

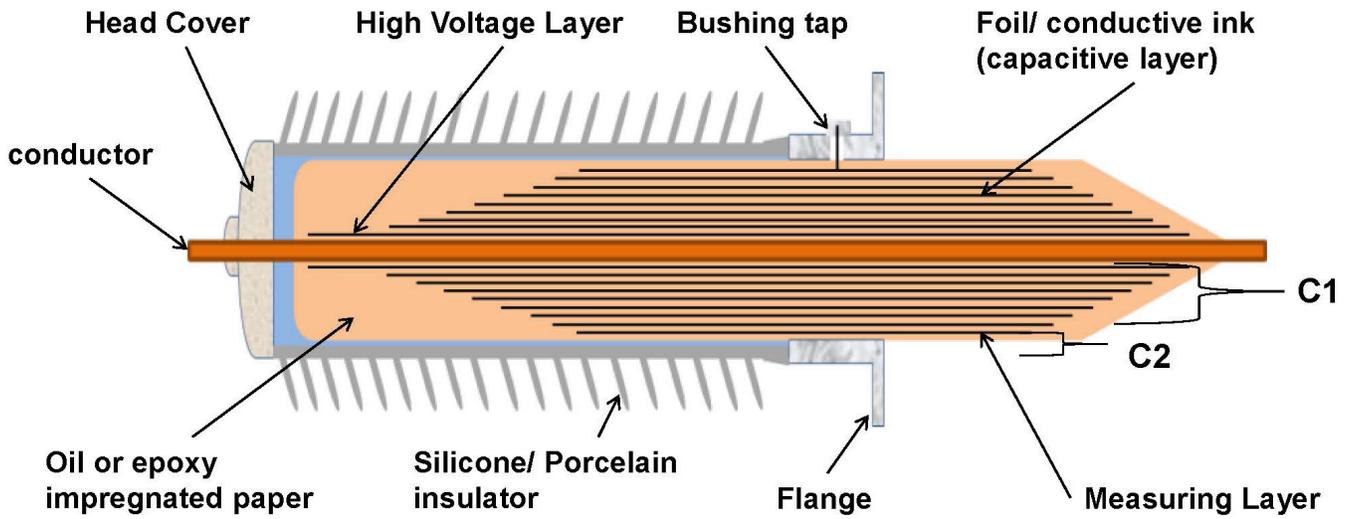
QUALITROL®

AUGUST 2020 • POWER GENERATION

A NEW APPROACH FOR TRANSFORMER BUSHING MONITORING



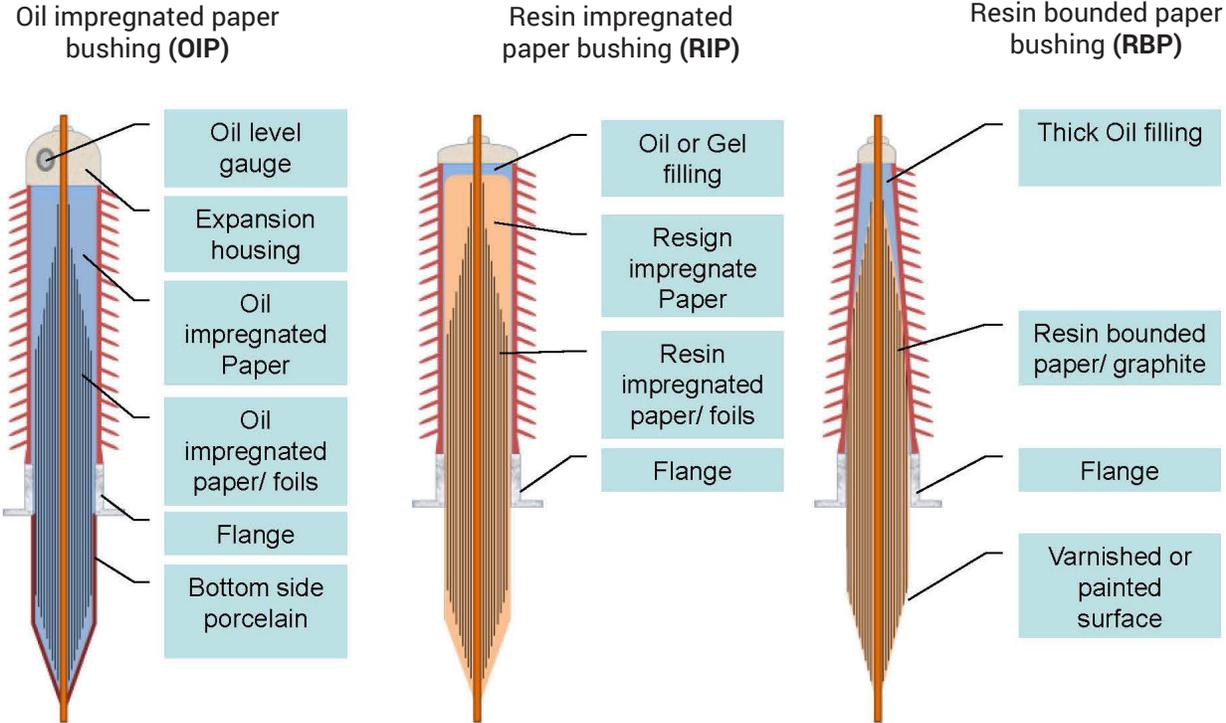
CONDENSER BUSHING CONSTRUCTION AND KEY COMPONENTS



