Very Low Frequency (VLF) Testing of Medium Voltage Motor and Transformer Circuits

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Wayne Johnson
EPRI

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Introduction

- A test has been developed that allows evaluation of medium voltage motors (and transformers) without disconnecting them from their cables
- The test provides better understanding of insulation degradation than dc testing and does not adversely affect the remaining life of old cable insulation

Very Low Frequency (VLF) Testing

- A compact, portable tan delta, high voltage test set operating at 0.1 Hz is used
- Voltage is applied in 2-minute steps of 0.5, 1.0, and 1.5 times line to ground voltage (1.2, 2.4, 3.6 kV for 4 kV circuits; 3.8, 7.6, and 11.4 kV for 13 kV circuits)
- Tan delta and its % standard deviation, VLF insulation resistance and capacitance are recorded for the insulation under test
- For motor circuits, the tan delta % standard deviation and VLF insulation resistance are the most important indicators of insulation health

Where We Began and Where We Got To

- The purpose of the initial work was to find a satisfactory withstand/return to service test to replace dc testing that would not cause early failure of aged polymeric cable insulation
- The effort began by applying standard tan delta testing on motors
- Tan delta testing had been successful on polymer insulated cables and did not adversely affect aged cable insulation
- For cable insulation, tan delta values are independent of cable length and insulation thickness allowing acceptance criteria to be developed

In the Beginning (continued)

- When tan delta was applied to motors, the results were related to each motor design and were not independent of motor size and insulation thickness
- Adjustment for motor capacitance or horsepower could not correct the tan delta enough to allow an acceptance criteria to be developed
- Too many factors affected the tan delta reading (insulation thickness and type, the length of the stator slots, and the design of the end turns)
- Where tan delta for cable had small increases with increasing voltage, most motors had large increases in tan delta as voltage was increased
- Development of acceptance criteria for tan delta was not practical

% Standard Deviation an Indicator of Discharging

- While the tan delta values were motor design and configuration dependent, the % standard deviation of the tan delta values were useful indicators of the presence of partial discharge or tracking in the circuit's insulation
- Small variations in tan delta from cycle to cycle indicates that discharging is occurring, and further investigation is necessary
- While tan delta testing cannot locate the source within the cable or motor, it will indicate when significant discharging or tracking is occurring

