

# The effects of drying time during manufacturing process on partial discharge of 83.3 mva 275/160 kv power transformer

*Siswanto*<sup>1</sup>, *Agus Indarto*<sup>1</sup>, *Radin Rahmatullah*<sup>1</sup>, *Chairul Hudaya*<sup>1,2\*</sup>

<sup>1</sup>Electric Power and Energy Studies, Department of Electrical Engineering, Faculty of Engineering University Indonesia, Kampus Baru UI Depok 16424, Republic of Indonesia

<sup>2</sup>Energy System Engineering, Faculty of Engineering University Indonesia, Kampus Baru UI Depok 16424, Republic of Indonesia

**Abstract.** Power transformer (PT), essential equipment in electrical power system proceeds complicated manufacturing process to meet high standard design. During manufacturing process of PT, the drying stage is of importance to remove excessive moisture contaminant on the solid insulation. This study investigated the effects of drying duration on partial discharge test of 83.3 MVA 275/160 kV PT. The partial discharge test measurements were carried out using IEC 60270 standards comprising of the capacitive network model based on the main quantity apparent charge concept. We found that the lowest partial discharge of 21 pC was achieved at 68 hours drying duration, while the highest value of 60 pC was reached at 81 hours drying time. The longer drying time may lead to initial degradation of cellulose insulation due to excessive heating. The amount of water extracted during drying effect to partial discharge also investigated. We conclude that the drying time at a higher and lower than 68 hours significantly contributes to the increased partial discharge values of PT.

## 1 Introduction

Power transformer (PT) constitutes a major portion of the capital equipment of the power grid and has significant role on the reliability of the power supply which heavily depends on the fault free-operation of transformer. The transformer failure rates have been found to follow “bathtub” curve composed of early infant mortality as the first stage. Infant mortality stage contributes to the extreme decreasing failure rate arising from imperfect material or lack of control process during manufacturing [1,2]. On the other hand, the statistical survey has shown that substantial portion of the transformer failures (~ 48%) are due to the failures on winding insulation system [2,3]. Thus, the transformer manufacturing process significantly determines the quality of the winding insulation and imposes the power transformer life.

Large power transformers (PT) proceed the complex design and take considerable time of complicated manufacturing process to meet tight standard design [4,5]. During this

---

\* Corresponding author: [c.hudaya@eng.ui.ac.id](mailto:c.hudaya@eng.ui.ac.id)

process, special attention must be given to the drying process to remove the excessive moisture contaminant from solid insulation. The solid insulation of PT is generally made of cellulose (C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>)<sub>n</sub> which is naturally hygroscopic [5]. It tends to excessively absorb additional moisture through exposure to humid environment especially on the tropical regions. The solid insulation shall be dried before it is impregnated with oil liquid insulation. In some cases, the excessive residual moisture is left on the insulation during drying process due to defect material, imperfect design or control process [5,6]. This residual moisture even in small quantity is extremely damaging for PT insulation, as it will reduce the dielectric withstand strength and accelerate the ageing process through chemical reaction which produces more moisture contents [6,7]. This phenomenon is also considered as the initial cause that lead to the partial discharge (PD) occurrence. The PD activity is classified as serious failure mode leading to the insulation breakdown failure [8]. It is therefore very important to keep the residual moisture to be very low concentration through the optimized drying duration during the manufacturing process.

In recent years, the increasing awareness on the transformer ageing have led the customers demanded the PT specifications with PD testing lower than the acceptance criteria of the internationally applicable codes and standards. To the best of our knowledge, there are no reports observing the effects of the drying duration on partial discharge of 83,3 MVA 275/160 kV power transformer. For this reason, the optimum drying time process to achieve lowest partial discharge testing was investigated. This paper will address the following research questions: (1) how many hours required for the drying time to achieve the lowest partial discharge testing value? (2) how is the relationship between the extracted water content, residual moisture and the partial discharge? (3) how to optimize the drying time of PT to achieve the efficient manufacturing process and fulfil the customer requirements on PD testing. These critical questions are utmost important for customer to keep the PD as the initial ageing prominent symptoms to a very minimum value and optimize the manufacturing process of PT, making the manufacturer easier to meet the expected delivery date.

