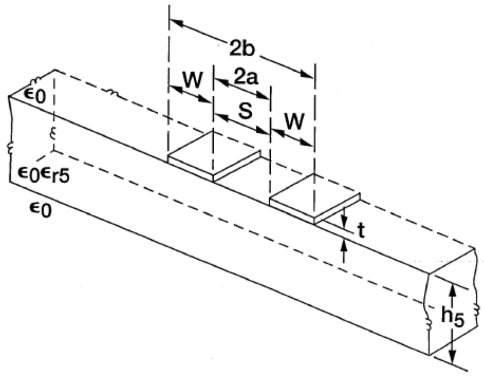

Figure-1. CPS schematic on a dielectric substrate of finite thickness [13].

The strip line construction can be in a combination of similar size (symmetrical) or different (asymmetrical) as shown in Figure-1. In this design, the symmetry of the CPS will be discussed.

The capacitance of the coplanar waveguide is expressed as [14]:

$$C_{CPS} = C_0 + C_5 \tag{1}$$

The capacitance C_0 is defined as [14]:

$$C_0 = \varepsilon_0 \frac{K(k)}{K(k')} \tag{2}$$

where K is the complete elliptical integral of the first kind. The arguments k and k' are given by [14]:

$$k = \sqrt{1 - \left(\frac{a}{b}\right)} \tag{3}$$

and

$$k' = \sqrt{1-k^2} = \frac{a}{b} = \frac{S}{S+2W} \tag{4}$$

Equations 3 and 4 show that both k and k' are dependent on the geometry of the CPS.

The effective permittivity of the CPS can expressed as [14]:

$$\varepsilon_{eff}^{CPS} = 1 + \frac{1}{2}(\varepsilon_{r5} - 1)\frac{K(k)}{K(k')}\frac{K(k_1')}{K(k_1)} \tag{5}$$

where:

$$k_1 = \sqrt{1 - \frac{sinh^2(\frac{\pi a}{2h_1})}{sinh^2(\frac{\pi b}{2h_1})}}$$

and

$$k_1' = \sqrt{1-k_i^2}$$

The phase velocity v_{ph} and characteristic impedance Z_0 are given by:

$$v_{ph}^{CPS} = \frac{c'}{\sqrt{\varepsilon_{eff}^{CPS}}} \tag{6}$$

$$Z_0^{CPS} = \frac{120\pi}{\sqrt{\varepsilon_{eff}^{CPS}}} \cdot \frac{K(k')}{K(k)} \tag{7}$$

where c' is the velocity of light.

ELECTROMAGNETIC SIGNAL

The electromagnetic pulses generated by the PD source can carry a wide band frequency signal depending on their rise time. In air, the propagation velocity of the electromagnetic signals is approximately as fast as the speed of light (c). In other media, the speed of the electromagnetic signal (v) depends on the permittivity and permeability of the material. This factor is called the refractive index of the material and is expressed as:

$$\eta = \frac{c}{v} = \sqrt{\frac{\mu\varepsilon}{\mu_o\varepsilon_o}} = \sqrt{\mu_r\varepsilon_r} \tag{8}$$

where $\varepsilon = \varepsilon_r\varepsilon_o$ is the permittivity of the material, and $\mu = \mu_r\mu_o$ is the permeability of the material (expressed as a product of its relative value and the absolute value of free space). In a vacuum, the propagation velocity of electromagnetic signals is the speed of light, i.e. 3 x 10^8 m/s.

Electromagnetic propagation modes

When electromagnetic signals travel, they carry both electric and magnetic components which are perpendicular to each other. Depending on the structure in which the electromagnetic signals propagate, there are three modes into which the propagated signals may be divided. The three modes are discussed below using the rectangular waveguide as an example.

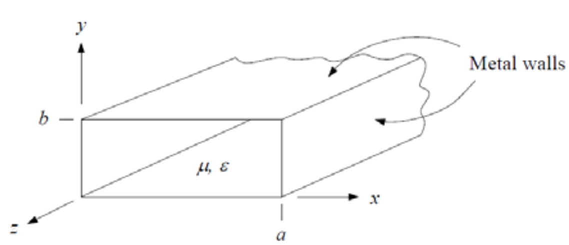

Figure-2. A rectangular wave guide [13].

