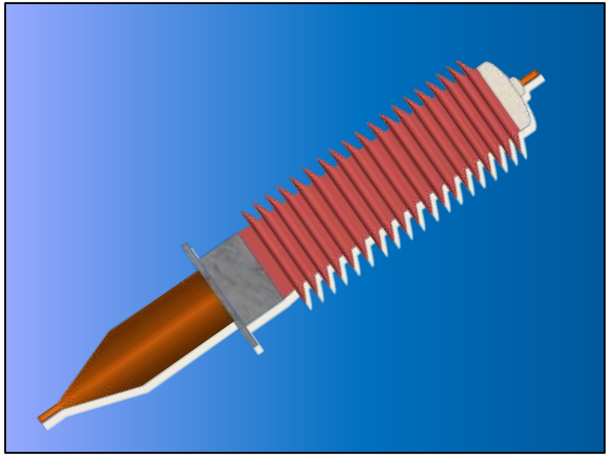
TRANSMISSION & SUBSTATION DESIGN & OPERATION SYMPOSIUM

THE UNIVERSITY OF TEXAS AT ARLINGTON

A New Approach for Transformer Bushing Monitoring

Statistical overview

Bushings

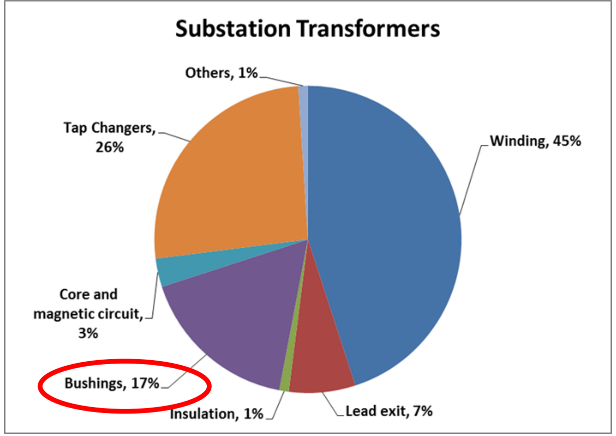


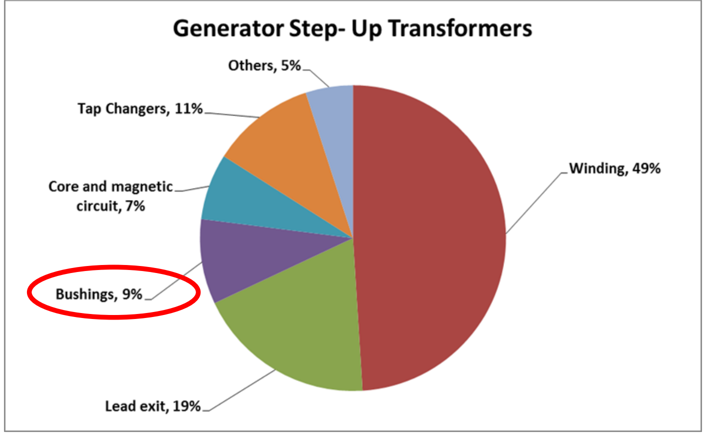
- Bushings are a critical component in electricity transportation
- They are used on transformers, reactors, instrument transformers and switchgear
- Capacitive bushings > 25kV have highest failure rate
- Average Price of Bushing = USD 10-20k

Transformer Failure Statistics

- Statistics show that substations transformers bushings contribute with 17% to the total transformer failures
- In case of generator step- up transformers, bushings contribute with 9%
- More than 50% of bushing failures are catastrophic and 70% of transformer catastrophic failures are caused by the bushings

