Piezoelectric Sensor using PZT Material for Partial Discharge Detection on Power Transformer

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Abstract. This paper presents an analysis of acoustic emission (AE) detection technique for partial discharge (PD) on power transformer using piezoelectric sensor. The AE PD detection technique using piezoelectric material is one of the popular method due to its low cost and compact size. A matching resonant frequency of AE sensor with PD signal which in range 10 kHz to 300 kHz is an important factor for this technique. An AE sensor that have a resonant frequency match with PD signal able to give an optimal performance. Therefore, a simulation on different dimensions of lead zirconate titanate (PZT) AE sensor using finite element method (FEM) is conducted in order to determine the performances in terms of resonant frequency, total displacement and generated voltage. The length of AE sensor is varied from 2 mm to 30 mm in order to reveal the influence of length dimension against generated voltage. Based on the obtained results, that 2 mm length of AE sensor able to generate voltage of 3.01 x10⁻⁵ mV at resonant frequency of 113.58 kHz which can be proposed toward PD detection on the power transformer.

1. Introduction

Power transformer is one of important high voltage (HV) equipment in the power network. It is well-known that the power transformer comes with a risk of partial PD. PD is the major problem of power transformer due to the degradation and insulation breakdown [1,2]. Increasing age of equipment and damage of insulation is one of the causes that PD occurs. Therefore, an early stage to recognize the location of partial discharge is important before any interruption or failure that can cause significant damage [3].

PD detection technique can be classified into optical detection, chemical detection, electrical detection, electromagnetic detection and acoustic emission (AE) detection [4-8]. The AE detection technique one of the popular methods to record the PD signal that can be placed inside or outside the equipment. The acoustic signal produced by PD within a range of 10 kHz to 300 kHz can be detected for the identification of the AE source [9,10]. The ability to provide electromagnetic noise immunity is one of the significant advantages of this technique. Moreover, the critical strength of the AE detection technique includes their ability to measure the PD in on-line monitoring condition. On-line monitoring
does not need to disconnect the equipment when measuring and can be carried out the measurement operates in 24 hours [11-13].

One of the AE detection application is a piezoelectric sensor that converting the vibration of the acoustic signal due to mechanical strain into an electric signal proportional to the stress applied. A cantilever structure is typically preferred to a transducer mass and volume relationship because of the high electrical energy [14]. There are several types of piezoelectric materials such as zinc oxide (ZnO), aluminum nitrate (AlN) and PZT [15-17].

Several parameters of cantilever also must be considered to meet criteria of acoustic signal bandwidth and sensitivity for selecting the correct piezoelectric sensor. Thus, there are different length dimension of the cantilever are designed and simulated in this project.

2. Design of Structure
In this section, the importance of theoretical, geometry, material properties and design procedure has been discussed.

2.1 Theoretical
The theoretical expression for the moment of inertia, \( I \) can be written as:

\[
I = \frac{bh^3}{12}
\]  

(1)

where \( b \) is width, and \( h \) is the thickness of the cantilever. The well-used formula for calculating the spring constant of the cantilever, \( k \) can be expressed as:

\[
k = \frac{3EI}{L^2}
\]  

(2)

where \( E \) is young’s modulus and \( L \) is the thickness of the cantilever. In order to find the mass, \( m \) the following expression is used:

\[
m = \rho h L w
\]  

(3)

where \( \rho \) is resistivity, \( h \) is the thickness of cantilever, \( L \) is the length of the cantilever and \( w \) is the width of the cantilever. Using equation (2) and equation (3), the resonant frequency, \( f_{\text{res}} \) can be calculated according to the following equation:

\[
f_{\text{res}} = \frac{1}{\pi} \left( \frac{\sqrt{k}}{\sqrt{m}} \right)
\]  

(4)

2.2 Model Configuration
The AE sensor with cantilever model is set at one end shaded region with blue colour which called as fixed constraints and another side is free as shown in Figure 1. A layer of PZT-5H is used with the variation of length from 2 mm to 30 mm with 2 mm incremental, 30 mm width and 1 mm thickness.
2.3 Material Properties

PZT is a ceramic perovskite that gives a characteristic piezoelectric effect which is often used in practical application such as electro ceramics industry [18]. There are several types of PZT material such as PZT-51, PZT-52, PZT-53 and PZT-5H. All the PZT material have the same Poisson’s ratio but different in young’s modulus. The smaller the young’s modulus, the larger the displacement and energy generation due to the deflection of the material [19]. In this project, PZT-5H is selected because of lowest young’s modulus compared to another PZT material. Table 1 shows the properties of PZT-5H.

