Loading Effect with Distributed Generation (DG) Injection on Distribution System on Temperature and Breakdown Voltage of Oil Transformer in Distributed System

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Abstract. Increasing of load demand causes the greater electrical power needed. When the transformer operation in overload conditions and hottest-spot temperature, it will accelerate the aging and failure in oil insulation of transformer. Application of distributed generation (DG) can provide the additional electrical power supply to the loads (household). So that, it can relieve the workload power transformer and reduce the acceleration of aging in oil insulation of transformer. This research will analysed the effect of loading capacity with DG injection using a PV generator on the condition of oil insulation on 150/20kV of electricity distribution system using ETAP software. Tests of this research are carried out on 24 hours of loading conditions on the distribution system. The calculation of isolation oil temperature was carried out using a mathematical formula according to the IEEE, and oil insulation would be tested with a breakdown voltage (BDV) test.

1. Introduction

The increasing of electrical power needed in electric power system will be affected for the performance of the power transformer which is the main component of the electrical power supplier. When the operation of transformer in overload conditions, it will be causes the transformer operation at the highest of heat point and overheating during the transformer operation. Thus, it will accelerate the aging and breakdown on transformer insulation system. In addition to loading capacity patterns, other factors that affect the life operation of power transformer and aging of isolation system are ambient and oil temperature, load losses and oil quality. Overloading and losses will be causes the temperature rise until reaches the hot-spot temperature during the operation of transformer and decreases the quality of oil isolation system. In this study, loading capacity is carried out in 24 hours of load consumption.

The application of distributed generation (DG) system is expected to overcome the problem of increasing the demand and fluctuating of loads on the electricity distribution system. DG is used for supply the additional power to the load that has increased in number due to increase the demand for the amount of electrical power that occurs at the certain hours every day. DG installation has a significant impact on the distribution system power flow, voltage profile, reduce power losses and increase the reliability of electrical power supply. The effect of DG application on loading of transformer and heat level caused by transformer can be identified by calculating the increase of oil temperature ($\theta_o$) to reach the oil hot-spot temperature ($\theta_h$) of the transformer insulating oil. Calculation of isolation oil temperature was carried out using mathematical formulation based on the standards of IEEE, and the isolation oil will be tested with breakdown voltage (BDV) test to identify the transformer isolation oil condition based on loading capacity and oil breakdown voltage.

For this study, PV location and PV power generation were performed at PV penetration levels of 5%, 15%, 25%,... (at 10% rate step) from the peak load. PV power injected on bus 5 connected to transformer of 50 MVA which supplies to 13 feeders. Current flow on transformer and losses on the system were recorded for each simulation using ETAP software to be parameter of hot-spot calculation and breakdown voltage test. This process and test system will described in section 2-3, and the results are presented in section 4.
2. Basic Consideration of DG Injection and Oil Heating Temperature

2.1 Distributed Generation (DG) Installation

DG is a small-scale generator or such as micro grid in the distribution network that has an impact on load loss by changing the power flows and voltage profiles. The injection of DG location is a direct connection to the network or connected to the feeder. Based on paper [1] and [2], PV installations reach 350 MW to 600 GW by 2010 to 2050. Chinese Electric Power Research Institute made the forecasts of renewable energy installations will account for 30 – 50% of the total electric power of distribution system or using the penetration level.

The linkages effect of DG installation on transformer performance is illustrated when the transformer initial conditions supply the peak load on the electric distribution system, it will causes the transformer loading reach the maximum capacity and the current flowing in the transformer will be even greater. Then, it will be increasing the heat into hot-spot temperature in the tank that generated during the transformer operation and generate the power losses. When the PV generator as a DG is installed on the secondary side of the power transformer, the DG will supply additional power to the load, so will be reducing the maximum capacity of the transformer loading and decrease the current installed on the secondary side of the power transformer, the DG will supply additional power to the transformer operation system. Thus, it will be decreasing the heat temperature on the transformer windings and losses will be smaller. So that, here the DG is able to reducing power losses and oil hot-spot temperature rise in the transformer operation system.