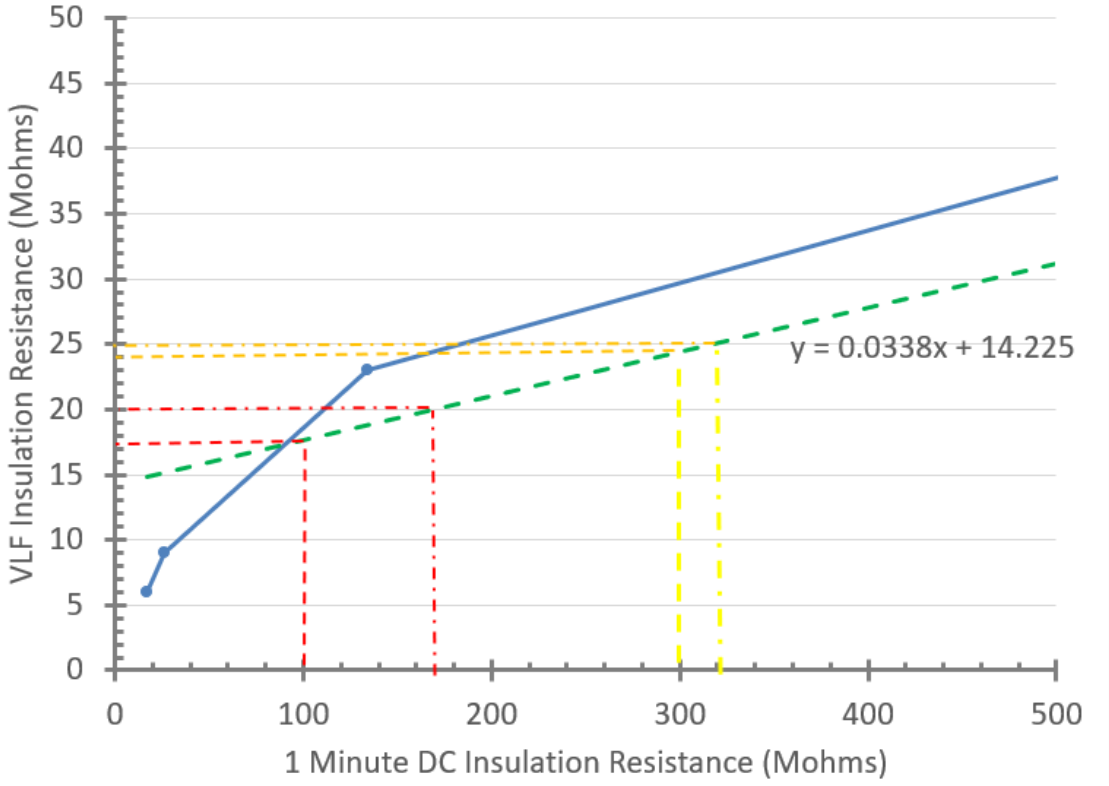
Partial Discharge and Tracking

- Partial discharge is caused by breakdown of air gaps in insulation that erodes the insulation leading to cut through and failure
- Tracking is discharging across the surface of an insulation that can also lead to failure
- These are high frequency phenomena that cause spikes in test set voltage and current
- The capacitance of the motor and cable insulation dampen the signals causing small changes in the measured tan delta that can be identified by increases in the % standard deviation of the tan delta value

The First Significant Insight: VLF Insulation Resistance

- In addition to tan delta, the test set provides the load resistance (hereafter called VLF insulation resistance) and the capacitance
- The capacitance value is governed by motor size, slot length, and insulation thickness
- The VLF insulation resistance is less dependent on the motor design and as the value decreases VLF IR is a strong indicator of insulation degradation allowing acceptance criteria to be developed
- Higher values of VLF insulation resistance are dependent on polarization and end turn characteristics

Comparison of VLF and DC Insulation Resistances

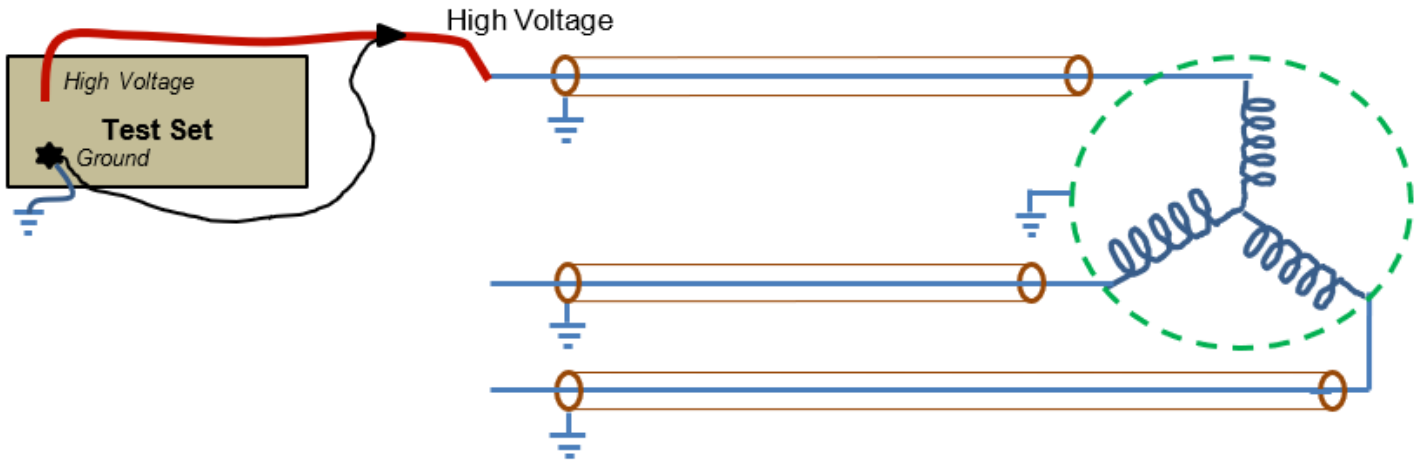


- The values of VLF insulation resistance are smaller than the dc values because polarization and absorption currents are always present during the 10 second VLF wave but greatly reduced after 1 minute of dc application
- The upper limits of VLF insulation are governed by absorption and polarization currents
- The lower VLF insulation resistance values are dominated by leakage current, which will lead to insulation failure