The C1 capacitance is the capacitance between the center conductor and the tap.

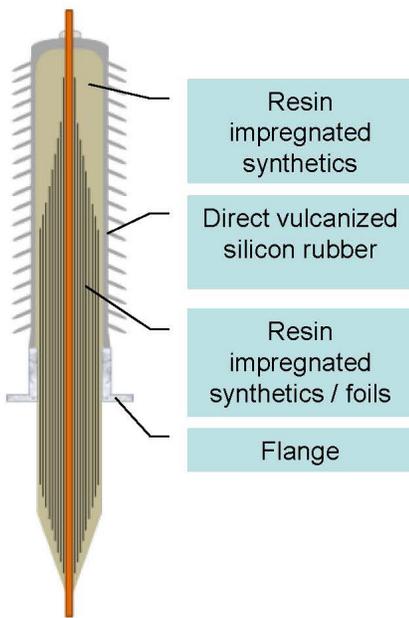
The C2 capacitance is the capacitance from the tap to ground.

TYPES OF BUSHINGS REGARDING TECHNOLOGY

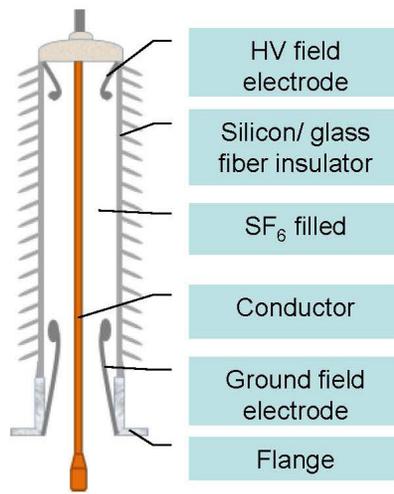


TYPES OF BUSHINGS REGARDING TECHNOLOGY

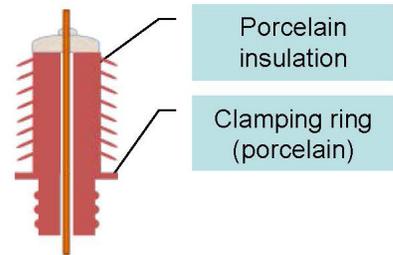
Resin impregnated synthetics bushing (RIS)



SF₆ filled hollow insulator bushing (for GIS)



DIN Bushings (porcelain or silicon – up to 36kV)

