The study of sweep frequency response analysis for inspecting the performance of transformer

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Abstract. Transformer had been widely used for supplying electric power to many motors, such as electric pump, fans, or conveyors. The motor voltage may vary that is depending on its power and speed between one to another motor. The load needs the transformer which generate the proper voltage. Unfortunately, the working performance of transformer is slowly decreasing because of its daily operation. The repetition of the transformer technical assessment by observing the transformer performance is needed. This study provides the periodical inspection of high-power transformer in maintenance and outage condition in the one of utility sites in Indonesia. The checking activity maintenance the eligible performance of the user device. The measurement of Sweep Frequency Response Analysis (SFRA) in the 5th unit had been inspected once in every six years. The measured result was obtained in 2007 and 2013. SFRA test diagnoses the characteristics of transformer winding and core by injecting low voltage at a certain frequency. If SFRA diagnoses the winding fault, then the transformer should be replaced or should get a major maintenance. The result of SFRA measurement provides the transformer winding and core still in a good condition because the shrinkage does not exceed 20% of its standard percentage. Therefore, the 500 kV power transformer, located in PT. YTL East Java, does not have to get serious maintenance.

1. Introduction

Performance of the transformer in a distribution power system should be in a good condition for increasing reliability transformer which followed standard. A method for knowing performance of transformer is electromagnetic vibration analysis[1]. It can detect the flux leakage and electromagnetic force under the short circuit fault. This method still needs acceleration sensor for checking the unusual vibration to the windings. Next test for knowing the performance of the transformer is Short–Circuit Impedance (SCI) test[2]. This method is simply comparing between actual voltage and current with the nominal voltage given by the factory. By doing a short circuit impedance test, the result only gives information about the winding at power frequency. Unfortunately, SCI test does not able to measures the detail information about which transformer active parts which is suffering the damage. Another method is Impulse Frequency Response (IFR) analysis[3]. This circuit test is more complicated than those two methods before. This method difficult for getting the complete information from the transformer such as the measurement of the circumstances physical of the transformer thin winding. It is also distorted by much harmonics because of its impulse signals. So that, it is usually injected by FFT to transform those impulse signals for obtaining the mechanical deformations of the windings and cores.
One of the most comprehensive measurements on the transformer deformation is Sweep Frequency Response Analysis (SFRA)[4], that is detecting deformation mechanic structure in the transformer. SFRA is a powerful tool[5], it can give comprehensive information on the winding mechanical structure and also the core and clamping structure. This is important as even little winding and core deformation in the winding and core can spread into a failure of the transformer under fault condition. Core damage can be caused by shrinking from a thin transformer, while damage’s core is caused by the short circuit. SFRA method discuss about detecting the deformation mechanic transformer. SFRA is a diagnostic tools that can get an indication from a mechanic fault like a core or winding movement, transformer and electric fault, for example, short – circuit and partial discharge[6]. Based on the injected input signal, there are different types of SFRA such impulse voltage-based analysis response frequency, sinusoidal sweep frequency response analysis, etc.[7].

The voltage amplitude of sinusoidal sweep signal in SFRA is constant, with swept range 20 Hz – 20 MHz. Generator signal is used as input to a terminal of winding thin transformer. Different frequency range is applied by different work which is based on sweep source. Signal bandwidth device and level ratio signal is determined too when the fault goes on [8]. In this method error function very familiar because multiplication by denominator and the result has been refracted[9].

Voltage signal frequency is injected to one of ends from winding transformer while the response is acquired from the other end. This methodology depends on reality when the transformer phase has the unique characteristic of a fingerprint transfer function which phase to the variation of transformer parameters like winding, resistance, inductance, and capacitance.

2. Methods
A work from China, collects and doing tests to the transformers data in the field. It ends up with the summation and comparation of the different methods deformation[10]. SFRA is a diagnostic device that has the most powerful to evaluate the damaged core or winding transformer. The shape of the analysis result in SFRA response track frequency thin transformer. The transformer fault position able to track within the deformation fr[11].