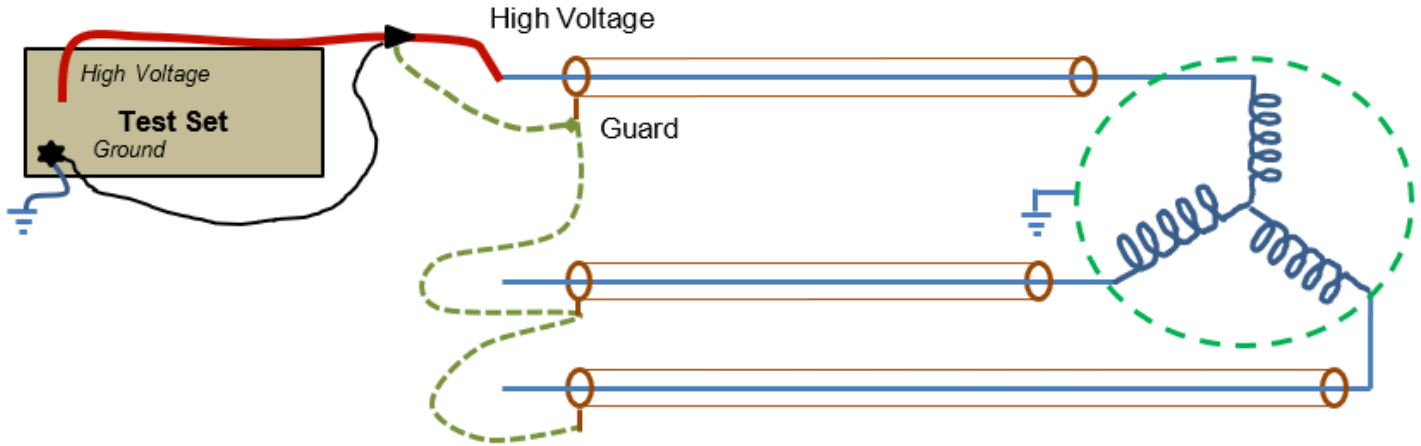
Second Significant Insight: Use the Cable as a Test Lead

- During a LEMUG meeting, attendees indicated that another test method allowed motor testing from the cable terminations by using the medium voltage cable as a test lead (cable guarded out)
- This method was attempted using the tan delta test set
- Some initial success occurred, but the guard current limit of the test set was too low causing the test set to trip on moderate length cables
- After the manufacturer increased the guard current limit, testing with the cable guarded out was successful

Testing Circuits



Circuit Test



Cable Guarded Out Test

Circuit and Cable Guarded Out Tests

- The Cable Guarded Out result provides the condition of the motor and lead insulation
- The Circuit test provides the condition of the overall cable and motor insulation including the splice between the motor and cable

VLF Acceptance Criteria for Motor Circuits

- **CGO Acceptance Criteria**

VLF Insulation Resistance	Assessment Criteria
>25 Mohms	Good
20< Mohms <25	Further Study Required
<20 Mohms	Action Required

- **% Standard Deviation Acceptance Criteria**

Condition	Percent Standard Deviation of Tan Delta Measurements at a Particular Test Voltage
Good	≤0.02
Further study required	0.02+ <% standard deviation <0.04
Action required	>0.04

Cable VLF Insulation Resistance

$$IR_{cable} = \frac{IR_{motor} \times IR_{circuit}}{IR_{motor} - IR_{circuit}}$$

where:

IR_{cable} = VLF insulation resistance of the three phases of the cable in parallel

$IR_{circuit}$ = VLF insulation resistance of the overall circuit under test

IR_{motor} = VLF insulation resistance of the motor = VLF insulation resistance of the circuit with the cable guarded out

- Often this can be done by inspection: If $IR_{circuit}$ and IR_{motor} are the same, the IR_{cable} has to be very high and is acceptable

Logical Assessment

- Logical evaluation of the results is necessary
  - If the problem is seen in the CIR and the CGO result, it is related to the motor and leads
  - If the problem is seen only in the CIR result, it is related to the cable
- The cable VLF insulation resistance should be calculated to determine the health of the cable
- The cable capacitance is the difference between the motor capacitance and the circuit capacitance
- With the cable VLF insulation resistance and the cable capacitance, the cable tan delta may be calculated for comparison to the cable acceptance criteria