	HIGHEST SYSTEM VOLTAGE [kV]					
FAILURES & POPULATION INFORMATION	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

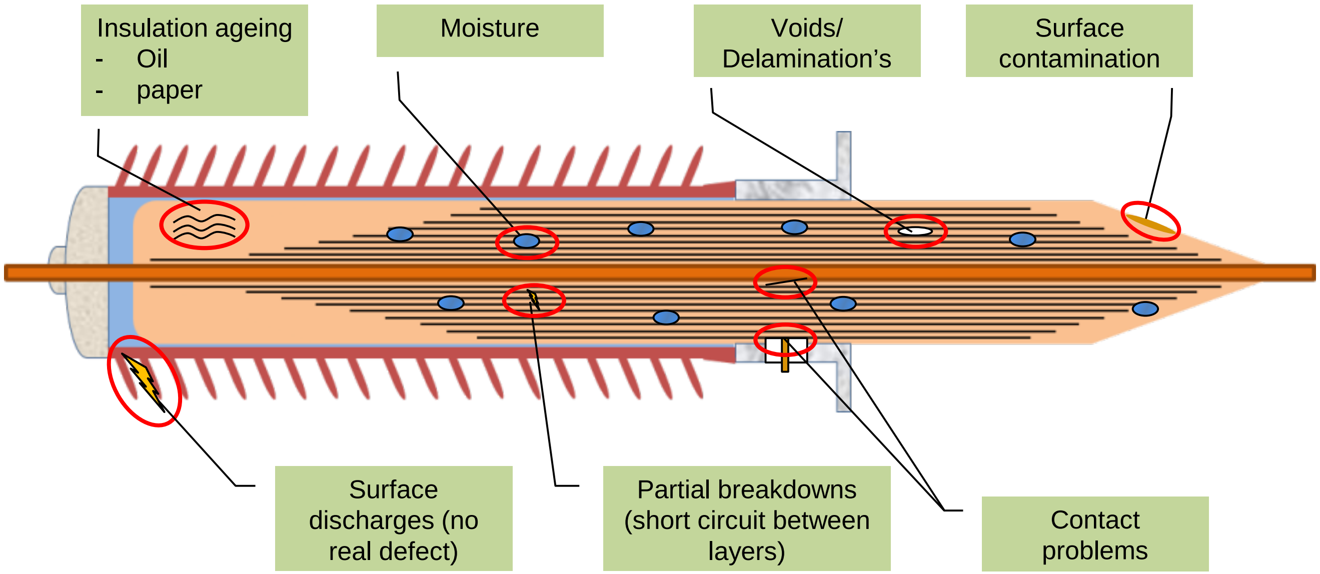
Bushing Failures

- Impact of a catastrophic failure can be tank rupture, violent explosions and fires
- **Result: Higher probability that a new transformer is needed versus failures of other transformer components**
- Violent explosions / fires have high risk of collateral damage and personnel injury/death
- **Result: Risk of injury claims, collateral damage to other S/S assets, insurance premium increases etc**
- Other economic impacts can include **– environmental fines, contractual penalties, loss of revenue**

The value/benefit of bushing monitoring is not related to the asset value (due to low replacement cost) but in ALL costs that could be incurred as a result of bushing failure