2.2 Transformer Losses

Transformer designed as a supplier of the required electrical power at a different voltage level. Transformers are generally operated in full-load conditions and at maximum efficiency with minimum losses at fundamental frequency. Transformer losses are generally classified into no-load losses and load losses. Where, \( P_{\text{TL}} \) is total loss, \( P_{\text{NL}} \) is no-load loss, and \( P_{\text{L}} \) load loss which classified into copper loss (\( P_{\text{cu}} \)) and core loss (\( P_{\text{h}} \)). Copper loss is caused by the load current flowing to windings depends on the load changes. Core loss (\( P_{\text{h}} \)) is caused by the hysteresis loss (\( P_{\text{h}} \)) and eddy current loss (\( P_{\text{EC}} \)).

2.3 Hot-spot Temperature as Function of Time

Hot-spot temperature is the highest temperature on the oil and winding of transformer which the most significant parameters to determine the transformer life based on the specified in the standards of IEEE and IEC 60076. In the transient conditions, hot-spot temperature \( \theta_h \) is described as a function of time which depends on the change of time or in different conditions, the load current and temperature also varies. In the transformer operation system, oil insulation will run into stress or pressure. The factors of stress for a long term can be affected to the aging in the electric insulation system and the higher hot-spot temperature rise of windings of transformer at load factor \( K \). Thus, the calculation of oil temperature as a function of time \( \theta_o(t) \) is shown in Equation (2.3) [2]:

\[
\theta_o(t) = \Delta \theta_o + \left[ \Delta \theta_o \left( \frac{1 + R K^2}{1 + R} \right)^t - \Delta \theta_o \right] f_1(t) \tag{2.3}
\]

Where, \( \theta_o(t) \) is Oil temperature with corresponding to a load factor, \( \Delta \theta_o \) is Top-oil temperature rise in the tank at the start, \( R \) is Load Ratio of load loss to no-load loss, and \( f_1(t) \) is the increasing of oil temperature rise is shown in Eq. (2.4) [6]:

\[
f_1(t) = \left( 1 - e^{-\frac{t}{\tau_{11}}} \right) \tag{2.4}
\]

Hot-spot temperature rise \( \Delta \theta_o \) based on the time change is as shown by following Eq. (2.5) [2]:

\[
\Delta \theta_o(t) = \Delta \theta_o + \left[ H \cdot g_1 \cdot K^2 - \Delta \theta_o \right] f_2(t) \tag{2.5}
\]

Where, \( f_2(t) \) is an increasing of gradient from the difference of hot-spot temperature rise and top-oil temperature rise, and shown in Eq. (2.6) [6]:

\[
f_2(t) = k_{21} \left( 1 - e^{-\frac{t}{\tau_{22}}} \right) - (k_{21} - 1) \left( 1 - e^{-\frac{t}{\tau_{22}}} \right) \tag{2.6}
\]

Where, \( \tau_{22} \) is time constant of winding transformer, \( \tau_{21} \) time constant of average oil transformer. When there is the decreasing of load, oil temperature \( \theta_o \) and the windings temperature \( \theta_w \) in the tank will be decrease. Thus, the oil temperature \( \theta_o(t) \) can be calculated in Eq. (2.7) [2]:

\[
\theta_o(t) = \left[ \Delta \theta_o \cdot \left( \frac{1 + R K^2}{1 + R} \right)^t \right] + \left[ \Delta \theta_o - \Delta \theta_o \right] f_3(t) \tag{2.7}
\]
Where, $\Delta \theta_{o,r}$ is top-oil temperature rise at the rated current, $x$ is Exponent factor of oil based on cooling method, and $f_3(t)$ is a decreasing of gradient from the difference of top-oil temperature rise and ambient temperature, and shown in Eq. (2.8) [6]:

$$f_3(t) = e^{x \frac{t}{k_{11} \tau_{o}}}$$ (2.8)