Table 1. Material Properties

| Material Properties       | PZT-5H          |
|---------------------------|-----------------|
| Young’s modulus, E (PA)   | $56 \times 10^9$|
| Density, $\rho$ (kg/m$^3$)| 7500            |
| Poisson’s Ratio           | 0.36            |

2.4 Design Procedure

The simulation is performed using FEM software. Two types of physics interfaces are used in this simulation which are solid mechanics and electrostatics. Boundary load, fixed constrain and piezoelectric material are declared in solid mechanics. While electrostatics assigned the ground, floating potential and charge conservation for the model.

There are two kinds of analysis used in this project. The first analysis used to evaluate the resonant frequency and another one is obtaining the total displacement and generated voltage of the cantilever.

3. Simulation Results

In this project, FEM simulation is used to analyze the resonant frequency, total displacement and generated voltage of AE sensor. The result is divided into two sections which are resonant frequency analysis and total displacement and electric potential analysis.

3.1 Resonant Frequency Analysis

The shape deformation and resonant frequency are demonstrated in Table 2.
Table 2. Different mode and shape of deformation with the resonant frequency.

| Mode | Shape of deformation | Frequency (kHz) |
|------|----------------------|-----------------|
| 1    | ![Mode 1](image1.png) | 0.532           |
| 2    | ![Mode 2](image2.png) | 1.293           |
| 3    | ![Mode 3](image3.png) | 3.252           |
| 4    | ![Mode 4](image4.png) | 4.107           |
| 5    | ![Mode 5](image5.png) | 4.690           |
| 6    | ![Mode 6](image6.png) | 8.144           |

These values of the simulation result were compared to the analytical result to validate the process. This was calculated as described in Equation 4. Due to bending behaviour for AE application, the first mode result is selected as the resonant frequency of the AE sensor [20]. Table 3 summarizes the result of analytical and simulation with the range of length used.
Table 3. The resonant frequency result for analytical and simulation for different model size.

| Size (mm) | Analytical (kHz) | Simulation (kHz) |
|-----------|------------------|------------------|
| 2 X 30    | 109.301          | 113.580          |
| 4 x 30    | 27.325           | 30.773           |
| 6 X 30    | 12.145           | 13.721           |
| 8 X 30    | 6.831            | 7.678            |
| 10 X 30   | 4.372            | 4.905            |
| 12 X 30   | 3.036            | 3.394            |
| 14 X 30   | 2.231            | 2.483            |
| 16 X 30   | 1.708            | 1.897            |
| 18 X 30   | 1.349            | 1.494            |
| 20 X 30   | 1.093            | 1.208            |
| 22 X 30   | 0.903            | 0.996            |
| 24 X 30   | 0.759            | 0.836            |
| 26 X 30   | 0.647            | 0.711            |
| 28 X 30   | 0.558            | 0.612            |
| 30 X 30   | 0.486            | 0.532            |

Figure 2 shows the influence of different length of AE sensor to resonant frequency that varied with 15 different lengths, starting from 2 mm to 30 mm with 2 mm separation.

![Figure 2. The variation of length against resonant frequency.](image)

From the plotted result, the resonant frequency is revealed to decrease when the length of cantilever dimension is increasing. As seen from equation (4), the resonant frequency is inverse to the square root of the mass.

3.2 Total Displacement and Electric Potential Analysis

Figure 3 shows the simulation deflection plot of 30 x 30 mm dimension cantilever, which obtains the displacement of $6.74 \times 10^{-8}$ μm.
Figure 3. Deflection plot of the cantilever.

Figure 4 shows the electric potential generated is high at the fixed end of the cantilever with a maximum value of $4.24 \times 10^{-5}$ mV for the cantilever with 30 x 30 mm dimension.

An overall summary of total displacement and electric potential with different size of cantilever are given in Table 4. The electric potential is the cumulative charge as a reaction to the mechanical strain [16].

| Size (mm) | Total Displacement (μm) | Electric Potential (mV) |
|-----------|-------------------------|------------------------|
| 2 X 30    | $2.69 \times 10^{-10}$  | $3.01 \times 10^{-5}$  |
| 4 x 30    | $1.15 \times 10^{-9}$   | $2.91 \times 10^{-5}$  |
| 6 X 30    | $2.32 \times 10^{-9}$   | $2.95 \times 10^{-5}$  |
| 8 X 30    | $3.99 \times 10^{-9}$   | $2.99 \times 10^{-5}$  |
| 10 X 30   | $6.04 \times 10^{-9}$   | $3.16 \times 10^{-5}$  |
| 12 X 30   | $8.58 \times 10^{-9}$   | $3.23 \times 10^{-5}$  |
| 14 X 30   | $1.18 \times 10^{-8}$   | $3.31 \times 10^{-5}$  |
| 16 X 30   | $1.59 \times 10^{-8}$   | $3.40 \times 10^{-5}$  |
| 18 X 30   | $2.03 \times 10^{-8}$   | $3.50 \times 10^{-5}$  |
| 20 X 30   | $2.56 \times 10^{-8}$   | $3.61 \times 10^{-5}$  |
| 22 X 30   | $3.14 \times 10^{-8}$   | $3.72 \times 10^{-5}$  |
| 24 X 30   | $3.83 \times 10^{-8}$   | $3.84 \times 10^{-5}$  |
| 26 X 30   | $4.79 \times 10^{-8}$   | $3.97 \times 10^{-5}$  |
| 28 X 30   | $5.60 \times 10^{-8}$   | $4.10 \times 10^{-5}$  |
| 30 X 30   | $6.74 \times 10^{-8}$   | $4.24 \times 10^{-5}$  |
From Table 4, it can be seen that the total displacement is increasing as the length of cantilever increase as plotted in Figure 5. While Figure 6 shows the relationship between length of cantilever and electric potential.

