On-line Monitoring for Bushing of Power Transformer

Thanapong Suwnansri*, Agkapon Pongmanee, and Cattareeya Suwanasri

Abstract— *This paper presents the on-line monitoring system for bushing of large power transformer. The system is aimed to detect the degradation of bushing and provides the alarm before bushing failure. Generally the high voltage bushing is produced as a condenser type bushing, consisting of several paper insulation layers separated with conductive foils for each layers. Thus the degradation of internal insulation will affect the value of capacitance and power factor of insulation. These two parameters can be monitored on-line by installing the sensing device at the test tap of bushing. Then the changing of insulation capacitance will lead to the change of leakage current value through bushing insulation. In case of perfect bushing, the leakage current of each bushing should be equal and the summation of all three phase leakage current should be zero. If one bushing has problem with internal insulation, the leakage current will be higher. This makes the summation of current to be greater than zero. This knowledge is used to develop the detection and decision making algorithms in microcontroller and the hardware will be developed to implement as on-line monitoring system for bushing of large power transformer in transmission system.*

Keywords— **Bushing, leakage current, on-line monitoring, power transformer.**

1. INTRODUCTION

Power transformer is one of the key equipment in transmission network. The failure of power transformer is catastrophic that leads to wide area power supply interruption. From the international survey and failure statistics recorded from Thailand transmission system, bushing failure is approximately 20 percent of transformer's failures. The main cause of failure is the aging of seal and gasket due to environmental heat and temperature variation. Moreover, the human error during maintenance can cause the loosen test tap, through which the moisture can pass to the inside insulation of bushing. Thus, the ingress moisture is the main reason of bushing failure.

Therefore, this paper presents the on-line monitoring system for bushing of large power transformer. The system is aimed to detect the degradation of bushing and provides the alarm before bushing failure. Generally the high voltage bushing is made as a condenser type bushing, consisting of several paper insulation layers separated with conductive foils for each layers. Thus the degradation of internal insulation will affect the value of capacitance and power factor of insulation. These two parameters can be monitored on-line by installing the sensing device at the test tap of bushing. Then the changing of insulation capacitance will lead to the change of leakage current value through bushing insulation. In case of perfect bushing, the leakage current of each bushing should be equal and the summation of all three phase leakage current should be zero. If one bushing has problem with internal insulation, the leakage current will be higher. This makes the summation of current to be greater than zero. This knowledge is used to develop the detection and decision making algorithms in microcontroller and the hardware will be developed to implement as on-line monitoring system for bushing of large power transformer in transmission system.

2. CONDENSER BUSHING

Construction

Generally, the bushing of power transformer is made as condenser type, consisting of several paper insulation layers separated with conductive foils for each layers as shown in Fig. 1.

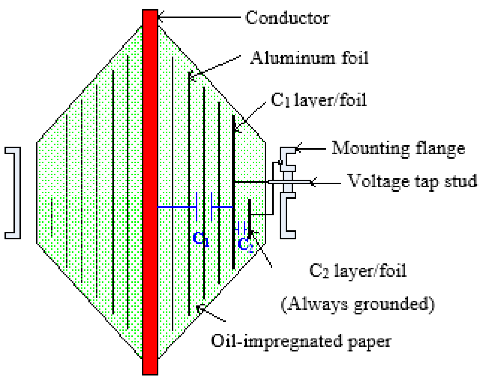

Fig.1. Construction Detail of Typical Condenser Type Bushing.

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The function of conductive aluminum foil in each layer is to obtain the equal voltage distribution in each layer. The space between internal surface of porcelain insulation and condenser set is filled with the insulation oil. Therefore, this condenser type bushing is called as oil impregnated paper or OIP bushing. The high voltage bushing consists of main capacitance C_1 and tap capacitance C_2 as shown in Fig. 2.

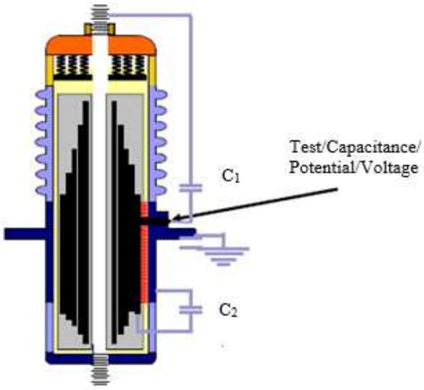

Fig.2. Main Capacitance of Condenser Type Bushing.