Bushing monitoring parameters

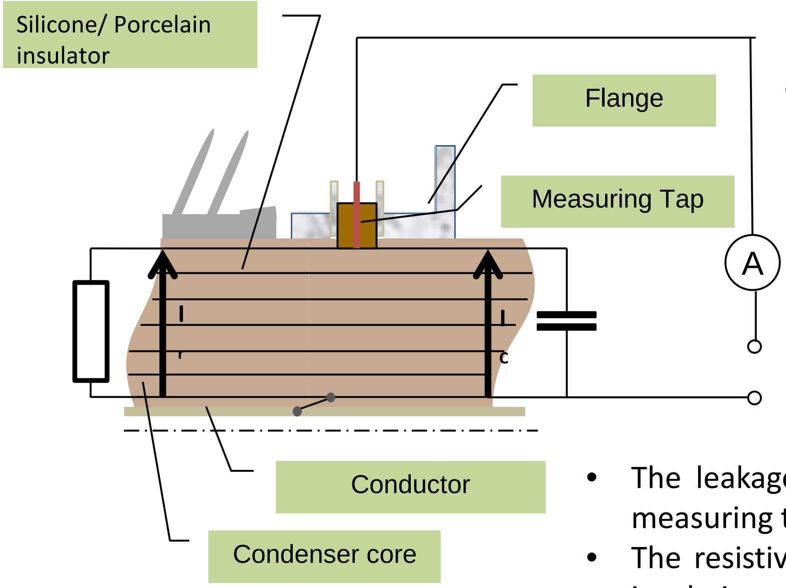
Typical bushing defects

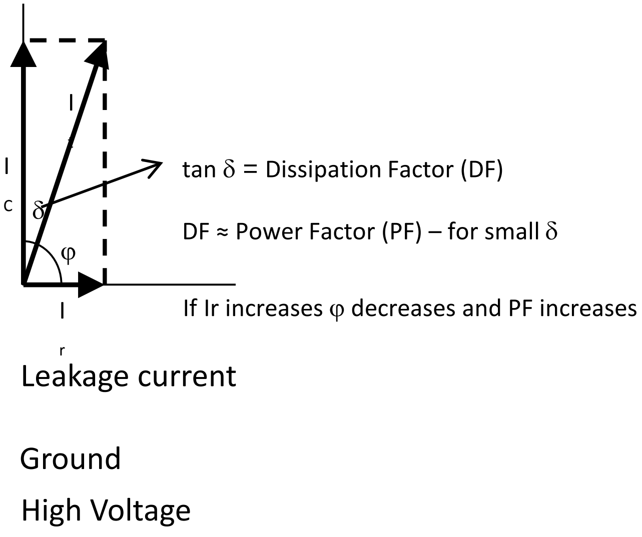


Detectability of different bushing phenomena's

Defect	Tan d / PF	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 d	-	+
Partial breakdowns	+/- If it is combined with erosion of insulating material	+	+/-
Contact problems	+ Shows up as an increased or unstable tan d	+ Shows up as decreased or unstable capacitance	+

Leakage Current

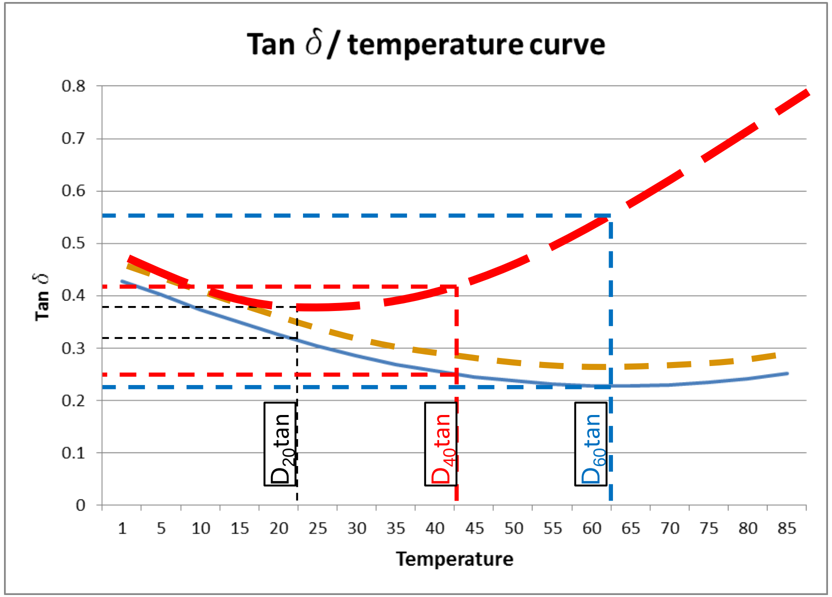


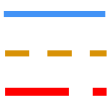


I_C - capacitive current
I_r - resistive current

- 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.