The core’s damage which is represented as shrinking by usage for years, causes short circuit on the transformer winding. So that, the transformer requires regular check firstly before and after maintenance or relocation. After a fault happening, several parts become malfunctioning such as cable connection to low voltage (LV) winding, high voltage (HV) winding, tap changer, and bushing. These failures can be reduced by spreading the protection of the transformer vitality.

2.1. Sweep Frequency Response Analysis (SFRA)
The famous method for detecting the deformation winding in transformer is Sweep Frequency Response Analysis (FRA). The HV winding frequently experienced the winding defects[12]. This method also been applied by PT. YTL East Java for knowing the transformer usage feasibility. This measurement had been done at least once in six years simultaneously with regular maintenance.

2.2. Phase based comparison
It can be assumed that the different set coil of transformer is identically manufactured besides its manufacturing tolerances. But, the measurements of real voltages and currents are sometimes short of data. Therefore, the comparison of the frequency response measurements in different interphases[13] should be very similar up to frequencies of the least 100 kHz. The limiting factor is in-line arrangement of the three coil sets in the transformer tank with the tap changer on one side. Therefore, the leads from the winding taps to the tap changer have different lengths for the different phases. This phenomenon causes deviations of the frequency response of different coils.

2.3. Time based comparison
Time based comparison means a comparison of frequency response measurements with the same system configuration (terminal connections etc.) on different transformers but identical in its construction. It is
outlined that the latest results are compared to the most recent results[14]. Thus, their behaviour should be rather similar besides manufacturing tolerances. This result is very similar or almost identical. The frequency response is up to 100 kHz according to the international experience with SFRA. Firstly, measurement typically only a phase by phase comparison remains. A time-based comparison can be performed beginning with the next SFRA measurements. Pre-condition for all comparison methods is high reproducibility of the measurement. This condition requires rebuilding the measuring set-up for each of the measurements as identical as possible. A good method to achieve this goal as to take photos of the measuring set-up. Measurements are typically performed using standardized automatic measuring systems[15].

2.4. Measurement Method of SFRA
The prior SFRA technic was done in simple equations[16]. A sinusoidal voltage source with variable frequency was connected to be the terminal of one of the three phases or at the correlated phase terminal in case of a delta winding[17]. Figure 1 shows the termination which is typically done with 50 Ω. The frequency response is defined as the ratio of the voltage (U2) measured at a winding terminal and the voltage (U1) applied to the correlated winding terminal point.

There are three possible combinations of the measured frequency responses for this phase-based comparison at the HV winding, namely: U–Mp; V–Mp and W–Mp. All other winding connections are left open. Additional measurements, such as SFRA with short-circuited winding or transfer admittance measurements are possible and sometimes reasonable, but not mandatory. The measured frequency responses (transfer functions) were performed in the frequency range 20 Hz – 2 MHz.

Figure 1. HV terminal connection on the measured transformer.

SFRA measurement, which its circuit is shown in Figure 2, is more accurate in the core frequency below 10 kHz. Due to the core form, the magnetization characteristic of the other phases up to 2 kHz. The residual magnetic flux density in the core may lead to differences in the comparison of time-based FRA sweeps. Therefore, it is recommended to do SFRA measurements first. Measurement begins performing a de-magnetization procedure before doing the other measurements.

Figure 2. The measurement circuit of frequency response in LV winding.
Frequency response measurements taken on the same transformer, which is located in Figure 3. The same system configurations are compared with a reference measurement. The reference measurement was taken before the current measurement. This comparison method allows direct conclusions about deviations of the core-and-coils assembly which might be occurred during the period in between these two measurements.

Figure 3. Transformer location within the site.

The nominal voltages and currents of the inspected transformer are given in the Table 1. This transformer has Y connection in HV side, while in another side, LV side, has Δ connection. It also built in several taps for controlling voltages on the load side. Electrical power supplied from generator is distributed to load, which is drawn in Figure 4, both in the inside and outside the site.