Under normal condition, C_1 is connected to ground via voltage tap cover between tap stud and mounting flange, while C_2 is connected to ground without any voltage stress. The degradation of internal insulation will affect the value of capacitance C_1 and power factor of insulation. These two parameters can be monitored on-line by installing the sensing device at the test tap of bushing. C_1 and C_2 will perform as voltage divider and the voltage drop across C_2 can be used with potential device. Then, the changing of insulation capacitance will lead to the change of leakage current value through bushing insulation. In case of perfect bushing, the leakage current of each bushing should be equal and the summation of all three phase leakage current should be zero. If one bushing has problem with internal insulation, the leakage current will be higher. This makes the summation of current to be greater than zero. The summation of three phase leakage current will be compared with the commissioning value or observed the increasing trend in order to set the alarm level. This knowledge is used to develop the detection and decision making algorithms in microcontroller and the hardware will be developed to implement as on-line monitoring system for bushing of large power transformer in transmission system.

Dielectric Loses

Dielectric losses are measured in units of watt loses whereby heat is generated due to these losses. Losses are created by the following causes.

- Natural resistance of the material
- Type of the material
- Polar molecules such as moisture
- Ionization of gases (partial discharge)

Losses will vary by the amount of dielectric material. Since bushing are not the same size and composition, comparison of watt losses between different manufactures, sizes, etc. is difficult. Therefore, the industry uses the power factor to quantify the condition of the bushing insulation system. As loss increases due to any the above causes, the power factor will be also increased. The tap is usually connected to the outer most foil and in some cases to the second to last foil. The C_2 capacitance is the capacitance from the tap to ground. Typically, the tap is grounded; therefore, the C_2 capacitance is not in the circuit during normal operation. Table 1 shows the capacitance of C_1 in bushing of power transformer (Oil-impregnate, paper-insulated type) rated 500 pF, 30.74 V.

Table 1. Capacitance of C_1 in Bushing of Power Transformer Rated 500 pF, 30.74 V

Case	C_1(pF)	ΔC_1	$V_{test\ tap}$ (V)	$\Delta V_{test\ tap}$	Decision
I	500 - 505	1%≤ΔC1	30.74 - 31.05	1%≤ΔC	Normal
II	506 - 515	1%<ΔC1 ≤3%	31.06 - 31.66	1%<ΔC ≤3%	Warning
III	516 - 525	3%<ΔC1 ≤5%	31.67 - 32.28	3%<ΔC ≤5%	Alarm (Low)
IV	526 up	ΔC1>5%	>32.28	ΔC>5%	Alarm (High)

Power Factor

Power Factor (PF) is the phase angle relationship between the applied voltages across a capacitance. The total current through the capacitance is given in Fig. 3.

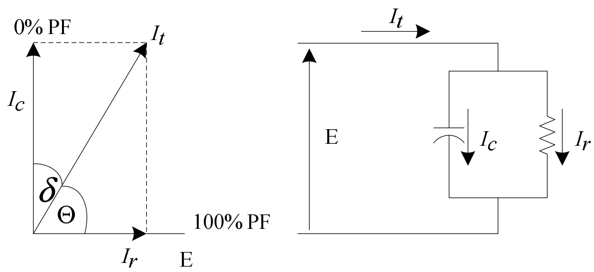

Fig.3. Power Factor Calculating Circuit

For example, power factor can be calculated as follows. Power is equal to Voltage (E) × Current (I_t) × Cosine (θ). Then it is similar to that Watts = E × I_r or Watts = E × I_t × Cosine (θ). Then power factor is calculated as in Eq. (1):

$$PF = Cos(\theta) = \frac{Watts}{E\ x\ I_t} = \frac{E\ x\ I_r}{E\ x\ I_t} = \frac{I_r}{I_t} \quad (1)$$

The variation of power factor should not vary out of the limitation zone (+0.02/-0.04). New bushing condition according to IEEE Std C57.19.01-2000) is given in Fig. 4.