Some additional on moisture in insulation of Bushings





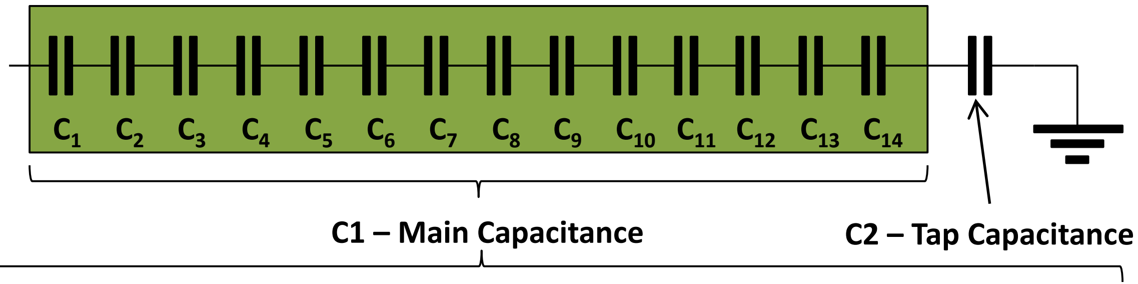
- The difference in tan d at 20°C for Bushings with moisture is small
- For higher temperatures the tan d gradient is increasing and the moisture content is more clearly to detect
- The difference between a dry and a wet bushing could be at 40°C 0.2%, which still needs a high accuracy to detect moisture/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

$D_{20}tan$ < $D_{40}tan$ □ $D_{60}tan$

Valid for wet bushings only!

Capacitance

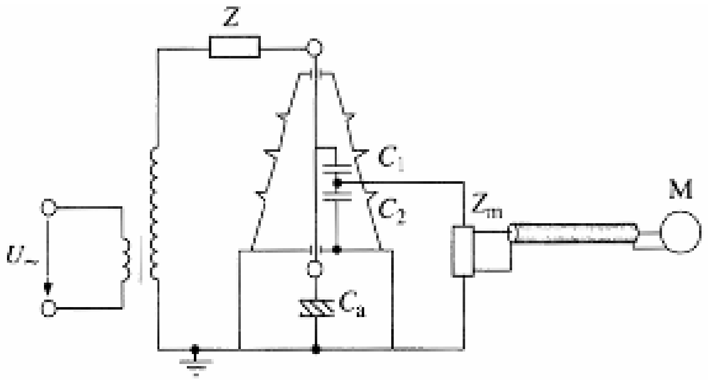
- In bushings there are a several capacitors in series



$$\frac{1}{C1_{\ total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_3} + \frac{1}{C_4} + \frac{1}{C_5} + \frac{1}{C_6} + \frac{1}{C_7} + \frac{1}{C_8} + \frac{1}{C_9} + \frac{1}{C_{10}} + \frac{1}{C_{11}} + \frac{1}{C_{12}} + \frac{1}{C_{13}} + \frac{1}{C_{14}}$$

- 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

Partial Discharges



- The measuring principle for online PD bushing monitoring used today is based on the IEC 60270 method
- The bushing capacitance is used as coupling capacitor
- This PD monitoring principle is applied to monitor the transformer but in some cases also to monitor the bushings

Monitoring Principles

1. **Capacitance monitoring**
   - It is one of the easiest method to apply to do online bushing monitoring
   - This method is aiming mainly on detecting partial breakdowns between one or more of the capacitive layers

2. **Sum of currents (Balanced current) method**
   - Summation of all currents under consideration of their phases (ideal case = 0)
   - Algorithms are considering increase of amplitude

3. **Reference signal method**

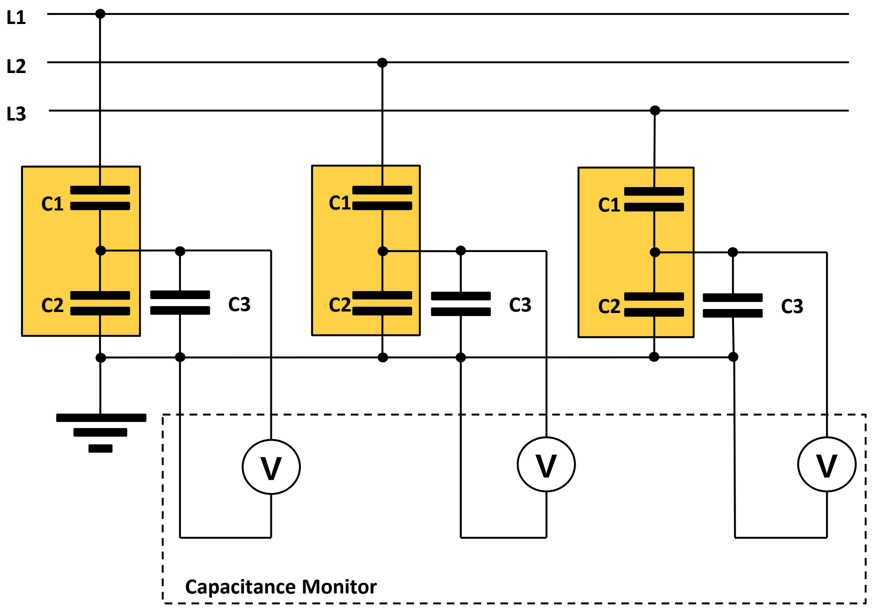
   a) External reference signal
      - Bushings will be compared to an independent reference source from the same phase (like VT, CVT or existing coupling capacitances)

