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CASE STUDY ON INSULATION DIAGNOSIS OF GENERATOR

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Abstract: Common nondestructive insulation diagnosis of generator includes insulation resistance measurement, dissipation factor measurement, and partial discharge measurement. The insulation resistance and dissipation factor imply the insulation condition of the whole insulation system, and the partial discharge measurement is usually adopted to be the indicator assessing the degree of insulation aging and the existence of servere defects.

Because of the large capacitance of generator, the capacity issue of movable power source is always concerned for the dissipation factors and partial discharge measurements. Therefore, alternative voltage sources for 50 Hz/60 Hz AC voltage source are developed: very low frequency (VLF) voltage source, and damped alternative current (DAC) voltage source.

Authors take defected generators as the example to compare different diagnoses measured by different voltage source: DC for insulation resistance measurement, VLF for dissipation factor measurement and DAC for partial discharge measurement. The result of insulation resistance measurement shows good insulation condition, but partial discharge measurement and dissipation factor measurement both indicate the existence of defect.

This paper demonstrates the execution of partial discharge measurement by DAC and dissipation factor measurement by VLF in the field, and the comparison of different diagnoses is also addressed.

1 INTRODUCTION

Common nondestructive insulation diagnosis of generator includes insulation resistance measurement, dissipation factor measurement, and partial discharge measurement.

The insulation resistance are recorded at 1st and 10th minutes since the DC test voltage is applied. The reading at 10th minutes indicates the insulation condition of insulation materials, and the ratio of these readings, which is called as polarization index (R10/R1), shows the degree of moisture absorption of the insulation material.

The dissipation factors are recorded at different AC voltage levels, which are called as tip-up, and the highest test voltage would be rated voltage of the generator under tested. The reading at rated voltage shows the insulation condition of insulation materials, and the tip-up implies the existence of severe partial discharge phenomena and degree of moisture absorption.

Partial discharge measurement is also recorded at different AC voltage, and the result shows the serious degree and the type of defects, which can be used to assess the risk of insulation breakdown.

Because of the large capacitance of generator, the capacity issue of movable power source is always concerned for the dissipation factors and partial discharge measurements. The same concern is also an important issue for the field testing of cable system, and there are alternative power sources developed for the field testing of cable system: very low frequency (VLF) voltage source [1], and damped alternative current (DAC) voltage source [2]. Hence, this paper also took these alternative power sources as the power source in field to execute the measurement of dissipation factor and partial discharge.

Authors take defected generators as the examples to compare different diagnoses measured by different voltage source: DC for insulation resistance measurement, VLF for dissipation factor measurement [3][4], and DAC for partial discharge measurement. Partial discharge measurement indicates the existence of defect, and other diagnoses all show good insulation condition [5][6].

During the insulation diagnostics, the bushings and windings are tested separately. There are two kinds of defects inside generators: one type is in bushing and the other one is inside winding.

Since the repair of bushing is simple and can be done immediately, the repair of winding is much difficult and can't be done immediately. Therefore, the generator is decided to be in service again, and the partial discharge phenomena are monitored till the preparation of repair is ready.

2 TEST METHODES

The insulation resistance and dissipation factor mainly measure the resistance of the insulation material, and the trend of the resistance implies the aging degree of insulation material. Once there is defect inside the material, the loss caused by the defect would be too small to affect the measurement of insulation resistance and dissipation factor. However, the local electric field would be enhanced and the partial discharge phenomenon would occur. Then the partial discharge measurement would indicate the existence of defect.

2.1 Dissipation Factor

Figure 1 shows the equivalent circuit of insulation material, and R_V and C_V are the equivalent insulation resistance and capacitance respectively. Once the AC test voltage is applied, the leakage current (I_T) can be divided into two parts: I_C and I_R. The ratio of I_R to I_C is the dissipation factor, which is called as tangent delta (tan(δ)), as shown in equation (1), and can be rewrote as 1/(2πfRC), where f is the frequency of the applied voltage.

$$\mathrm{Tan}(\delta)=I_R/I_C=Z_C/Z_R=(V/R)/(2\pi fCV)=1/(2\pi fRC) \qquad (1)$$

According to equation (1), the tan delta would increase as the frequency decrease as shown in fig. 2, and it implies that the assessment of insulation aging would be easier as the frequency is lowered. In other words, the equivalent resistance would be constant at different frequency, and the equivalent capacitive reactance would chang as the frequency varies, such as kΩ at power frequency and MΩ at 0.1 Hz. Once the insulation resistance varies a small range, the tan delta would show larger variety at 0.1 Hz then that at 60 Hz.