## 2 Methodology

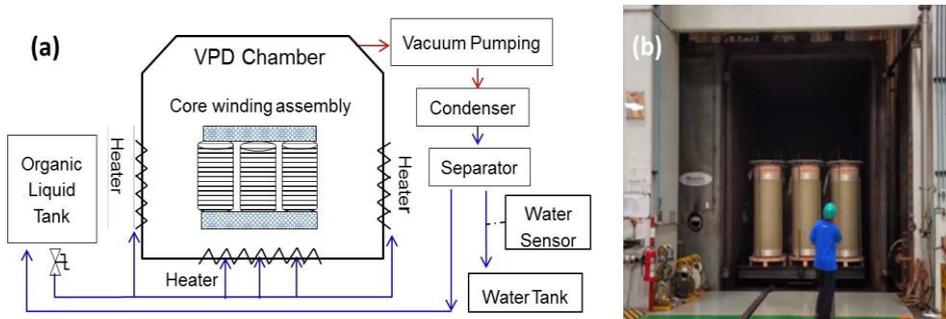
In this study, six (6) identical and newly developed PTs with specification shown on the table 1 were investigated and tested at the factory, in Indonesia. We used the study cases emphasizing the drying process and partial discharge testing during the manufacturing process.

**Table 1.** Power transformer specification

Description	value	units
Nominal rating	83.3	MVA
Voltage rating	275/160	kV
Group Vector	Dyn11	-
Number of phase	1	-
Frequency	50	Hz
Impedance	14.5	%
Solid insulation weight	~3500	kg

### 2.1 The drying process during manufacture

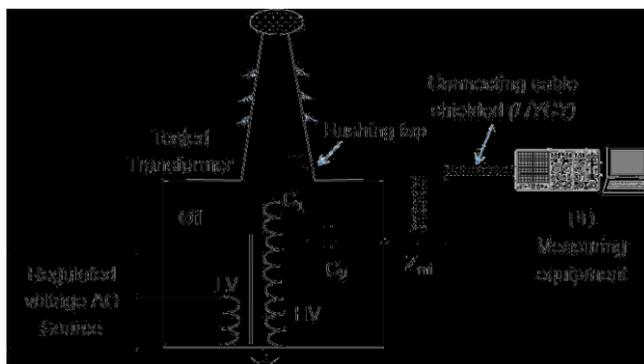
In our experimental work, the vapor phase drying (VPD) method was employed to remove the moisture contaminant within the cellulose insulation, as shown in Figure 1 [9]. Briefly, the method combines heat and vacuum-based apparatus simultaneously to achieve faster and more efficient drying process. A special vapor of organic liquid with elevated temperature of 110°C was used as heat precursors. When the hot vapor circulated over the winding assemblies, it would transfer heat to the solid insulation parts until the moisture of winding insulation was removed by mass diffusion from inner layer to the outside surface of insulation, evaporated as water vapor. The water vapor and condensed organic liquid taken out by vacuum pumping system was then condensed and the separated organic liquid was recirculated on the next drying cycle. By lowering the pressure of the VPD chamber and maintain constant heating temperature, it allowed water to evolve from liquid to vapor state reducing the required thermal energy. The vacuum pressure was set to  $10^{-3}$  bar.



**Fig. 1.** (a) VPD chamber for drying process during manufacturing of the power transformer. Figure is redrawn from [9] with some adjustment according to PT manufacturer VPD facility, (b) Photo of real VPD chamber for drying the power transformer.

### 2.2 Methods for partial discharge testing

The PD testing and measurements were carried out in compliance with IEC 60270 standard [10]. The PD was modelled as a capacitive network based on the apparent charge concept, known as ABC model.



**Fig. 2.** PD testing circuit with bushing tap coupling method,  $C1$  = bushing capacitance,  $C2$  = capacitance between bushing with grounding,  $Z_{mi}$  = measuring input impedance. Figure is redrawn from [11] with some adjustment.

Bushing tap coupling method was used to connect the measuring impedance between earthed transformer tank and bushing tap terminal. The commercial PD measuring equipment Omicron MPD 600 is connected to the terminal through the shielded coaxial cables (LiYCY) to measure and record PD. A gradually raise of AC voltage up to ~325 kV was applied across the low voltage (LV) winding, following the test voltage procedure stipulated on the IEC-60076-3 [11]. The circuit configuration test set-up for an induced voltage test of PT using bushing tap coupling method for PD measurement is shown in Figure 2.