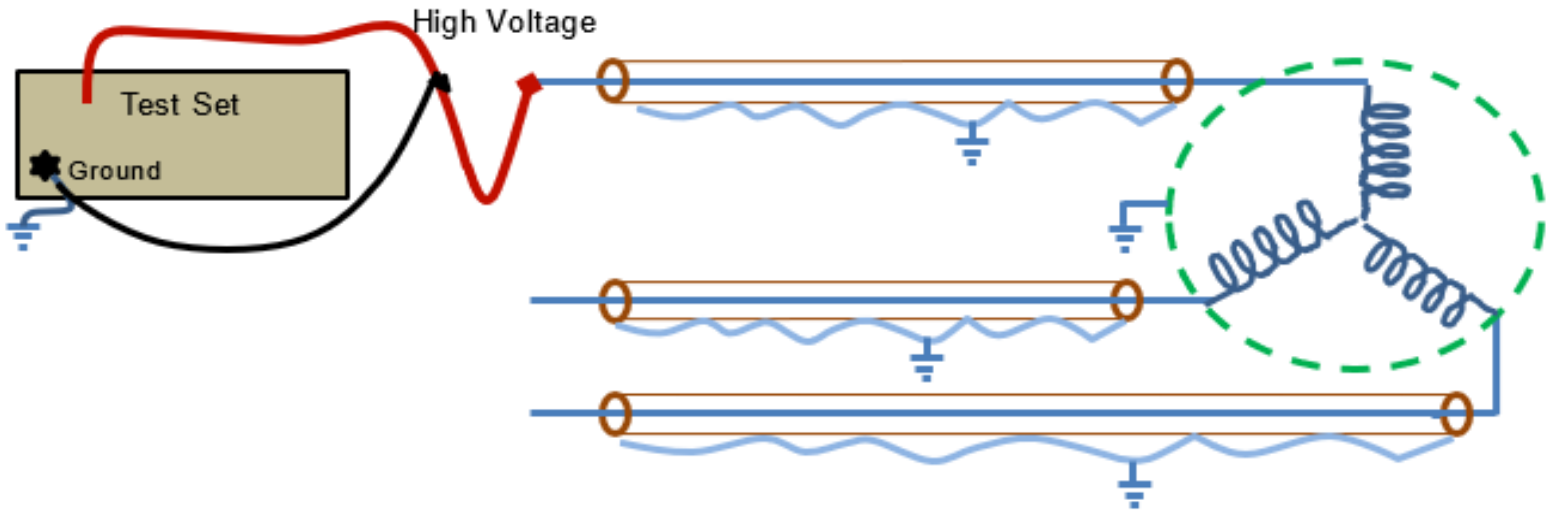
Third Insight: Be Aware of Moist Windings

- The tests during the first year and a half were all done during dry periods of the year
- However, subsequent tests during a very wet spring indicated that non-sealed motor insulation systems are greatly affected by moisture on the winding (Nothing new; we just hadn't seen it during the research)
- The capacitance of the winding increases when wet and the insulation resistance greatly decreases; recording the motor temperature and humidity at the time of the test is important to interpreting results

Fourth Insight: Testability of Circuits with Non-shielded Cables

- During the research, testing was performed successfully on non-shielded cable
- Previously, testing of non-shielded cable was considered useless
- However, the partial grounding of the cable surface by trays and conduits provides enough capacitance to allow testing
- Additionally, the condition of insulation at the grounded points is of high importance.
  - If low VLF insulation resistance or high % standard deviation occurs, the insulation is failing at that point and a ground will occur
  - If a second ground occurs, a phase-to-phase fault will occur

Test of a Circuit with a Non-shielded Cable



Note: The surface of a non-shielded cable is at conductor voltage during operation and test. Do not touch the cable surface.