Where, $k_{11}$, $k_{21}$, $k_{22}$ is the thermal model constant as function of time. The hot-spot temperature rise at rated loss $\Delta \theta_h(t)$ is given by following the Eq. (2.9) [6]:

$$\Delta \theta_h(t) = H \cdot g_r \cdot K^y$$ (2.9)

The overall or total hot-spot temperature $\theta_h(t)$ equation based on increasing and the decreasing of loads represented by following Eq. (2.10) [6]:

$$\theta_h(t) = \theta_{a} + \theta_{o}(t) + \Delta \theta_h(t)$$ (2.10)

Where, $H$ is Hotspot factor ($H = 1.3$ for power transformer), $g_r$ is the gradient of average windings temperature to the average oil transformer at rated load, and $y$ is exponent factor of windings based on cooling method. The estimation of hot-spot temperature calculation that according to the step functions of time above is called as exponential solution. Based on the standards of IEC 0076 the exponential solution is calculated using the constant parameter as shown in Table 2.1 [6].

| Symbol | ONAN | ONAF | OF | OD |
|--------|------|------|----|----|
| Oil exponent ($x$) | 0.8 | 0.8 | 1.0 | 1.0 |
| Winding exponent ($y$) | 1.6 | 1.3 | 1.3 | 2.0 |
| Constant ($k_{11}$) | 1.0 | 0.5 | 1.0 | 1.0 |
| Constant ($k_{21}$) | 1.0 | 2.0 | 1.3 | 1.0 |
| Constant ($k_{22}$) | 2.0 | 2.0 | 1.0 | 1.0 |
| Time constant ($\tau_{o}$) | 180 | 150 | 90 | 90 |
| Time constant ($\tau_{w}$) | 4 | 7 | 7 | 7 |

Source: IEE Guide for Loading Mineral Oil-Immersed Transformers

2.4 Standard of Loading Transformer Temperature

Based on the standard of ‘IEEE Guide for Loading Mineral Oil-Immersed Transformer’, there is standard limit for load and temperature of transformer loading capacity. When the transformer loaded in normal conditions, the hot-spot temperature limit is 98°C. When the transformer loaded over the rated power with the temperature rise of 65°C, the top-oil temperature rise should be at 110°C, conductor hot-spot temperature rise at 180°C, and the maximum total loading capacity for transformer is 200%.

3. Simulation and Calculation

3.1 Data of Transformer Specification

In this study, the system test applied using 2 transformers as shown in Table 3.1.

| Transformer 50 MVA | Transformer 60 MVA |
|-------------------|-------------------|
| Classification    | Specification     | Classification | Specification     |
| No-load           | 62.5 kW           | No-load        | 75 kW            |
| Rated Voltage     | 150 kV/ 20 kV     | Rated Voltage  | 150 kV/ 20 kV    |
| Rated Current     | 206/ 1443 A       | Rated Current  | 231/ 1732 A      |
| Rated Capacity    | 3 phase, 50Hz     | Rated Capacity | 3 phase, 50Hz    |
| Impedance         | 9.2 %             | Impedance      | 10.3 %           |
| Type Core         | Shell             | Type Core      | Shell Dia B      |
| Cooling Method    | OFAF/ ONAN/ ONAF  | Cooling Method | ONAN/ ONAF       |
| Standard of       | Top-Oil : 53°C    | Standard of    | Top-Oil : 55°C   |
| Temperature Rise  | Winding : 58°C    | Temperature Rise | Winding : 60°C   |

3.2 Loading Capacity in Wonokromo Substation

In this study, will discusses the PV installation system effect and temperature calculation on the oil temperature rise at 24 hours of loading transformer on the Wonokromo Substation 150/ 20 kV which
supplied of transformer 50 MVA connected to 13 feeder and 60 MVA connected to 4 feeder. Then, the fluctuation of load and hot-spot temperature in the tank will be tested to identify the breakdown voltage (BDV) of the transformer oil insulation. Figure 3.1 indicates the loading data includes of residential and industrial.