Table 1. The name plate of transformer 50 BAT.

| High Voltage Vector Diagram Terminal | Position | Voltage (kV) | Current (A) |
|-------------------------------------|----------|--------------|------------|
| 1                                   | 575.56   | 768          |
| 15a                                 | 512.50   | 862          |
| 15b                                 | 512.50   | 862          |
| 15c                                 | 512.50   | 862          |
| 29                                  | 448.44   | 985          |

| Low Voltage Vector Diagram Terminal | Voltage (kV) | Current (A) |
|-------------------------------------|--------------|-------------|
| 21.00                               | 21.03        |             |
3. Results and Discussion

Different response from fingerprint can identified the transformer when get a signified distortion. The result from SFRA can be different from short-circuit impedance test because in this method approach by short-circuiting one of the transformer terminals. Therefore, this method just showed general result such as impedance from each phase.

Figure 4. The single line diagram of 50 BAT generator transformer.

Figure 5. The frequency response of tap 1 in HV winding: TF1 = 1N/1U
It can be clearly seen that the frequency responses, in Figure 5 until Figure 8, are identically lined. Even though the SFRA measurements are practically done in the different terminals, but the responses below about 10 kHz are alike and more influenced by the core misaligned. There is no such deviation, the frequency responses should be very similar or even identical up to a few 100 kHz. Due to the core form, the magnetization characteristic of the other phases up to 2 kHz. The residual magnetic flux density in the core may lead to differences in the comparison of time-based FRA sweeps. Therefore, it is recommended to do SFRA measurements in the beginning.
In 2013, the frequency responses were slightly decreased the BAT transformer. It showed no suspiciousness of interference, then measurement did not show typical deviation on the HV and LV windings. In the Table 2, frequency analysis sub – band sensitivity, transformer BAT includes the region 1 which its point lesser than 2 kHz its mean main core shrinkage happens but measurement which has been done, does not show deviation.

**Table 2. Frequency analysis sub – band sensitivity.**

| Region   | Range            | Component         | Failure sensitivity                                      |
|----------|------------------|-------------------|---------------------------------------------------------|
| Region 1 | Less than 2 kHz  | Main core         | Core deformation, open circuit                          |
|          |                  |                   | shorted turn, residual magnetism                         |
|          |                  | Bulk winding      |                                                         |
|          |                  | Inductance        |                                                         |
| Region 2 | 20 kHz – 20 kHz  | Bulk component    | Bulk winding, movement between                        |
|          |                  |                   | winding and clamping structure                         |
| Region 3 | 20 kHz – 400 kHz | Main winding      | Deformation within the main or tap winding              |
| Region 4 | 400 kHz – 1 MHz  | Main winding      | Movement of the main and tap                            |
|          |                  |                   | winding                                                  |
|          |                  | Tap winding       | Ground impedances variation                             |
|          |                  | Test winding      |                                                         |

**Figure 8.** Frequency response of tap 1 in LV winding: TF1 = 2U/2V

**Figure 9.** Representation of damage limit in transformer core and winding.
Figure 9 is the result of SFRA measurement in LV winding, in measurement produces a decrease of frequency on lesser than 2 kHz. SFRA measurement in PT. YTL East Java limits damage in the winding and core indicates components that get shrinkage are the main core, bulk winding, inductance. From that figure, it can be noted too that the shrinkage does not exceed 20% from standard percentage. In this condition, the transformer had been working in good condition since 2013. Then in 2019, the measurement has already implemented again with the same technique. The damage can be predicted that is mostly approaching 20%. The measurement of SFRA in the 5th unit had been done once in every six years. In 2019 maintenance has been done again as an effort to maintain the performance that meets the requirements for the feasibility of the used transformer.

4. Conclusion

The 500kV power transformer had been inspected in PT. YTL East Java Indonesia once in six years. This SFRA measurement is based on existing standards. After checking up, the measured transformer will be operating again by switching it to the power system connection. The measurement of SFRA in the transformer in 2007 and 2013, infers the transformer is in a good condition. The inspection should be scheduled while measuring the transformer damage before working again. In addition, the insulation in SFRA measurement can be estimated by observing the change in the chart that affects the winding and core of the transformer. Moreover, the result of SFRA measurement provides the transformer winding and core still in a good condition because the shrinkage does not exceed 20% of its standard percentage. Therefore, the 500 kV power transformer does not have to take serious maintenance.