   b) From sister bushing
      - Bushings from different transformer and same phase will be measured against each other (bridge circuit or phase shift measurement)

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

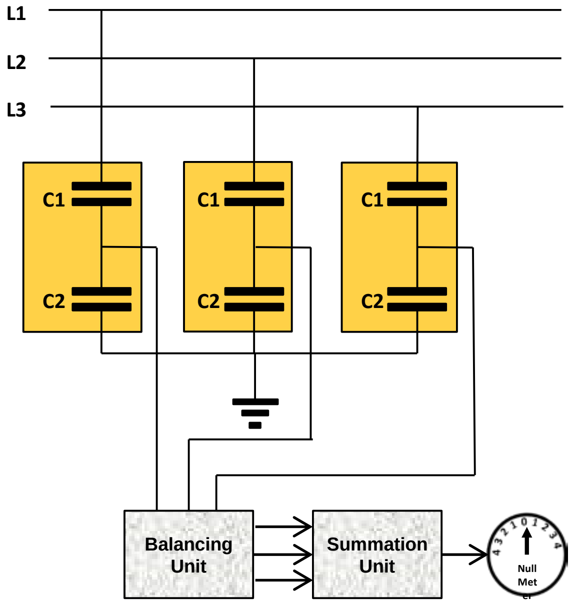


Conclusion: Increase of capacitance and contact problems can be detect in a simple way. Other changes (e.g. moisture, degradation of insulation) can not be detected.

On-line Bushing Monitoring balanced current method

Balance current method

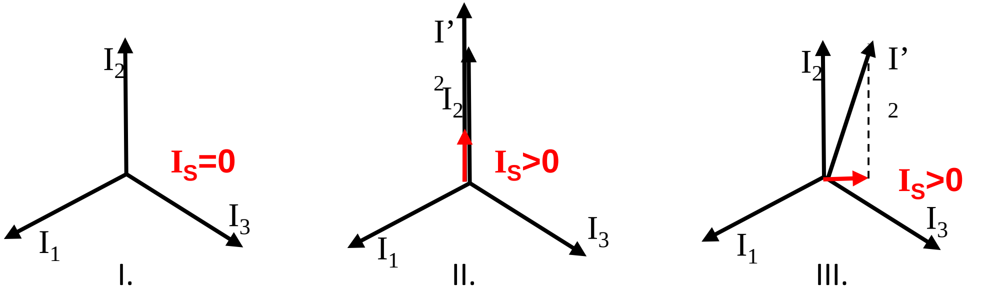
- Assumption: all phases will have absolutely the same voltage amplitude, the phase angles between the phases are perfectly 120 degree and same temperatures
- Under those circumstances the sum of all bushing leakage currents will be zero
- A change in the amplitude of a single leakage current will be counted as capacity increase
- An increase of the current sum is counted as Power Factor increase of a certain bushing
- In reality the phase voltages, angles and temperatures 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 principles

- Ideally, the sum of the three bushing currents should be zero
- In reality, not all parameters are equal from each phase
- During commissioning of the system, the leakage currents are adjusted so the sum of the (3) currents is equal or close to zero