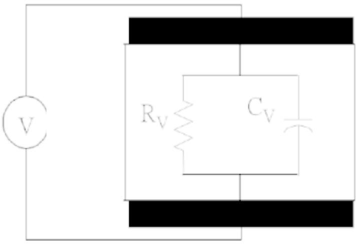


Figure 1: Equivalent circuit of insulation material

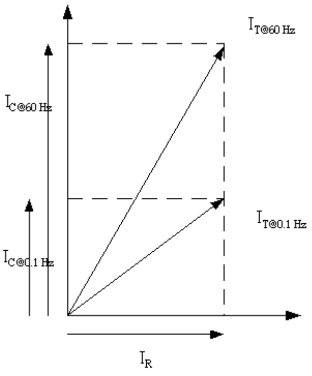
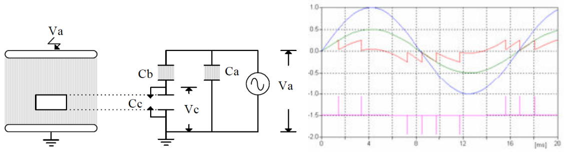


Figure 2: leakage current

2.2 Partial Discharge Measurement [7]

Figure 3 shows the equivalent circuit to explain how partial discharge takes place. The defect and insulation material forms a voltage divider, and they get different intensity of electric fields. Once the intensity of electric field in the defect exceeds the breakdown electric field of the material, there is a spark bridging the defect, as show in fig. 3.

The sparking would induce several phenomena, such as light, sound, electric transients, heat, and etc.. Then the partial discharge phenomenon would be detected by the observation of these phenomena as shown in fig. 4. Because the dimension of these defects are usually small, the insulation resistance and the dissipation factor usually would be influenced, and only the partial discharge measurement can detect the defects sensitively.



(a) Equivalent circuit (b) Waveforms

Figure 3: Example of void inside insulation material

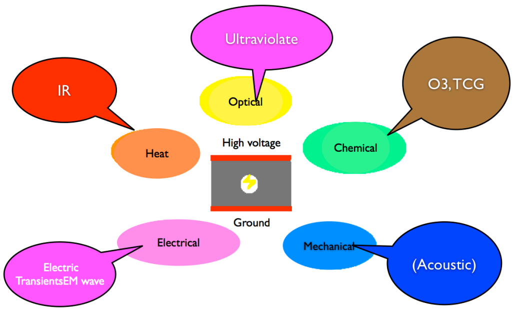


Figure 4: Physical phenomena caused by partial discharge.

3 VOLTAGE SOURCES

Because the capacitance of the generator could up to several μF, the required capacity of power source should be large enough to energize the generator, and it could be determined by equation 2, where f is the frequency of test voltage, C is the capacitance of the generator, V is the rms value of test voltage, and Q is the required capacity.

$$Q=2\pi fCV^2 \qquad (2)$$

For example, a 13 kV generator with the capacitance of 1 μF would require the power source to provide 64 kVA at rated voltage of 13 kV with 60 Hz. This would ba a heavy equipment, and is unsuitable to be a portable power source. As shown in equation 2, the required capacity of power source would decrease while the frequency of test voltage decrease. Hence, VLF power source and DAC power source are developed by this concern.

3.1 Very Low Frequency (VLF) Power Source

VLF power source is an AC power source with frequency less than 1 Hz. As shown in equation (2), the capacity of power source could be smaller as the frequency of voltage is lower. Therefore, for a 13 kV generator with the capacitance of 1 μF, the capacity of power source with 0.1 Hz would be 110 VA, which is about 600 times smaller than that of 60 Hz, and the size would also small enough to be portable.

There are several types of VLF power source as shown in fig. 5. Among them only the type with sinusoidal waveform can be used for diagnostics, and others could only be used for voltage withstand test.

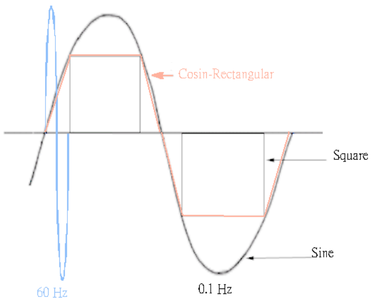


Figure 5: Waveforms of different VLF power sources

3.2 Damped AC (DAC) power source

The oscillating wave test system (OWTS)[1] is taken as DAC source, and the configuration is shown in fig. 6. The DC source will charge the object under test (OUT) to the test voltage, and then IGBT closes quickly to form a resonance circuit (capacitance of OUT and inductance of OWTS) as shown in fig. 7. Because of the DC source and the oscillating waveform by line resonance, the DAC power source has the advantage of small capacity requirement and the similar result to power frequency.