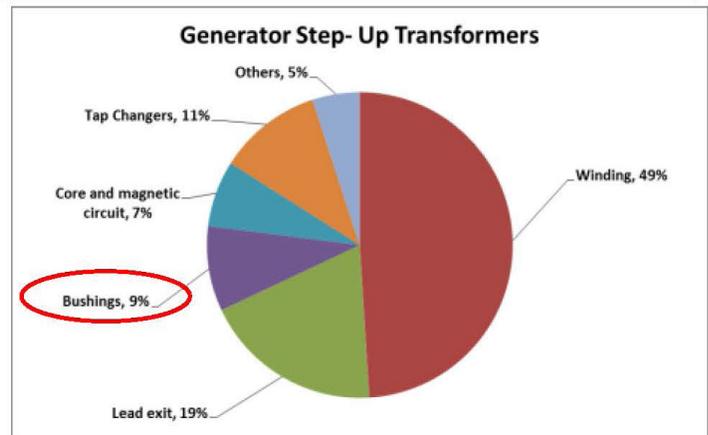
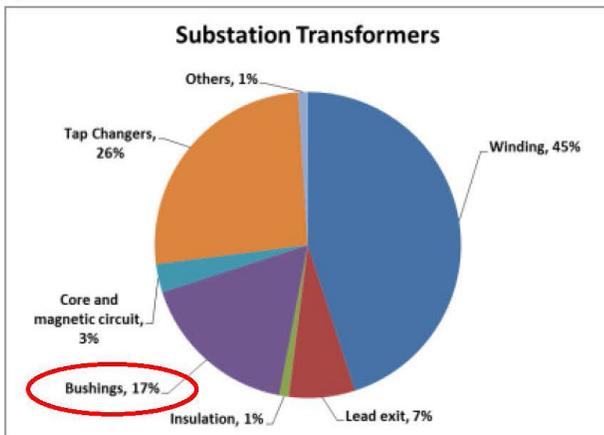


For these two types of bushings, no tan d and capacitance measurements are possible. There is no condenser body (no measuring layer) existing.

TRANSFORMER FAILURE STATISTICS

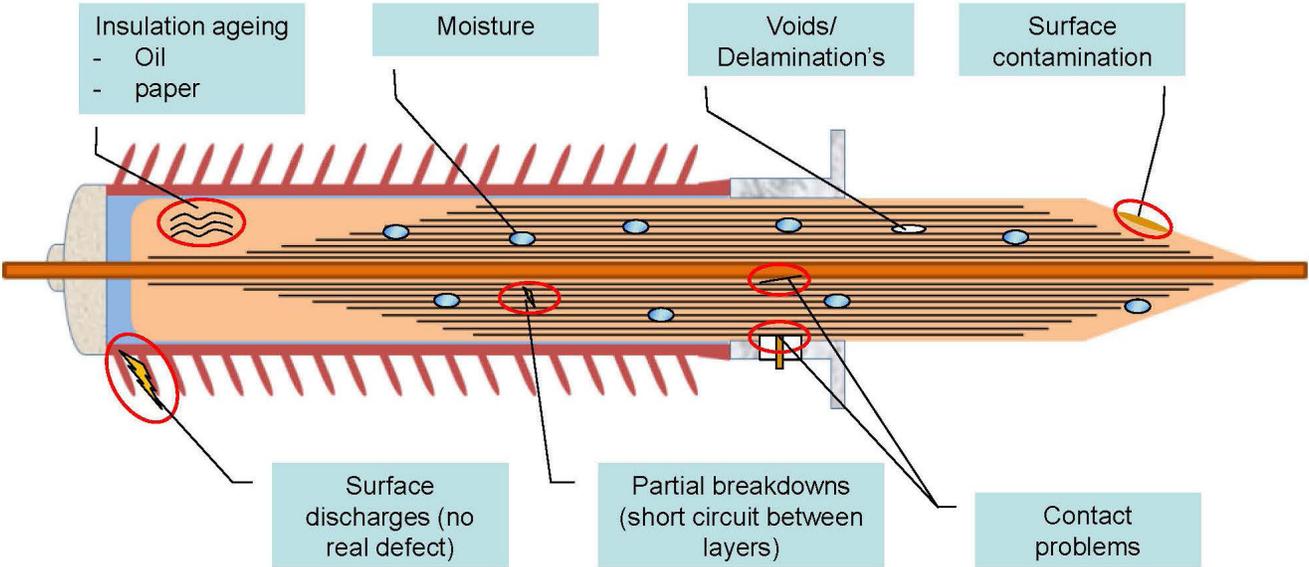
- The newest transformer statistic shows, that in case of substations bushings contribute with 17% to the total failure rate of transformers.
- In case of generator step- up transformers, bushings contributing with 9%
- More than 50% of bushing failures are catastrophic

FAILURES & POPULATION INFORMATION	HIGHEST SYSTEM VOLTAGE [kV]					
	69 kV < 100	100 kV < 200	200 kV < 300	300 kV < 500	kV 700	All
Failures	145	212	163	154	11	685
Transformer -Years	15220	48994	47473	41569	959	156186
FAILURE RATE/ YEAR	0.95%	0.43%	0.34%	0.37%	1.15%	0.44%