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Assume the waveguide with rectangular shapes in Figure-2 is filled with a non-dissipative medium. If the waveguide lies along the z direction, then the electric and magnetic fields along the waveguide are expressed as:

$$H_x = \frac{j}{k_c^2}\left[\omega\varepsilon\frac{\partial E_z}{\partial y} - \beta\frac{\partial H_z}{\partial x}\right] \tag{9a}$$

$$H_y = -\frac{j}{k_c^2}\left[\omega\varepsilon\frac{\partial E_z}{\partial x} + \beta\frac{\partial H_z}{\partial y}\right] \tag{9b}$$

$$E_x = \frac{-j}{k_c^2}\left[\beta\frac{\partial E_z}{\partial x} + \omega\mu\frac{\partial H_z}{\partial y}\right] \tag{9c}$$

$$E_y = \frac{j}{k_c^2}\left[-\beta\frac{\partial E_z}{\partial y} + \omega\mu\frac{\partial H_z}{\partial x}\right] \tag{9d}$$

where $k_c^2 \cong k^2 - \beta^2$, $k^2 \cong \omega^2\mu\varepsilon$ and β is the phase constant.

The field patterns which accompany the wave propagation can then be distinguished within the three modes [13]:

1. Transverse electric (TE) Mode, in which the electric field component is transverse to the direction of propagation. For TE mode, the condition is $E_z = 0$ and $H_z \neq 0$.
2. Transverse magnetic (TM) mode, in which the magnetic field component is transverse to the direction of propagation. For TM mode, we have the condition: $H_z = 0$ and $E_z \neq 0$.
3. Transverse electric and magnetic (TEM) mode is a mode where both electric and magnetic components are transverse to the direction of propagation. In this condition E_z, $H_z = 0$ everywhere.

In a transformer tank, the PD signal travelling in TEM mode [3], thus to test the sensor one must use a camber with TEM mode capability.

TEM CELL DESIGN

Sensors constraint to design TEM cell

The purpose of transformer monitoring extends from PD detection and recognition to PD localization. To be able to undertake UHF PD transformer monitoring, a sensor with capabilities to detect signals in the UHF frequency range is needed. For power transformer monitoring, the UHF sensor is inserted into the transformer tank to capture the electromagnetic waves emitted by the PD source. There are two ways of installing the sensor: via the oil drain valve [15] or the dielectric window [16]. The size of the oil drain valve imposes a constraint on the sensor dimension, while the dielectric window can be created with an appropriate size to accommodate the sensor. However, the placement of a dielectric window sensor needs an additional hole to be fabricated on the transformer tank. The size of the PD sensor discussed in this paper should not more than 10 cm as the author sensor dimension in the previous paper [17, 18].

TEM cell dimension

A parallel plate is one of conductor arrangements which transverses both electric and magnetic signals. The cell structure is shown in Figure-3 and consists of two aluminium plates with different widths. The bottom plate is connected to ground and the top plate is of a specific width positioned at a specific distance from the bottom one so that the cell meets the required impedance. The cell was designed to meet the impedance of the antenna, i.e. 50 ohms.

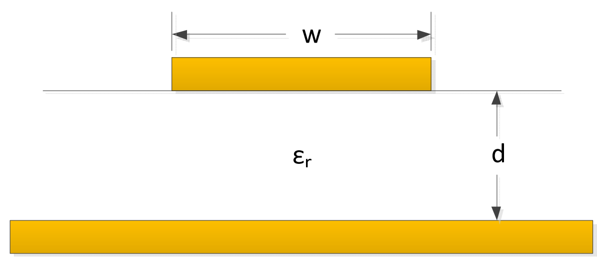

Figure-3. Ross section of strip line geometry.

The impedance of the strip line for w/$d \geq 1$ is defined by [19]:

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_r}\left[w/d + 1.393 + 0.667\ln(w/d + 1.444)\right]} \tag{10}$$

or if the characteristic impedance Z_o is known, the w/d ratio can be calculated as

$$\frac{w}{d} = \begin{cases} \dfrac{8e^A}{e^{2A}-2} & for\ \ w/d < 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln(2B-1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right\}\right] & for\ \ w/d > 2 \end{cases} \tag{11}$$

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where:

$$A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r + 1}{2} + +\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right)}$$

$$B = \frac{Z_s \pi}{2 Z_o \sqrt{\varepsilon_r}}$$

With:

Z_s = impedance of free space (for air ≈ 377 ohms),
ε_r = dielectric constant of substrate (air),
w = width of metal strip,
d = thickness of substrate (air),

RESULT AND DISCUSSIONS

TEM cell

Most of the TEM cells are designed to have 50 ohms of characteristic impedance. The open TEM cell used in this thesis is also designed to work at 50 ohms. This is done so that the cell has same impedance as the sensors. Using Equations 8 and 9, the TEM cell dimensions can be determined.

The largest sensor diameter is 10 cm and attached to a connector with a length of 4.8 cm. This is the size limitation for the TEM cell dimensions. By using Equations 10 and 11 we get the width and height of the cell as 50 cm and 11.5 cm respectively. The impedance with this cell structure is 51.1347 ohms. For the exact Z_o = 50 ohms, the height of the cell is 11.2 cm. However, a precise construction is difficult to build and also a sag factor might also have to be included for the middle section of the cell. The diagram of the TEM cell are shown in Figure-4.