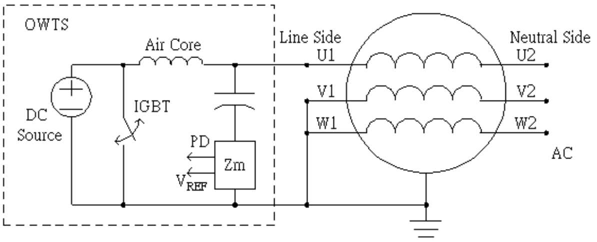


Figure 6: Configuration of OWTS

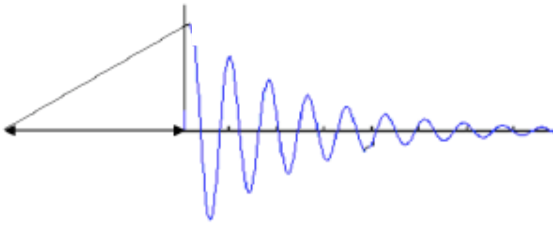


Figure 7: Waveform of DAC power source

4 FIELD TEST

One power plant has three generators, and the insulation diagnosis of the generators ' stators had carried out during the preventive maintenance. The items of insulation diagnosis are insulation resistance measurement, dissipation factor measurement, and partial discharge measurement. The result of insulation resistance measurement are several tens GΩ for #1 and #2 generators, and are several hundreds MΩ for #3 generator. Because the weather condition were different during measurements, the lower reading of #3 generator was caused by the rainy day without any drying.

The partial discharge measurement showed that there were abnormal partial discharge signals inside these generators. Dielectric dissipator factor measurements were used to separate the possible defected parts from the whole generators.

4.1 Partial Discharge Measurement

Figure 8 shows the test procedure, and the step voltage is 2 kV_{RMS}. The amount of shots is 10 times for every step and is 50 times for the highest voltage [5][6]. Among all measurements, the abnormal partial discharge signals occurred after 4^{th} shot at certain voltage level implying that the amount of shots at certain voltage level should be more than 4, or the partial discharge phenomenon might not occur.

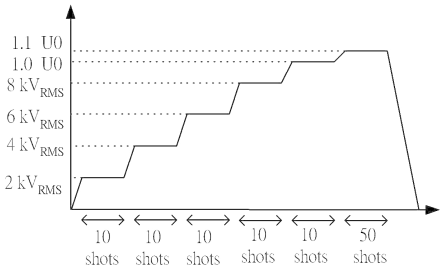


Figure 8: Voltage steps and the amount of shots.

Figure 9 shows the measured result at rated phase-to-ground voltage (U0), and the phase-resolved partial discharge (PRPD) pattern shows normal partial discharge phenomenon inside winding. Figure 10 shows another measured result at U0, and the PRPD pattern shows abnormal partial discharge phenomenon.

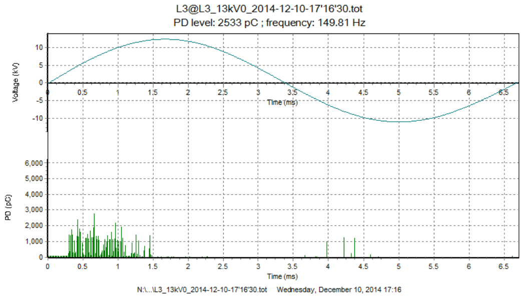


Figure 9: PRPD pattern measured by OWTS (normal)

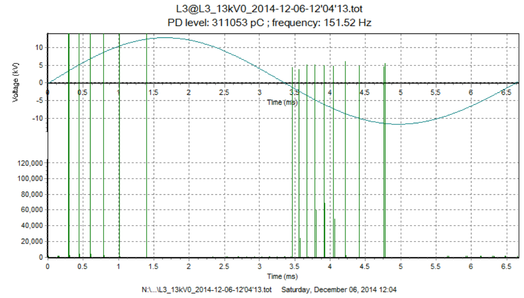


Figure 10: PRPD pattern measured by OWTS (abnormal)

Because the partial discharge measurement includes winding and bushings, the winding and bushings were disconnected and the winding itself was retested to confirm the partial discharge source. Figure 11 shows the result at 1.1 U0, and the abnormal PRPD pattern is disappeared. Therefore, the defected part is supposed to be bushings.

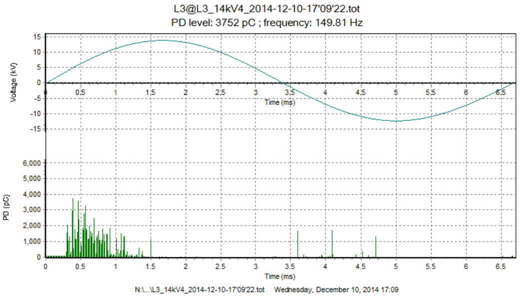


Figure 11: PRPD pattern measured by OWTS (normal, after the replacement of defected bushing)

However, one winding still has abnormal partial discharge measurement after the disconnection of bushings, and the ultrasound detector (CTRL UL101) is used to locate the partial discharge source. As the test voltage is applied by OWTS, the duration of the sound caused by partial discharge signals is too short to be detected. The test voltage is then applied by VLF power source, and the longer duration of the sound caused by partial discharge signal makes the location easier.