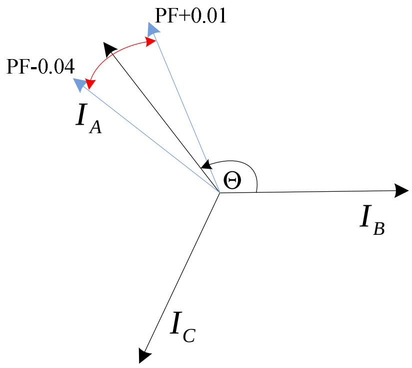

Fig.4. Change in Phase Angle.

3. BASIC THEORY

Bushing On-line Monitoring

In past decades, the off-line monitoring method was used to determine the quality of the bushing insulation. The bushing tests were performed and compared the measured power factor and capacitance to nameplate values or previous tests. Presently, the on-line monitoring method is introduced in order to observe performance of the bushing in real time. Some parameters for both methods are listed as shown in Table 2.

Table 2. Basic Testing Parameter Comparison

Parameters	Off-line Testing	On-line Testing
Applied Voltage	X	
Leakage Current	X	X
Phase Angle between Voltage and Leakage Current	X	
Frequency	X	X

Current Summing

By far, the most common method to monitor bushings is the sum of current method. Fig. 5 shows the installed bushing sensor that use for measure the $V_{test\ tap}$. The concept of measurement has shown in Fig. 6 a block diagram of a bushing monitoring system that uses the sum of currents method. During commissioning the indicator is balanced to zero. The purpose of the balancing circuit is to take into account the differences in system voltages and phase fluctuations and bushing characteristics. As a defect develops the complex conductivity of the bushing insulation changes and the current and its phase angle in one of the phases also changes. Therefore, the indicator will no longer be zero. The amplitude of the change reflects the severity of a problem. Three phase angle indicates in which phase is experiencing the change.

Fig.5. Installed Bushing Sensor.

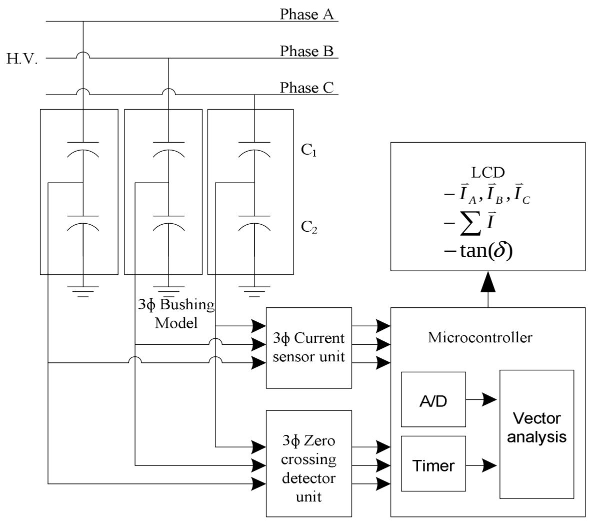

Fig.6. Current Detection from Voltage Tap Circuit.

The change in the sum of currents can be approximately represented by Eq. (2) under the assumption of a single defective phase:

$$\sum I = \frac{\Delta I}{I_0} \approx \sqrt{(\Delta \tan \delta)^2 + \left(\Delta C_1 / C_1^0\right)^2} \qquad (2)$$

where:

$\sum I$ - Parameter Sum of Currents

$\Delta \tan \delta$ - Tangent Delta Change,

$\Delta C_1 / C_0$ - Relative Change in Bushing Capacitanc e,

C_0 - Initial Capacitanc e Reading,

I_0 - Initial Sum of Current Value.

Ideally, the sum of the three bushing currents should be zero. In reality, not all parameters are equal from each phase. Therefore during commissioning of the system, the monitor is placed in a balancing mode, and the monitor self-adjusts so the sum of the currents is equal or close to zero.

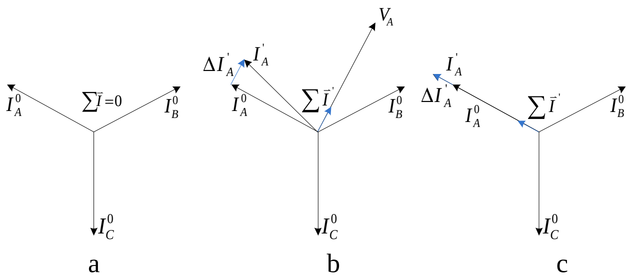

Fig.7. Current Summing Difference Mode.