3.3 Current Flowing in Transformer

The calculation is taken from sample of transformer loading capacity of \( P = 21.84 MW \) which supplied by transformer 1 of \( S = 50 MVA \). Maximum current flowing on the windings of transformer 1 (\( I_{FLA} \)) and current flowing at rated load is calculated below:

\[
I_{FLA} = I_{FLA \ prim.} + I_{FLA \ sec.} = \frac{S}{\sqrt{3} \times kV \ prim.} + \frac{S}{\sqrt{3} \times kV \ sec.} \tag{3.1}
\]

\[
I_{rated \ load} = I_{FLA} \times \%loading \ TR \tag{3.2}
\]

3.4 Losses in Transformer

Losses calculation in transformer is determined from the resistance \( R \) and current flowing (\( I_{rated \ load} \)) in primary and secondary windings as shown in equations below:

\[
Z_{base \ (ohm)} = \frac{kV^2}{MVA} ; \quad R_{real \ (ohm)} = R_{(pu)} \times Z_{base} \tag{3.4}
\]

In this study, the calculation of losses is determined from the total copper loss of primary and secondary windings as shown in Equation (3.5):

\[
P_{cu} = (lp^2 \cdot R) + (ls^2 \cdot R) \tag{3.5}
\]

The other losses is from the core loss includes the eddy current loss (\( P_{EC} \)) and hysteresis loss (\( P_h \)). The total transformer loss is:

\[
P_{LL} = P_{cu} + P_{EC} + P_h \tag{3.6}
\]

3.5 Average of Winding Temperature Rise

Hot-spot temperature rise determined with the gradient of average winding temperature (\( \Delta \theta_w \)) and top-oil temperature rise in the tank at the start (\( \theta_o \)). \( \Delta \theta_w \) is calculated as shown in equation below:

\[
\Delta \theta_w = \frac{R_{2-winding}}{R_{1-winding}} (235 + \theta_o) - 235 \tag{3.7}
\]

Where, \( R_1 \) is the resistance at start, \( R_2 \) is the resistance at loss load (shutdown test), and constant of 235 is the winding correction factor for copper.

3.6 Top-Oil and Hot-Spot Temperature

Calculation of top-oil temperature is determined by load factor (\( K \)) and losses ratio (\( R \)) as shown in below:

\[
K = \frac{Load \ at \ time - n}{Transformer \ rated \ load} ; \quad R = \frac{Total \ load \ loss}{no-load \ loss} \tag{3.8}
\]
The average of oil temperature $\theta_o(t)$ can be calculated corresponding the increases and decreases of loading capacity as explained in Equation (3.9):

$$
\theta_o(t) = \left[ \Delta \theta_o \cdot \frac{1 + R \cdot \Delta t}{1 + R} \right] + \left[ \Delta \theta_o \cdot \frac{1 + R \cdot \Delta t}{1 + R} \right] x \left( e^{-\frac{t}{\tau_{\Delta t}}} \right)
$$

(3.9)

The hot-spot temperature rise correspond the constant of $H=1.3$ and $y=1.6$, is shown below:

$$
\theta_h(t) = \theta_o + \theta_o(t) + H \cdot g \cdot y
$$

(3.10)

3.7 PV Installation using ETAP

In this distribution system of Wonokromo Substation as shown in Figure 3.2, the determination of PV power injection based on PV profile is 5%, 15%, 25%,... (with the rate step of 10%) from the peak load. PV power injected on bus 5 connected to 13 feeders. Figure 3.3 indicates PV power injection based on daily load and actual PV profile, when the peak load is 33.52 MW on bus 5. PV power injection is carried out during the certain hours when the beginning of sun rises until evening or increasing load into peak load which occurs from 6 a.m. to 6 p.m. includes the residential and industrial load.