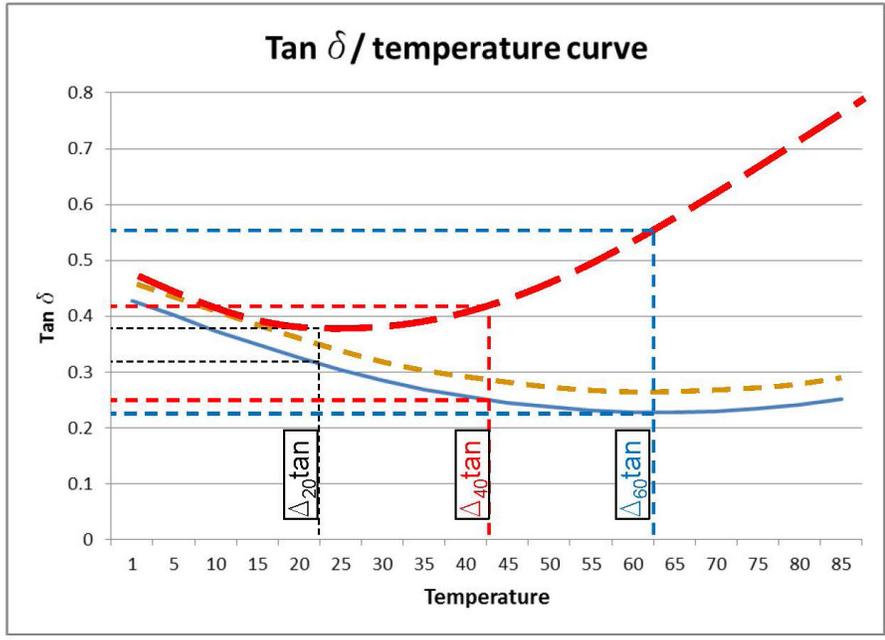
Source: WG A2.37, Transformer Reliability Survey: Interim Report, No. 261 - April 2012 ELECTRA

TYPICAL BUSHING DEFECTS





SOME ADDITIONAL ON MOISTURE IN INSULATION OF BUSHINGS



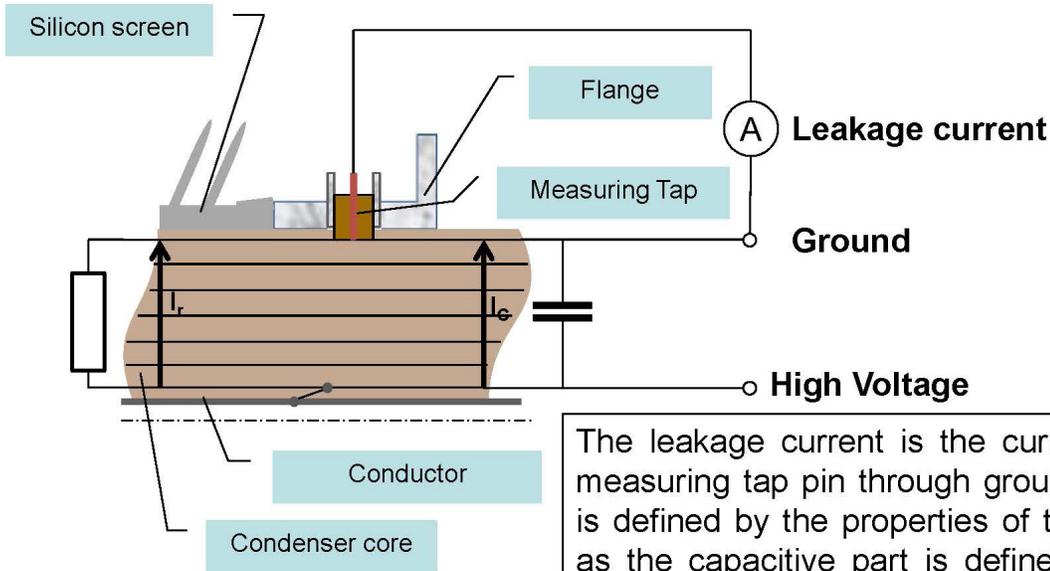
- Dry bushing
- - Normal aged bushing
- - Bushing with moisture

The difference in $\tan \delta$ at 20°C for Bushings with moisture is small. For higher temperatures the $\tan \delta$ gradient is increasing and the moisture content is more clearly to detect. Nevertheless the difference between a dry and a wet bushing could be at 40°C 0.2%, which still needs a high accuracy to detect moisture/insulation aging early enough.

$$\Delta_{20tan} < \Delta_{40tan} \ll \Delta_{60tan}$$

Valid for wet bushings only!