Both ends of the cell are tapered and bend. The end of the top electrode is then decreased to 1 cm width and bent so that the distance between the top electrode and the bottom plate is 2.5 mm.

The sensor diameter is 10 cm which is used as a constraint in the design process of the TEM cell. The electromagnetic field between the two plates must be uniform and has a height which is at least the size of the sensor. Using Maxwell electromagnetic field software [20], the dimension of the cell can be determined, and where the top electrode width is 50 cm the electric field is fairly uniform with a coverage width of 25 cm, Figure-5.

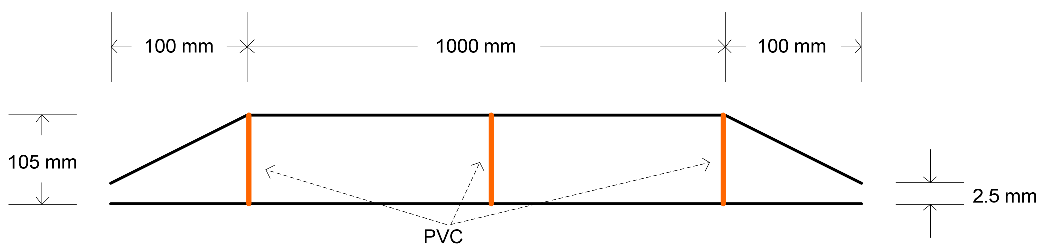

Figure-4. Side view of the TEM cell diagram.

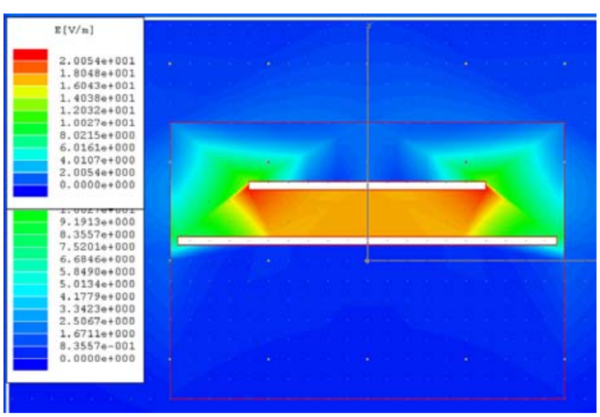

Figure-5. Field plot of designed strip line.

Step pulse response

The rise time of the step pulse input was around 0.5 ns and the length was maintained for quite a long time so the sensor response was only due to the changed input voltage. Figure-5 shows typical step pulse response of monopole sensor which has 10 cm of length.

The aim of the step pulse response is to establish the response of the sensors to fast change of rise time signals such as PD signals. Knowing the step response means that the most suitable sensor for a specific PD application can be selected. As example, for the purpose of PD localization, the sensor with the lowest oscillation response and therefore the fastest to reach maximum energy is likely to be used [17]. The lowest level of oscillation means that the first peaks of the signals are easier to pick up. Thus error due to false determination of the peaks can be minimised. Also, from the step pulse response, one can conclude the ability of the sensor to detect the electromagnetic signal emitted by the PD source. From the experiment, the TEM cell shows its ability to produce similar field at the TEM cell space thus produce constant impedance, 50 Ohm. The step pulse signal travel along the TEM cell space with only small bump due to difference between the calculated TEM cell impedance (around 51 Ohm) and the 50 Ohm termination installed at the receiver end of the TEM cell. This little bump almost no effect to the sensor response thus can be omitted.

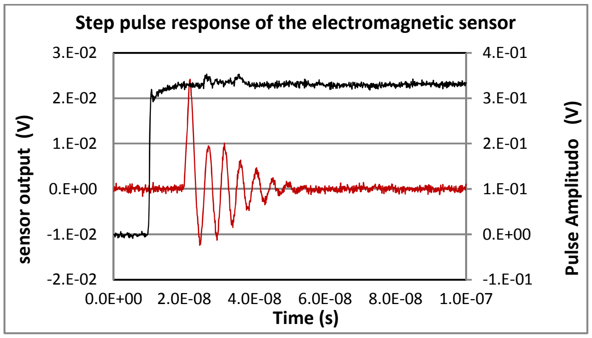

Figure-6. Step pulse response of the Log-spiral sensor.

CONCLUSIONS

The designed TEM cell has dimension of 1200mm length and 105 mm height and construct using alumina material. By using Maxwell electromagnetic field software, the field inside the TEM cell space is proven to be uniform thus able to be used to test an electromagnetic sensor. The TEM cell has a good capability to test the electromagnetic sensor as the step input shown has almost no disruption thus prove that the TEM cell has uniform impedance. The step pulse response of the electromagnetic sensor showed this TEM cell good capability.

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