### 3 Results and discussion

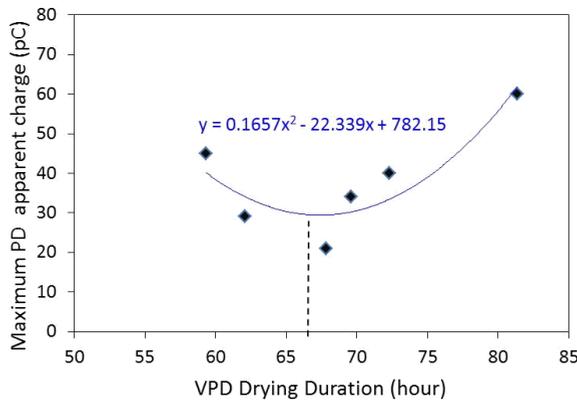
#### 3.1 Effects of drying period on the partial discharge

The drying period represents the accumulation of thermal energy involved in the heat transfer mechanism absorbed by solid insulation. It must remove the excessive water contaminant without degrading the cellulose properties due to excessive heating. The moisture diffusion inside cellulose structure was a very slow process which can be modelled by Fick's law

$$\frac{\partial c}{\partial t} = D(C, T) \frac{\partial^2 c}{\partial x^2} \tag{1}$$

where  $D(C, T)$  is the moisture diffusion coefficient in solid insulation ( $m^2/s$ ),  $C$  is the local moisture concentration ( $mol/m^3$ ) and  $T$  is the temperature ( $^{\circ}C$ ). The PTs have different drying period ranging from 59-82 hours depending on the water extraction rates. Figure 3 shows the relationship between maximum partial discharge apparent charge magnitude and different drying period. The PD testing results at drying duration both shorter and longer than 68 hours exhibited an increase trend. Polynomial regression analysis is applied to find the optimum drying time as follows:

$$\frac{\partial y}{\partial x} = \frac{\partial(0.1657x^2 - 22.339x + 782.15)}{\partial x} = 0 \tag{2}$$



According Lawson *et al.*, the excessive thermal energy lead to initial ageing processes which cause physico-chemical structure changing on the cellulose insulation material [12].

**Fig. 3.** PD apparent charge test result with different drying period

The excessive drying thermal energy accumulations absorbed by cellulose solid insulation have adverse effect on cellulose structure as it will break the polymer chain and decrease the degree of polymerization value. The shortened polymer chain will reduce the physical properties of the cellulose insulation then reduce the PD inception voltage. Thus, the PD apparent charge tests increase as initial ageing symptom at the drying period longer than the optimum time. While the drying time less than 68 hours does not have enough thermal energy to remove the excessive residual in the solid insulation, which leads to the increasing PD apparent charge result.

### 3.2 Effects of water extraction on partial discharge

In principle, the water moisture is conductive material which has low resistivity so that easily conduct the electric charge. We found that the highest PD test result achieved at the water extraction of 146 gram, while the lowest PD test result reached at the water extraction of 2,232 gram. The amounts of water extracted during drying process determine the insulation residual moisture condition and have inverse proportional with PD test result as the residual moisture will increase the apparent charge conductivity, as reported by Suleiman and colleagues [13]. They found that the conductivity of kraft paper cellulose insulation increase proportionally with the moisture content values, depending on the dielectric response polarization dan depolarization current measured. Similar finding was also observed in [14], in which the surface partial discharge on the oil impregnated paper increased in linear with the moisture content during the experimental works. Figure 4 shows the relation between amounts extracted water content with PD apparent charge test results.