![Figure 3.2 Single Line Diagram of Substation](image)

![Figure 3.3 Daily Load Consumptions and PV Profile](image)

3.8 Oil Heating and Breakdown Voltage (BDV) Test

Heating oil insulation in the oven is applied to reducing the water content in the oil and generates the maximum value of oil BDV. Oil insulation heated at a fluctuating temperature per day in a week. Parameter of temperature is from the hot-spot ($\theta_h$) calculation without and with PV injection.
Breakdown voltage (BDV) test applied to identify the existence of contaminants and characteristics of oil transformer. The injection of testing voltage is 100kV AC, and the distance between two electrodes is 2.5mm. Based on the standard of IEC, when BDV value is >50kV, indicates a high dielectric strength of oil and the BDV value is <40kV, indicates the existence of contaminants and low oil quality.

4. Test Result and Analysis

4.1 Current and Losses on Distribution System

Current flowing in transformer and losses generated on network system are equivalent with the loading capacity. The higher of loading capacity, generates the greater of current flow and losses on distribution system. Thus, in this case is analysed the effect of DG power injection for current flow and losses on Wonokromo Substation 150/ 20 kV.

Figure 4.1 Current Flows in Transformer

![Figure 4.1 Current Flows in Transformer](image1)

Figure 4.2 Losses on Substation System

![Figure 4.2 Losses on Substation System](image2)

Figure 4.1 and 4.2 indicates the decreasing of current flow in transformer 1 (50 MVA) and losses on distribution system after injected by PV generator. The highest of current in normal system at load of 33.51 MW which supplied by transformer 1 (50 MVA) is 1150.9 A and after injected by PV power, the current flow ($I_{TR}$) decrease into 50% that is 579 A. While, there is no significantly changes in transformer 60 MVA between normal system and after PV injection. The current flow in normal system is 985.1 A and after injected by PV, the ($I_{TR}$) current flow decrease up to 984.7 A. This caused by the PV injection applied on bus 5 connected to transformer 50 MVA which supplies 13 feeder. Thus, there is no effect on transformer 2 (60 MVA). Figure 4.2 indicates the highest loss ($P_{loss}$) in normal system is 0.926 MW at total load of 62.27 MW. The decreasing of losses after injected by PV into 30% that is equal to 0.601 MW. In figure above, can be seen that after the deactivated of DG injection at 7 p.m.,
there are increasing of transformer current flow \( (I_{TR}) \) up to 1153.8 A, and increases losses on the system \( (P_{loss}) \) up to 0.851 MW.

![Figure 4.3 Top-Oil Temperature](image1)

**Figure 4.3 Top-Oil Temperature**

![Figure 4.4 Hot-Spot Oil Temperature](image2)

**Figure 4.4 Hot-Spot Oil Temperature**

Figure 4.3 and 4.4 indicates the comparison of top-oil and hot-spot temperature in normal system and after injected by PV generator. Top-oil temperature \( (\theta_o) \) in normal system of transformer 1 (50 MVA) at 12 p.m. is 29.37°C and after injected by PV, the decreasing of top-oil is 15.0°C. While, after the deactivated of DG injection at 7 p.m., top-oil is increase up to 28.32°C. While, in transformer 2 (60 MVA), top-oil temperature \( (\theta_o) \) in normal system is 21.25°C and \( \theta_o \) after injected by PV is 18.21°C.

Figure 4.5 indicates the hot-spot temperature \( (\theta_h) \) which is the hottest spot of oil transformer. The decreasing of oil temperature is equivalent as the decreasing of current and losses after DG injection by PV generator. The highest of hot-spot temperature \( (\theta_h) \) of transformer 50 MVA is occurs at 12 p.m. The \( \theta_h \) in normal system is 71.50°C and \( \theta_h \) after injected by PV generator is decreasing up to 20%, which is 53.3°C.