LEAKAGE CURRENT

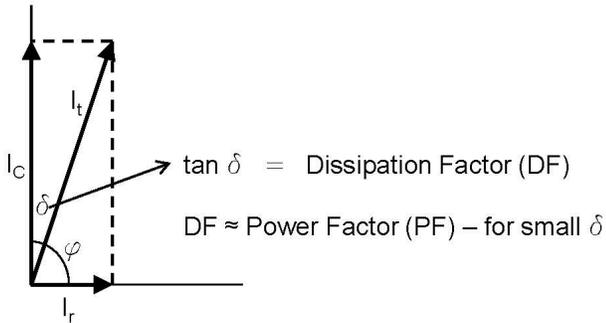


I_c - capacitive current
 I_r - resistive current

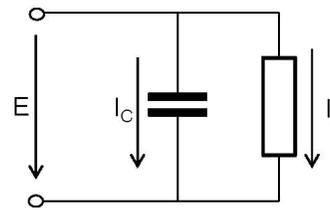
The leakage current is the current flowing from the measuring tap pin through ground. The resistive part is defined by the properties of the insulating system, as the capacitive part is defined by the mechanical and electrical design. A part of the leakage current is flowing also along the surface. Due to surface contamination or strong surface discharges, the resistive current can be influenced.

POWER FACTOR ($\approx \text{TAN } \delta$)

Equivalent circuit



Equivalent circuit



Phase angle between the applied voltage across a capacitance and the total current through the capacitance

$$\text{Power} = \text{Voltage (E)} \times \text{Current (I}_t\text{)} \times \text{Cosine } (\varphi)$$

$$\text{Watts} = E \times I_r$$

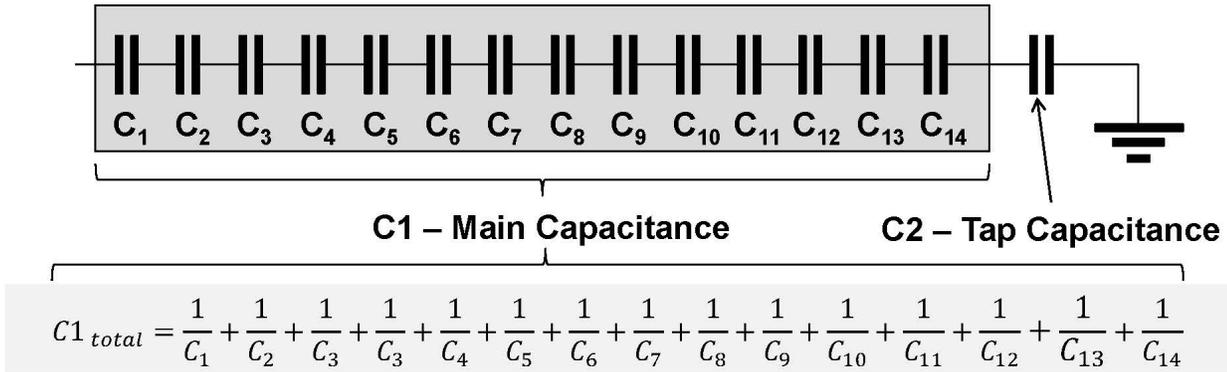
$$\text{Watts} = E \times I_t \times \text{Cosine}(\varphi)$$

$$\text{PF} = \text{Cosine}(\varphi) = \text{Watts}/E \times I_t = E \times I_r / E \times I_t = I_r/I_t$$

If I_r increases φ decreases and PF increases

CAPACITANCE

In bushings there are a several capacitors in series



- When a capacitor layer shorts out, the value of the capacitance will always increase
- The capacitors in series act as a voltage divider
- If a capacitor shorts out the voltage at the tap will increase in proportion
- Also, as the voltage varies the leakage current will vary.
- Therefore, if the voltage increases, there will be an increase in leakage current