Figures 7(a), 7(b), and 7(c) explain the method in vector format. Figure 7(a) shows all three currents from the bushing test taps perfectly balanced and the sum equal to zero. If there is a change in tangent delta in the phase-A bushing, an additional active current will pass through the phase-A bushing insulation and the new current I'_A, thus throws the system out of balance. The consequent imbalance vector is equal to the tangent delta change and directed along the phase-A voltage vector in Fig. 7(b). A change in capacitance is shown in Fig. 7(c). This additional current is perpendicular to the phase-A voltage. The consequent imbalance is now positioned along the vector I^0_A.

Voltage Magnitude Trend

The magnitude of the change is an indicator of the problem's severity, and the vector change indicates that bushing is going bad as shown in Fig. 8 whether the power factor or capacitance is changing. The chart and plot shown in Fig. 9 show a recent example of a bushing that is going bad.

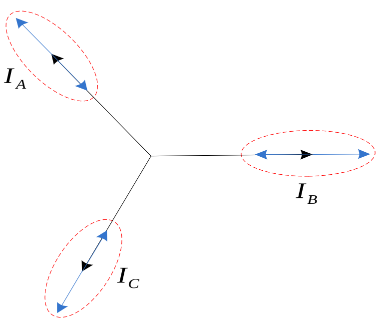

Fig.8. Change in Amplitude

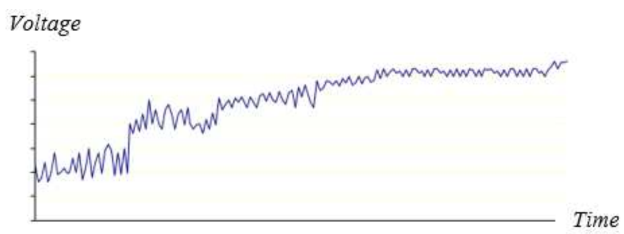

Fig.9. Investigation on Voltage Magnitude Trend

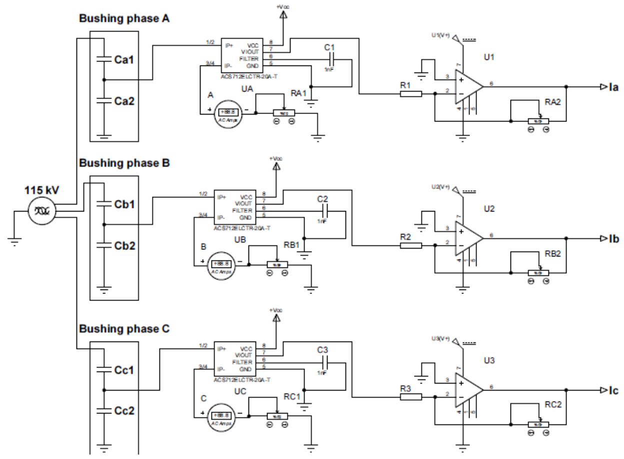

Fig.10. Sensor Circuit

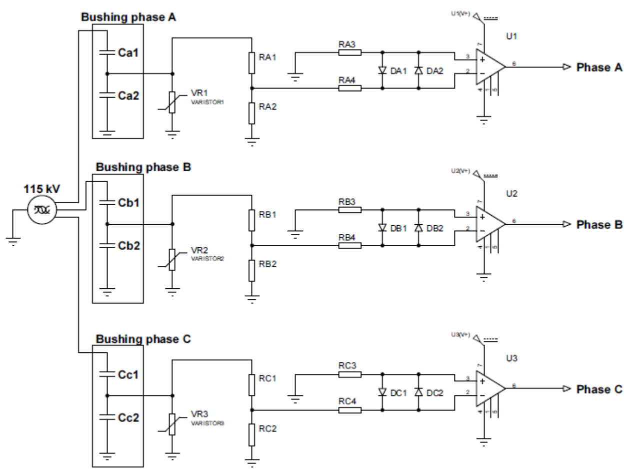

Fig.11. Zero Crossing Detector Circuit

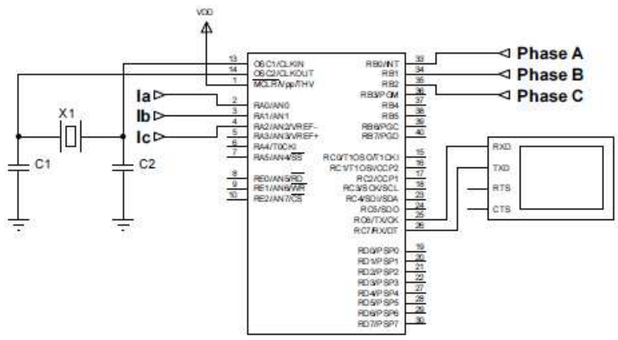

Fig.12. Microcontroller Circuit.