In transformer 2 (60 MVA), there is no significantly changes in hot-spot temperature \( (\theta_h) \). After the DG power injection deactivated at 7 p.m., the \( \theta_h \) increase up to 56.8°C. This is caused after the substation system injected by DG, current flow on transformer and losses on the substation will be decreasing. Thus, it will affect to the decreasing of winding temperature \( (\theta_w) \), top-oil \( (\theta_o) \), and hot-spot temperature \( (\theta_h) \) of transformer oil insulation. In transformer 2 (60 MVA), there is no significantly changes in hot-spot temperature \( (\theta_h) \). The \( \theta_h \) in normal system at 12 p.m. is 57.9°C and after injected by PV is only decreasing up to 54.9°C. In addition from the influence of ambient temperature \( (\theta_a) \), this is caused by the DG injection is only applied on bus 5 connected to transformer 50 MVA. Thus, the decreasing of oil insulation is only significantly changes in transformer 1 (50 MVA).
4.2 Breakdown Voltage (BDV) of Oil Insulation

In this study, oil BDV tested in temperature change as shown in Table 4.1.

| No. | $\theta_h$ (°C) | BDV (kV) | Description                      |
|-----|-----------------|----------|----------------------------------|
| 1   | 46              | 70.9     | Temp. change per 1 hour (for a week) |
|     | 57              |          |                                  |
| 2   | 46              | 69.2     | Temp. change per 3 hour (for a week) |
|     | 57              |          |                                  |
| 3   | 46              | 67.8     | Temp. change per 5 hour (for a week) |
|     | 57              |          |                                  |

![Figure 4.5 Oil Heating Temperature Change Per Hours](image)

In this case, for identify the temperature of transformer oil on the characteristics of oil quality and failure of oil insulation is using BDV test. From the figure above, can be seen that the temperature of oil heating changed per 24 hours (for a week) is generates the lower of BDV value of 59.6 kV. When the temperature change of 46°C and 57°C changed per 5 hours (for a week) generates the BDV of 67.8 kV, when the temperature changed per 3 hours (for a week) generates the BDV of 69.2 kV, when the temperature changed per 1 hour (for a week) generates the BDV of 70.9 kV. This is caused by the longer time and the higher of oil heating temperature (within standard of < 98°C), will be reducing the water content in the oil. Thus, it will be generates the greater of oil breakdown voltage (BDV).
5. Conclusion

The injection of DG system using PV generator to the bus of distribution system can cause the decreasing of power losses on the system and current flow on transformer operation system. Scenario of location and PV power injection are influencing the decreasing of losses capacity on the daily load consumptions. In this paper, several researches have been noted when considering the maximum PV penetration to the decreasing of power losses on the distribution system of 150/20kV and maximum penetration was nearly above 60%. In this case, the location of DG injection is applied on bus 5 connected to the transformer 50 MVA which generates the higher losses and the maximum penetration applied on the system is 50% (for normal loading capacity).

The highest of current in normal system at load of 33.51 MW supplied by transformer 50 MVA is 1150.9 A and after injected by PV power, the current flow decrease into 579 A. While, there is no significantly changes in transformer 60 MVA between normal system and after PV injection. The current flow in normal system is 985.1 A and after injected by PV, the current flow decrease into 984.7 A. The highest loss in normal system is 0.926 MW at total load of 62.27 MW and after injected by PV, the decreasing of losses into 0.601 MW.

Injection of PV power on the system is decreasing the current flows in the transformer and losses on the system. Thus, it will be equivalent with the decreasing of hot-spot oil temperature and the BDV of oil insulation. The highest of hot-spot temperature ($\theta_h$) of transformer 50 MVA is occurs at 12 p.m. The $\theta_h$ in normal system is 71.50°C and $\theta_h$ after injected by PV generator is decrease into 53.3°C. After the DG power injection deactivated at 7 p.m., the $\theta_h$ increase up to 56.8°C. The hot-spot temperature is taken for oil heating parameter. The longer time and the higher of oil heating temperature (within standard of < 98°C), will be reducing the water content in the oil. Thus, it will be generates the higher of oil breakdown voltage (BDV).

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