ON-LINE BUSHING MONITORING PARAMETERS CHALLENGES

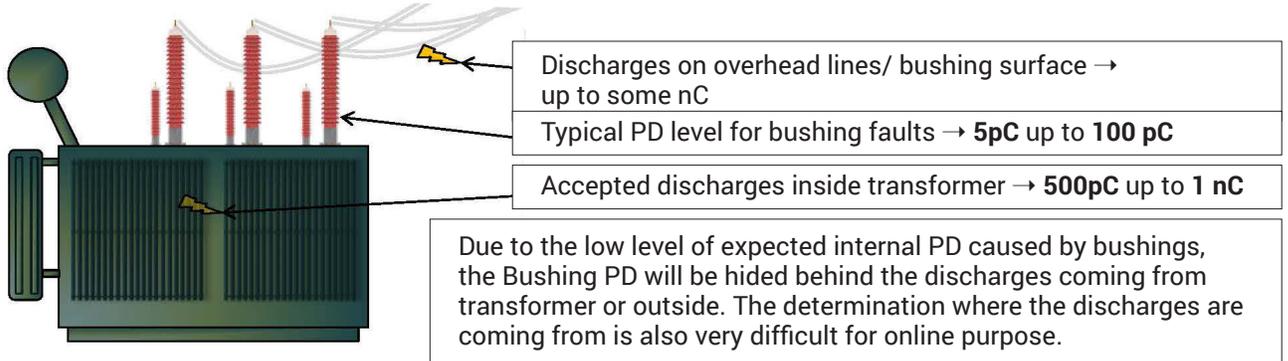
PARTIAL DISCHARGE

Advantage:

- Can be measured with conventional PD techniques
- Gives an early warning before the oil or the solid insulation system is partly damaged

Disadvantage:

- Very difficult to determine between external and internal discharges
- Bushing discharges are usually small compared to corona discharges or discharges out of the transformer tank. Therefore most of the time the discharges of the bushing itself will not be early enough detected.





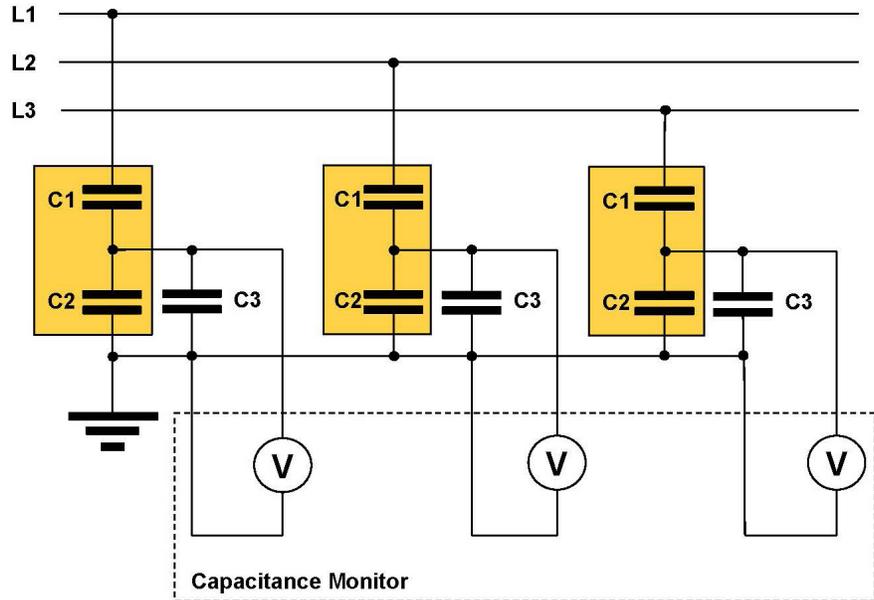
DETECTABILITY OF DIFFERENT BUSHING PHENOMENA'S

Defect	Tan δ	Capacitance	Partial Discharge
Insulation aging	+	-	-/+ Detectable if discharges are the cause of the degradation/ aging
Moisture	+	-	-
Void/ Delamination	(+) After a certain time once the dielectric material starts to corrode	-	+
Surface contamination	+	-	+/- If the surface contaminations are creating surface discharges
Surface discharges	+/- Surface discharges with a high intensity can be seen by a unstable tan δ	-	+
Partial breakdowns	+/- If it is combined with erosion of insulating material	+	+/-
Contact problems	+	+	+
	Shows up as an increased or unstable tan δ	Shows up as decreased or unstable capacitance	

ON-LINE BUSHING CAPACITANCE MONITORING

CAPACITY MONITORING

- Capacitor C3 (in μF range) will be connected between bushing tap and ground
- The voltage across C3 will be compared to the line voltage or to the voltages across the C3- capacitors at the other phases
- If C1 is increasing (partial breakdown) the voltage across C3 will drop down (by more than 1%) permanently