References

[1] Hao F, Wen H, Zhao H, Li Z. 2019. Electromagnetic vibration analysis method of short circuit in transformer winding based on field circuit coupling. J Phys Conf Ser; p 1311.

[2] Liu H, Gan Z, Liu X, Yang F, Wang C, Wang C. 2019. Theoretical and simulation study on online monitoring technology of transformer short-circuit impedance. IOP Conf Ser Mater Sci Eng; p 486.

[3] Huang JJ, Tang WH, Xin YL, Zhou JJ, Wu QH. 2018. Fault Identification for Transformer Axial Winding Displacement Using Nanosecond IFRA and SFRA Experiments. IOP Conf Ser Mater Sci Eng; p 366.

[4] Devadiga AA, Harid N, Griffiths H, Barkat B. 2019. An Alternative Measurement Approach to Sweep Frequency Response Analysis (SFRA) for Power Transformers Fault Diagnosis. 2019 54th Int Univ Power Eng Conf UPEC 2019 - Proc: pp 1–4.

[5] Pandya AA, Parekh BR. 2014. Interpretation of Sweep Frequency Response Analysis (SFRA) traces for the open circuit and short circuit winding fault damages of the power transformer. Int J Electr Power Energy Syst;62: pp 890–6.

[6] Rahimpour H, Mitchell S, Tusek J. 2016. The application of sweep frequency response analysis for the online monitoring of power transformers. Proc 2016 Australas Univ Power Eng Conf AUPEC 2016.

[7] Secue JR, Mombello E. 2008. Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers. Electr Power Syst Res;78: pp 1119–28.

[8] Jayarathna KLIMPB, Sampath Ediriweera WEP, Lucas JR, Samarasinghe R. 2018. Modelling transfer function of power transformers using sweep frequency response analysis. MERCOn 2018 - 4th Int Multidiscip Moratuwa Eng Res Conf: pp 500–5.

[9] Gite P, Sindekar AS. 2017. Investigating mechanical integrity in power transformer using sweep frequency response analysis (SFRA). Proc - 2017 IEEE Int Conf Electr Instrum Commun Eng ICEICE;2017-Decem: pp 1–6.

[10] Lu W, Ma J, Ma B. 2020. Research on Winding Deformation Detection and Diagnosis Technology of Power Transformer. J Phys Conf Ser; p 1453.

[11] Khanali M, Hayati-Soloot A, Høidalen HK, Jayaram S. 2017. Study on locating transformer
internal faults using sweep frequency response analysis. Electr Power Syst Res;145: pp 55–62.

[12] Bagheri M, Naderi MS, Blackburn T, Phung T. 2012. FRA vs. short circuit impedance measurement in detection of mechanical defects within large power transformer. Conf Rec IEEE Int Symp Electr Insul: pp 301–5.

[13] Gayfutdinova ER, Bulatova VM, Ilkevich AR. 2020. The method of power transformers and autotransformers windings condition determination. IOP Conf Ser Mater Sci Eng; p 791.

[14] Behjat V, Vahedi A, Setayeshmehr A, Borsi H, Gockenbach E. 2010. Identification of the most sensitive frequency response measurement technique for diagnosis of interturn faults in power transformers. Meas Sci Technol; p 21.

[15] IEEE. IEEE Std C57.13-2008 (Revision of IEEE Std C57.13-1993) IEEE Standard Requirements for Instrument Transformers. vol. 2008.

[16] Ludwikowski K, Siodla K, Ziomek W. 2013. Investigation of transformer model winding deformation using sweep frequency response analysis. IEEE Trans Dielectr Electr Insul;19: pp 1957–61.

[17] Murawwi E Al, Mardiana R, Su CQ. 2012. Effects of terminal connections on sweep frequency response analysis of transformers. IEEE Electr Insul Mag;28: pp 8–13.

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