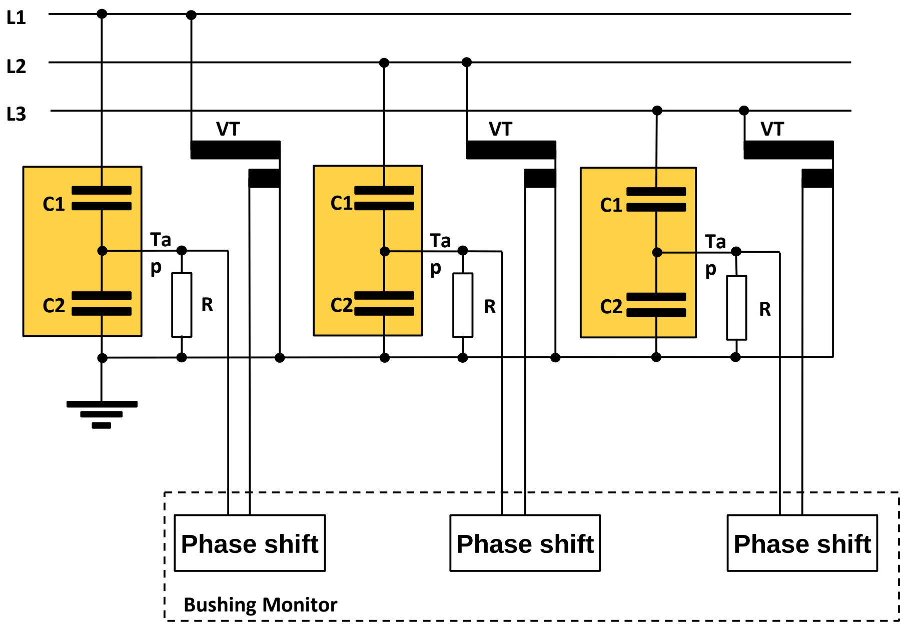
I. All three currents perfectly balanced and the sum equal to zero
II. A change in capacitance results in additional current perpendicular to phase voltage
III. A change in tangent delta results in additional active current, increase in DF (resp. PF)

- The magnitude of the change is an indicator of the problem's severity
- The vector change indicates which bushing is going bad and
- Whether the power factor or capacitance is changing

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 ϴ
- 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

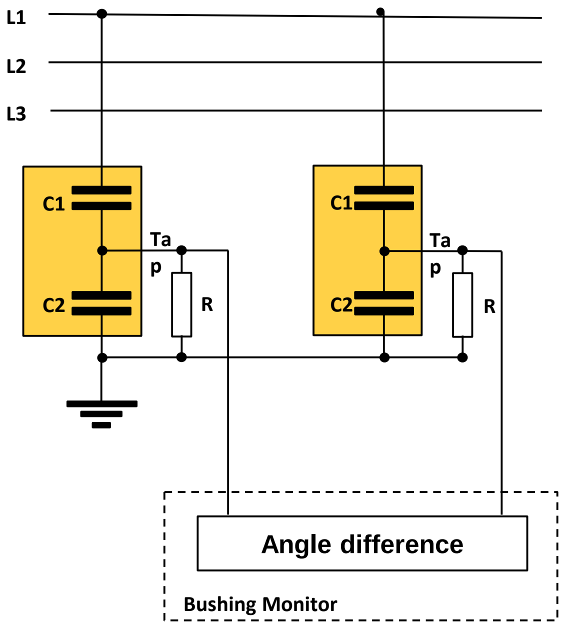


Conclusion: Applying advanced software algorithms for noise and disturbance reduction allows achieving a high accuracy in phase difference measurement

Bushing Monitoring Comparative signal method

Comparative Method

- The angle difference of the two bushings leakage currents connected to the same phase is measured in two channels
- In one channel one of the bushings is used as a reference, in the other the other bushing is used as a reference
- The behavior of the angle (+/-) in both channels identifies the bushing where the Delta angle is changing
- The magnitude of the angle change determines the Tan δ/power factor
- The line to measured voltage ratio is determined during commissioning
- With the RMS value of the leakage current and the phase voltage the capacitance is calculated