4.2 Dissipation Factor

Due to too high resonance frequency by small capacitance of bushings, the OWTS can't be applied to do partial discharge measurement on bushings. Hence, the dielectric dissipate factor measurement by VLF power source is adopted, and the measurement result of bushings at #2 generator's line side is shown in fig. 12. From fig. 12, the C-phase bushing shows severe aging as comparing to other two bushings. Therefore, the replacement of C-phase bushing is recommended. After the replacement, the partial discharge measurement on whole C-phase winding is redone, and the abnormal partial discharge signals are disappeared.

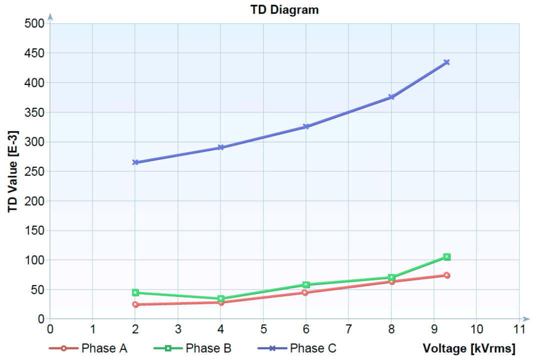


Figure 12: measured Tip-up curve of bushings

Because the capacitance of bushings and winding are quite different, the dissipation factors of bushings and windings are measured separately and together, and the results are shown in table 1. As shown in table 1, the defected line side bushing has higher tangent delta value, and it only slightly affects the result of whole winding. It implies that the dissipation factor won’t reflect the effect caused by defect inside small part as the measurement is done for a whole system. In this case, the winding and the bushings should be disconnected to be able to detect the defect inside bushing, or the result will shows good insulation condition of the whole winding.

5 CONCLUSION

Among the insulation diagnosis in this case, insulation resistance measurement is easily affected by the environment, especially humidity, and the measured result should be interpreted carefully.

The partial discharge measurement by DAC power source shows good performance on detecting defects in this case. However, there is one thing needed to be keep in mind that the amount of shots at every voltage level should be more than 4th to ignite the partial discharge activity in some situation.

Because of large difference between bushings and winding, the increased leakage current caused by defects in bushings would be ignored as comparing to the leakage current induced by good winding, and the tanget delta shows less sensitivity of defects inside bushing as the measurement is done for whole winding. Hence, it is recommended that the dissipation factor is measured separately for every single part rather than whole combined system to avoid misinterpretation of the results.

The alternative AC power source, DAC and VLF, both show the good performance in this case, and is practicable for the insulation diagnosis of generator.

REFERENCES

[1] IEEE Std. 400.2, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (Less than 1 Hz)

[2] IEEE P400.4, Draft Guide for Field-Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current Voltage (DAC)

[3] IEEE Std. 286, IEEE Recommended Practice for Measurement of Power Factor Tip-up of Electric Machinery Stator Coil Insulation.

[4] IEEE Std. 433, IEEE Recommended Practice for Insulation Testing of AC Electric Machinery with High Voltage at Very Low Frequency.

[5] E. Gulski, H. J. van Breen, J. J. Smit, P. N. Seitz, P. Schikarski, “Partial Discharge Detection in Generator Stator Insulation Using Oscillating Voltage Waves”, Proceeding on Electrical Insulation Conference and Electrical Manufacutring & Coil Winding Conference, 2001, p.p. 331-p.p. 334.

[6] Corne van Eeden, “Measurement of partial discharges and dielectric losses on rotating machines using damped AC voltages”, Master’s Thesis, 2010.

[7] IEC 60034-27: Rotating electrical machines - part 27: off-line partial discharge measurements on the stator winding insulation of rotating electrical machines

Table 1: Summary of dissipation factor measurement

Applied Voltage	**Line side bushing**			**Neutral side bushing**			**Only winding**			**Whole winding**		
	I (uA)	**C (nF)**	**TD (‰)**	**I (uA)**	**C (nF)**	**TD (‰)**	**I (uA)**	**C (nF)**	**TD (‰)**	**I (uA)**	**C (nF)**	**TD (‰)**
2 kV	2	2	265	2	2	24.7	646	516	13.5	649	520	14.5
4 kV	4	2	290	3	2	28.6	1296	520	15.3	1304	521	16.4
6 kV	6	2	326	5	2	44.8	1950	518	17.2	1961	521	18.5
8 kV	8	2	376	7	2	63.9	2604	519	19.4	2618	522	20.9
9.3 kV	10	2	435	9	2	74.5	3031	520	20.9	3049	522	22.6