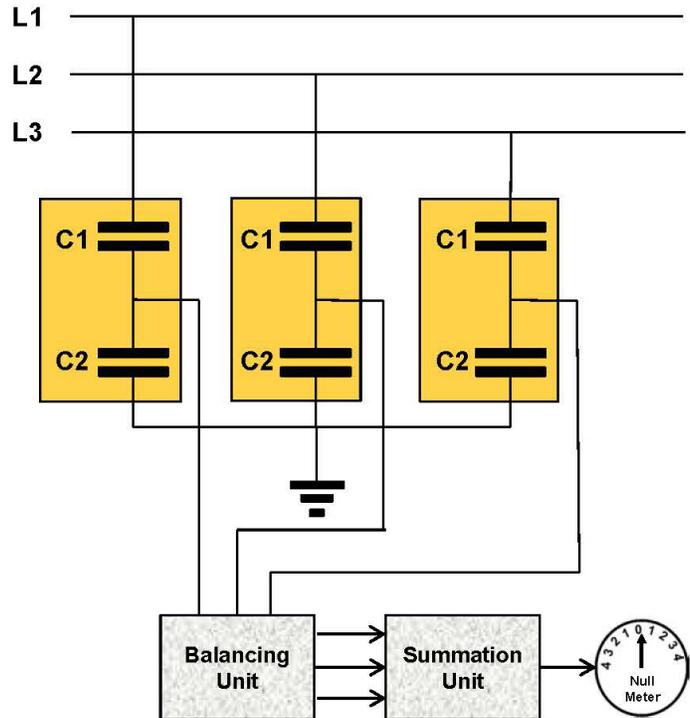
CONCLUSION

Increase of capacitance and contact problems can be detect in a simple way.
Other changes (e.g. moisture, degradation of insulation) can not be detected.

ON-LINE BUSHING MONITORING BALANCED CURRENT METHOD

BALANCE CURRENT METHOD

- Assumption: all phases will have absolutely the same voltage amplitude and the phase angles between the phases are perfectly 120 degree
- Under these circumstances (assuming all bushings have the same temperature and the same condition) the sum of all bushing leakage currents will be zero
- A change in the amplitude of a single leakage current will be counted as capacity increase
- An increase of the current sum without increased single leakage current is counted as Power Factor (Dissipation Factor) increase of a certain bushing
- In reality the phase voltages and angles are fluctuating according to the balance of the load and the network conditions



CONCLUSION

The fluctuation of the measured values prevents to detect changes of the insulation system causes by e.g. moisture or creeping degradation or aging. Only changes in capacitance (partial breakdowns) or big changes in Dissipation factor (Power factor) can be detected



ON-LINE BUSHING MONITORING BALANCED CURRENT

SOME THOUGHTS ABOUT INACCURACY REGARDING TYPICAL PHASE AND VOLTAGE ASYMMETRIES DUE TO UNBALANCED LOAD:

1

Considering typical phase and voltage asymmetries (0.2 degree for the phase and 1.0% for the voltage), the following deviations for the leakage currents of the different phases can be assumed:

- 1 to 1.5% in amplitude (follows the voltage)
- 0.2 degree in angle
- Comparing the leakage currents of different phases that will result in an error of:
 - 1 to 1.5% in the capacitance determination
 - 0.0035 in $\tan \delta$ absolute (absolute $\tan \delta$ value for a typical RIP Bushing is 0.00325)

2

While the capacitance inaccuracy can be compensated by consideration of the real phase voltage, the phase angle imbalance is difficult to compensate.