Two bushings mounted in different transformers

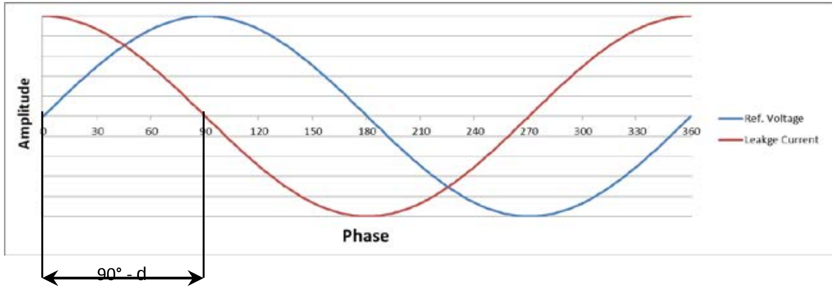
Bushing Monitoring Comparative signal method

Reference signal method

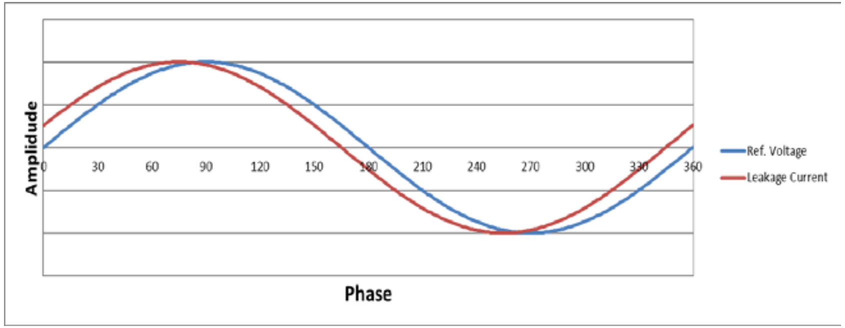
- The reference signal and the bushing signal are 90 degree minus the angle delta (δ) due to the resistive part of the insulation.

Comparative signal method

- A second bushing tap output is used as a reference
- The expected angle between the two signals 0° plus/minus the difference δ-angles of the two bushings
- This method gets also direct Tan δ/power factor and capacitance readings after the calibration

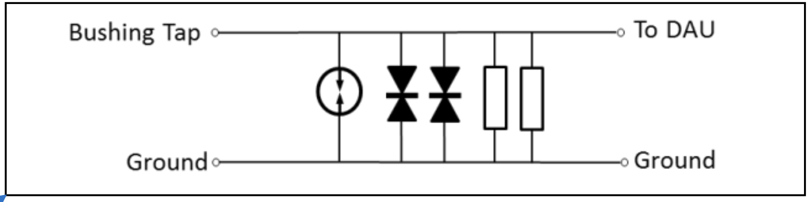


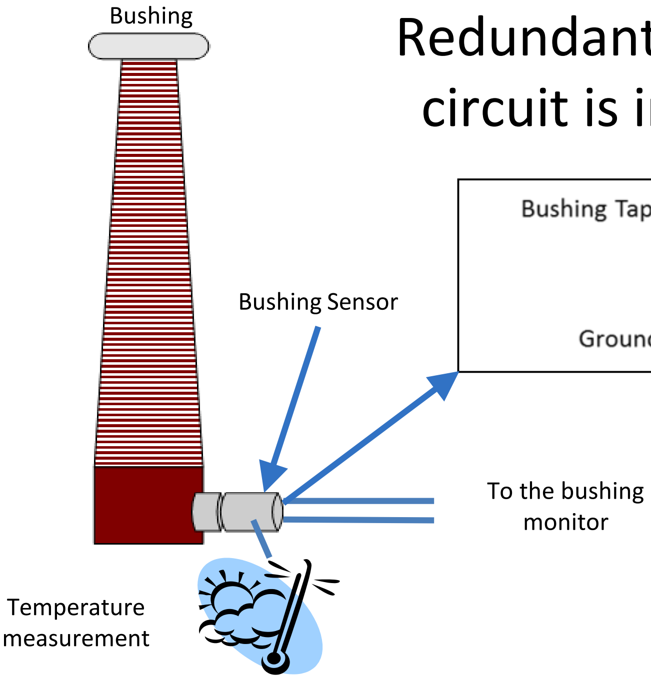
Phase shift measurement



Bushing Monitoring Solution

Redundant protection from open circuit is included at the sensor






Thank you