![Figure 5. Relationship between length and total displacement.](image)

![Figure 6. Relationship between length and electric potential.](image)

From the graph above, it is observed that the increasing length of cantilever would increase the total displacement and electric potential.

4. Conclusion
As to conclude, total displacement and generated voltage of proposed dimension PZT-5H AE sensor at PD signal frequency are successfully simulated using FEM approach. The dimension of 2mm length, 30mm width and 1mm thickness is the most suitable parameter which producing 113.580 kHz resonant frequency with electric potential of $3.01 \times 10^{-5}$ mV that could be used as an acoustic sensor for the partial discharge detection.
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References

[1] A. Z. Abdullah, M. N. K. H. Rohani, M. Isa, H. Hamid, S. N. M. Arshad, and M. Othman 2018 IEEE 7th International Conference on Power and Energy (PECon) (1) 405–408.

[2] S. H. K. Hamadi 2018 IEEE Student Conf. Res. Dev. Inspiring Technol. Humanit. SCOReD 2017 (2018) 451–455

[3] N. D. Roslizan 2020 J. Phys. Conf. Ser., (1432) 012004

[4] M. N. K. H. Rohani 2019 Int. J. Integr. Eng., (11) 237–243

[5] D. K. Mahanta and S. Laskar, 2016 “ABDU-Journal Eng. Technol (4) 142–145

[6] M. Siegel, M. Beltle, S. Tenbohlen, and S. Coenen, 2017 IEEE Trans. Dielectr. Electr. Insul. (24)

[7] Y B Wang, D G Chang, Y H Fan, G J Zhang, J Y Zhan and X J Shao 2017 IEEE Trans. Dielectr. Electr. Insul. (24) 3647–3656

[8] C. C. Yii, M. N. K. H. Rohani, M. Isa, S. I. S. Hassan, B. Ismail, and N. Hussin 2015 IEEE Student Conference on Research and Development, SCOReD 2015 345–350.

[9] N. A. Akashah, M N K Rohani, A S Rosmi, M Isa,, N Rosle, B Ismail and C L Wooi 2020 J. Phys. Conf. Ser. (1432) 012004

[10] A R Irfan, M Z M Zarhamdy, S M Sazli, P M A Asraf, N A Shuaib, and A Azlida 2019 AIP Conference Proceedings 2129 020180

[11] A. Z. Abdulllah, M. Isa, M. N. K. H. Rohani, S. A. S. Jamalil, A. N. N. Abdullah, and N. Azizan, 2019 Int. J. Power Electron. Drive Syst. (10) 2190

[12] M N K H Rohani, M Isa, M Syahril, C C Yyi, A S Rosmi and B Ismail, 2018 J. Phys. Conf. Ser., (1019) 1

[13] H Salaheddine, M M Isa, L M Ishak,N K H R Mohamad, C Y Chai, I Baharuddin, S Muhammad 2018 IEEE Student Conference on Research and Development: Inspiring Technology for Humanity, SCOReD 2017 (2018) 392–397

[14] C. Borzea and D. Comeaga 2019 3S Web Conf., 112

[15] M. Kabir, H. Kazari, and D. Ozevin, 2018 Sensors Actuators, A Phys.(279) 53–64

[16] A S Rosmi, S I Syed Hasan, Y Wahab and M Mazalan, 2015 Appl. Mech. Mater. (793) 407–411

[17] T Hang, J Glaum, Y A Genenko, T Phung and M Hoffman, 2016 Acta Mater. (102) 284–291

[18] K Srinivasa Rao, G Srinivas, M S Prasad, Y Srinivas, B Shudheer and A Venkateswar Rao, 2013 Am. J. Mater. Sci. (2) 179–184

[19] Q Sunder, Bakialakshmi 2014 International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, IJAREEIE (3) 8958–8965

[20] U. M. Jamain, N. H. Ibrahim, and R. A. Rahim, 2014 IEEE International Conference on Semiconductor Electronics, Proceedings, ICSE, 263–266.