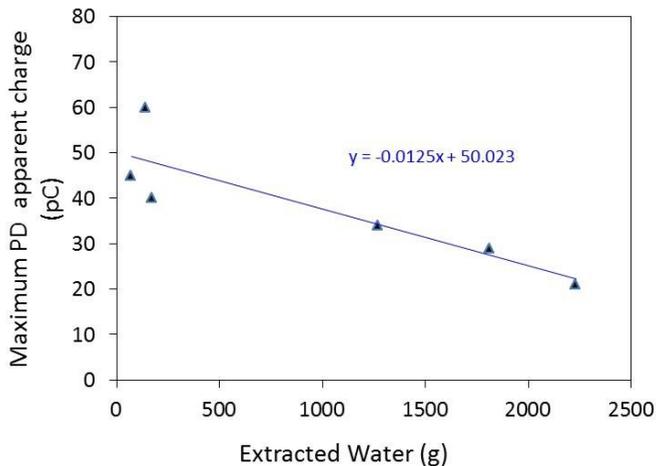


Fig. 4. PD apparent charge test result with different water extraction.

## 4 Conclusions

The effects of drying time and extracted water content during manufacturing process on partial discharge of 83.3 MVA 275/160 kV power transformers have been investigated. We found that the two process parameters significantly affected to the PD results. We observed that the lowest partial discharge of 21 pC was achieved at 68 hours of drying duration, while the highest value of 60 pC was reached at 81 hours of drying time within the acceptance criteria. Using polynomial regression, it was concluded that the optimum time

was 67.4 hours. The longer drying time might lead to the cellulose initial degradation due to accumulated excessive heating, meanwhile the shorter drying period than optimum one might not effectively remove the excessive residual moisture content which tend to increase the PD values. The amounts of water extracted during drying process determine the insulation residual moisture condition and have inverse relationship with PD results, since the residual moisture content would increase the apparent charge conductivity. We conclude that the drying time at a higher and lower than 67.4 hours significantly contributes to the increased partial discharge values of PT. The future research could be focused on the effect of the other parameters i.e. impregnation pressure, solid insulation press-board forming to investigate the dominant parameter affecting the partial discharge testing.

## Acknowledgments

The authors would like to thank the financial support provided by Universitas Indonesia through the 2018 PITTA funding scheme managed by Directorate Research and Community Engagement (DRPM) Universitas Indonesia.

## References

1. V.I. Kogan et al., "Failure analysis of EHV transformers", *IEEE Transaction on Power Delivery*, **3**, 672 (1988)
2. S. Tenbohlen, J. Jagers, F. Vahidi, "Standardized survey of transformer reliability", *Conference Preceeding of ISEIM*, 593 (2017)
3. Daniel Martin, Judith Marks, Tapan Saha, "Survey of Australian PT failures and retirements", *IEEE Electr. Insulation*, **33**, 16 (2017)
4. D.J. Allan, A. White, "Transformer design for high reliability", *IEE Power Engineering Jurnal*, **5**, 66 (1995)
5. James Harlow, *Power Transformer Engineering* (CRC Press, Boca Raton, 2012)
6. J. Gielniak et al., "Moisture in cellulose insulation of power transformers – statistics", *IEEE Trans. on Dielectric and Elect. Insulation*, **20**, 982 (2013)
7. CIGRE Working Group A2.30, "Moisture equilibrium and moisture migration within transformer insulation systems", Technical Brochure no 349 (2008)
8. Peter H.F Morshuis, "Degradation of solid dielectric due to internal PD: some thought on progress made and where to go now", *IEEE Trans. on Dielectric and Elect. Insulation*, **12**, 905 (2005)
9. LE Feather, "Drying and oil impregnation of PT insulation", *IEEE Elect. Insulation Conference*, no. 32C3-8 (1965)
10. IEC 60270, *HV test techniques - Partial discharge measurements*, (2000)
11. IEC 60076-3, *P.T.- 3: Insul. levels, dielectric tests and ext. clearances in air*, (2013)
12. W.G. Lawson, M.A. Simmons, P.S. Gale, "Thermal ageing of cellulose paper insulation", *IEEE Tran. on Elect. Insulation*, **12**, 61 (1977)
13. A.A. Suleiman et al, "Moisture effect on conductivity of kraft paper immersed in PT vegetable based insulation oils", *IET Generation, Transmission & Distribution*, **11**, 2269 (2017)
14. Lianwei Bao et al., "Influences of moisture content on surface PD behaviors of OIP insulation under pulsating DC voltage", *IEEE HV Eng. And Application*, (2016)