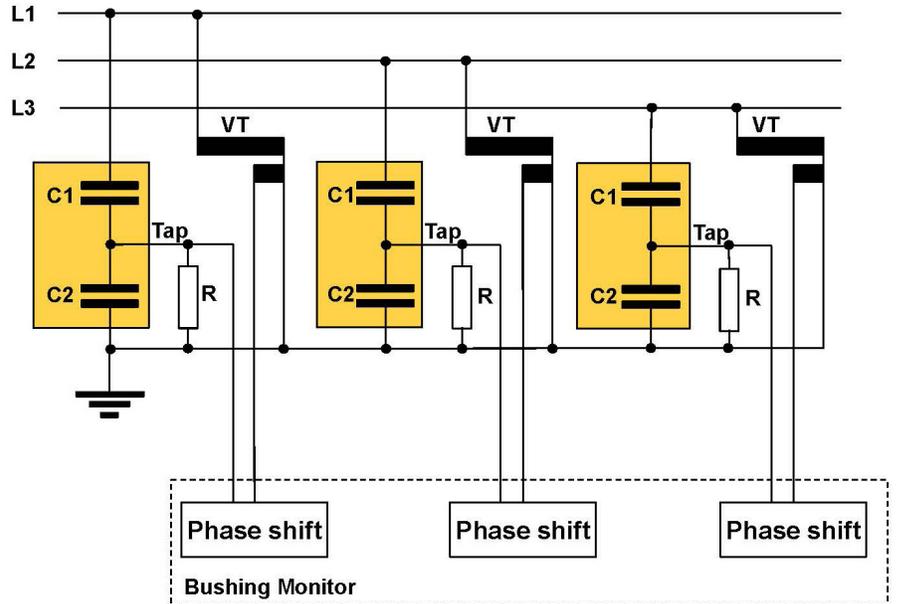
3

As result, changes caused by degradation of insulation material and moisture hardly can be clearly detected.

BUSHING MONITORING REFERENCE SIGNAL METHOD

REFERENCE METHOD

- The phase difference of the bushing leakage current and the reference voltage will be measured
- 90° - phase difference represents the angle Delta
- The phase difference represents direct the angle Phi
- By using the RMS value of the leakage current and the RMS value of the phase voltage the capacitance can be calculated.
- Bushings measured independently



CONCLUSION

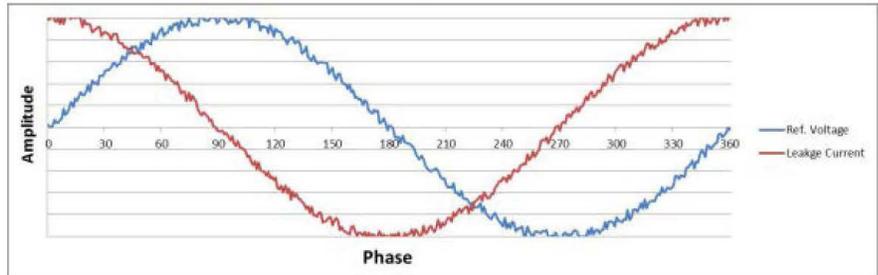
Applying advanced software algorithms for noise and disturbance reduction allows achieving a high accuracy in phase difference measurement.

ON-LINE BUSHING MONITORING PHASE SHIFT METHOD

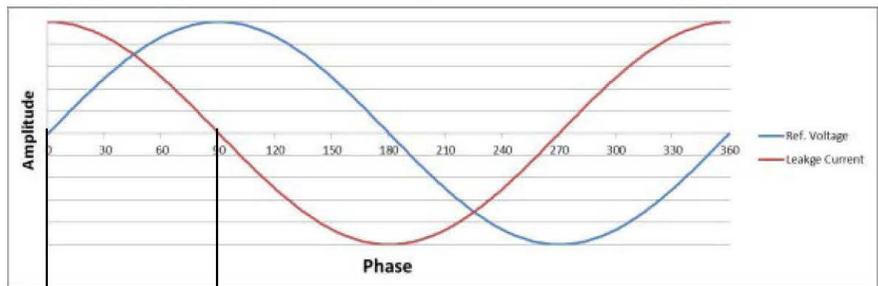
SIGNAL PROCESSING

- Noise and harmonics needs to be eliminated by advanced software algorithms
- The accuracy of the phase measurement is better then 0.1mrad (0.0057 Degree)
- The accuracy enables to detect changes in tan d form e.g. 0.325% to 0.340%
- That enables to detect moisture increase, insulation system aging and degradation early enough
- Temperature compensation will be necessary to achieve this accuracy

Raw Signal



↓ Software algorithm



Phase shift measurement

$$90^\circ - \delta$$



CONCLUSION

1. By using a reference signal for online Power Factor measurements on bushings, each bushing can be measured separately and independent from each other.
2. Using the reference signal from the same phase as the bushing is connected too, the fluctuation of the measured Tan Delta (Power Factor) values can be reduced and the accuracy can be increased to detect even upcoming faults connected to moisture problems or other faults in an easy stage.
3. As there are not always VT available (or only in one phase) alternative methods, described for example in different papers looking promising and will be further tested.



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