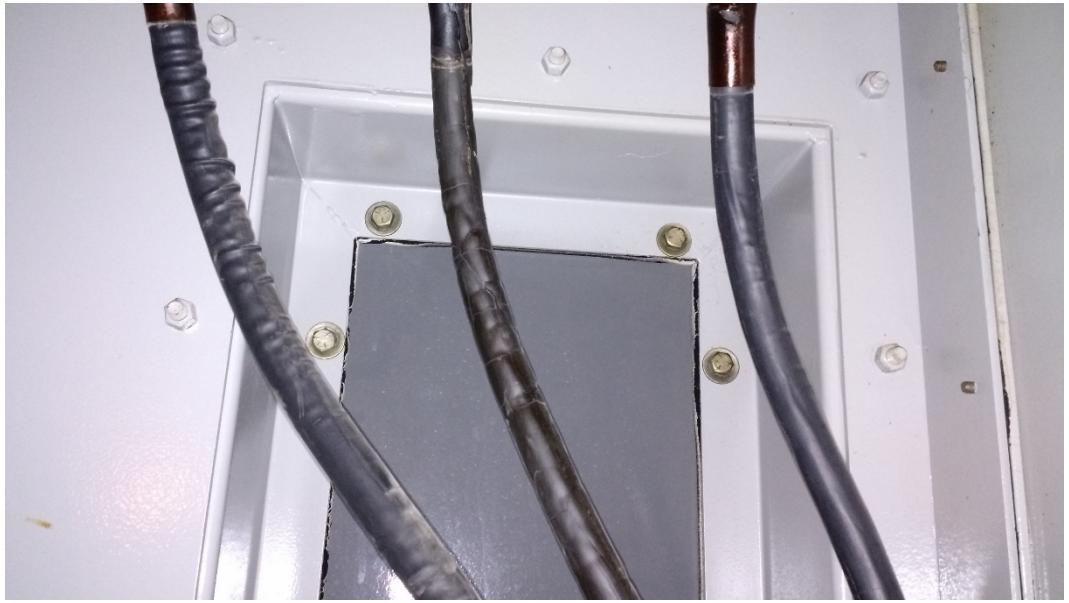
- The cable insulation is grounded randomly by tray rungs and conduit surfaces.
- The condition of the insulation at the grounding points is important to the continued function of the circuit
- The test only will indicate good or deteriorated insulation.
- Separation of the motor from the cable is necessary to determine which has the problem

Fifth Insight: New Plants Have Problems

- Testing at a five-year-old plant identified a number of lead box issues including grossly over heated lead insulation and severe discharging at lead pass throughs

Severe Discharging at Lead Support

Grossly Overheated Lead Insulation



Sixth Insight: DC Insulation Resistance Does Not Always Indicate Actual Condition

- Good or reasonably good dc insulation resistance does not always indicate good ac condition

- At a motor shop, a motor with a severe partial discharge issue measured 150 Mohms on the shop's and author's dc insulation resistance test at 2500 V.
- At 2400V (second step of TD test), the VLF insulation resistance went to 0 indicating failure.
- In the five-year-old plant, a lead that was nearly shorted to ground had a 6 Gohm dc insulation resistance.
- At 1200 V, the VLF insulation resistance indicated a near short
- Other results during the research indicated that dc insulation results can be misleading with respect to ac condition of the insulation

Field Use Insights

- Don’t do CIR and CGO on different days.
  - The conditions will be different and the cable calculation will likely be wrong.
  - Do these tests on the same shift with as little time between them as possible
- Partial discharge (% standard deviation results) are affected by points in the lead area including those on tie wraps and wires for paper tags, and also by proximity to plastic used as standoff from the lead or cable phase surface

- The potential gradient will be highest at any corner or sharp point leading to discharging to the air
- Use Corona Balls or clay to round out sharp corners

DC Insulation Resistance Testing versus VLF Tan Delta Testing

- The research determined that dc insulation resistance testing does not damage ethylene propylene rubber (EPR) insulation.
- However, it also determined that dc insulation resistance results are often misleading
- DC insulation resistance is performed at 2500 Vdc for 4160 V circuits and 5000 Vdc for 13 kV circuits
- At these voltages, dc does not cause partial discharge excitation, so partial discharge, if present, will not be observed
- Excitation of partial discharge may also be affected by reversal of the voltage during ac excitation.
- The increase and decrease as well as reversal of voltage gives a better indication of the presence or absence of discharging