When performing on-line monitoring, the key diagnostic factor is the sum of currents and the phase angle of the sum. Only estimates of the power factor and capacitance can be made since all the data required to calculate the absolute power factor and capacitance is not available, as it is for off line tests. For this reason, on-line bushing monitoring provides relative calculation of power factor and capacitance. When the system goes out of balance, estimates are made on the change of power factor and/or capacitance. Fig. 10 shows the sensor circuit that use to detect the voltage at test tap. The $V_{test\ tap}$ is a key of capacitance measurement. Similarly, the phase angle can be detected via the zero crossing detection technique as shown in Fig. 11. These values are then added/subtracted to baseline values (nameplate or recent test values) entered into the system. The vector analysis will be calculated by microcontroller as shown in Fig. 12. The microcontroller will get data from both sensor circuit and zero crossing detector circuit and indicate on LCD for help local maintenance know the status of bushing.

If a user has a three phase off-line test set, all the data required is available. For on-line monitoring the following conditions apply:

- The line voltage at the bushing terminals is assumed to be constant on all three phases.
- The phase angles between the phase voltages are constant.
- In additional to the leakage current, the phase angles between Phase A-B and A-C are also measured. The frequency of leakage current is measured from the obtained waveform by performing noise rejection using software filter, performing wave shaping to determine the cycle timing subsequently and recalculating the frequency from known period of one cycle.

4. RESULT AND DISCUSSION

The capacitor testing was done in four different cases. The results are given in Table 3. These four different cases have a same capacitance rating as 500 pF at 30.74 V.

Table 3. Measured Capacitance of C_1 from Measurement System, Rated 500 pF, 30.74 V

Case	C_1(pF)	ΔC_1	$V_{test\ tap}$ (V)	$\Delta\ V_{test\ tap}$	Decision
I	503	0.60%	30.92	0.60%	Normal
II	509	1.08%	31.29	1.08%	Warning
III	519	3.80%	31.91	3.80%	Alarm (Low)
IV	528	5.60%	32.46	5.60%	Alarm (High)

From the Table 3, the capacitance value of C_1 will directly effect to $V_{test\ tap.}$ So, the capacitances changing from 4 cases different are described as bellows.

Case I: The capacitance of C_1 changed from 500 pF to 503 pF mean that the delta capacitance increases to 0.60%. Then it can be concluded that the bushing was in normal condition because the delta capacitance is not more than 1%.

Case II: The capacitance of C_1 changed from 500pF to 509 pF mean that the delta capacitance increases to 1.08%. Then it can be concluded that the bushing was in “warning” condition because the delta capacitance is in length of $1\%<\Delta C_1\leq 3\%$. So the operator should be keep real time monitor.

Case III: The capacitance of C_1 changed from 500pF to 519 pF mean that the delta capacitance increase to3.80%. Then it can be concluded that the bushing was in “Alarm (Low)” condition because the delta capacitance is in length of $3\%<\Delta C_1\leq 5\%$. So the operator should be follow system shutdown procedure and change the new busing into system.

Case IV: The capacitance of C_1 changed from 500 pF to 528 pF mean that the delta capacitance increases to 5.60%. Then it can be concluded that the bushing was in “Alarm (High)” condition because the delta capacitance is more than 5%. So the system will emergency shutdown.

5. CONCLUSION

The diagnostic technique for on-line monitoring of bushing is presented in this work. The degradation of internal insulation will affect the value of capacitance and power factor of insulation. Then the changing of insulation capacitance will lead to the change of leakage current value through bushing insulation. The technique continuously monitors the sum of current in three phases in order to detect the change in value of high voltage capacitance. The sensor circuit and vector analysis in microcontroller has been developed to simulate the degradation of transformer bushing. The status of bushing is indicated in the display as well as warning signal to inform the maintenance officer to correct the problem before bushing failure. The developed system has been tested for several simulation cases and can be further implemented into the hardware for practical application with power transformer in transmission system.

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