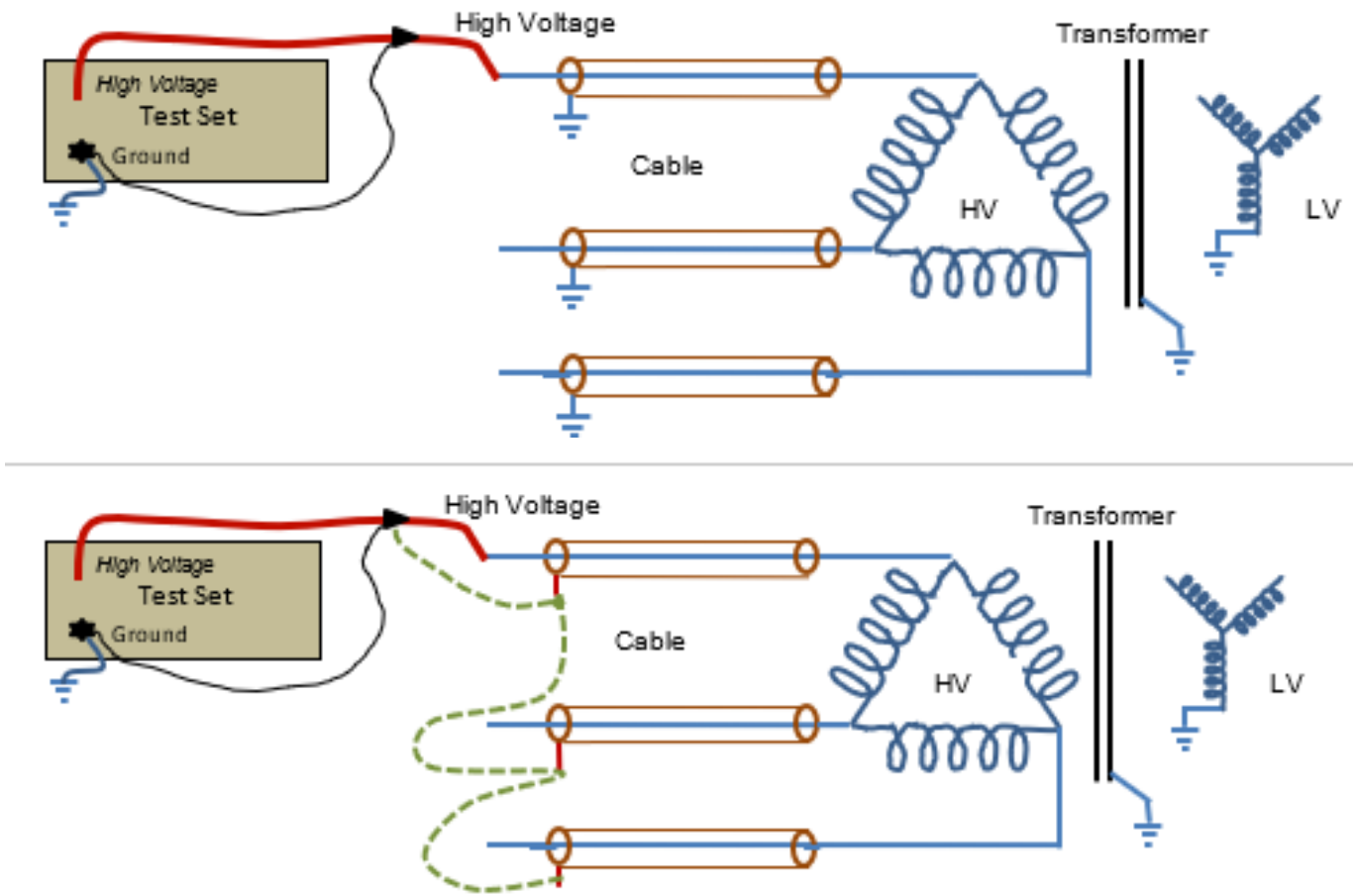
The Reports

- 3002016077, Medium Voltage Motor and Cable Very Low Frequency (VLF) Tan Delta Testing from the Cable Termination, Final Report, November 2019
- 3002013161, Field Guide for Very Low Frequency Tan Delta Testing of Medium Voltages Motors from the Cable Terminations, November 2018

Further Application of Circuit Testing

- As a follow-on to motor circuit testing, plant distribution transformer circuit testing has been performed
- Dry, encapsulated and oil filled transformers have been tested
- Circuit and cable guarded out tests are also applicable to transformer circuits
- Testing of additional transformers occurred in 2020 to allow VLF insulation resistance assessment criteria to be developed

Transformer Circuit Testing



LV winding must be grounded to verify HV to LV insulation and to prevent a ***personnel hazard*** from retained voltage on low voltage winding.

Conclusions

- VLF testing provides better insights than dc testing and does not cause damage to medium voltage cable insulation
- Use of the method allows determination of the motor and cable condition without breaking of the motor to cable termination, easily saving a shift of work if the cable motor were tested separately
- VLF tests provide a better understanding of the condition of the insulation in ac motors than dc tests by identifying the presence of partial discharge, if it is occurring
- If a problem is observed, it can be traced to the motor or cable without further testing allowing a determination on how to proceed with further testing or repair
- The test method has now been applied to dry and oil filled distribution transformer circuits as well

Questions