New Insights and Complications in Determining Generator Stator Insulation Absorption Current Exponents and Constants from Polarization Index Test Data

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Abstract

Significant errors may occur in calculating the generator insulation Polarization Index (PI), absorption current exponent (n), and the insulation constant (K), from standard PI test data. The paper addresses a previously undocumented PI response that occurs which is the cause of the subject errors. A simple approach is described to eliminate these errors especially when using the IEEE Standard 95-2002TM [1] to correct for leakage current. IEEE Standard 43-2000TM [2] is also useful regarding associated PI and insulation resistance calculations.

In addition laboratory test data will be presented showing the relation between stator bar insulation temperature and the insulation constants K and n.

Introduction

The Polarization Index test is a fairly common generator stator winding test. The test result, referred to as the PI, is said to be automatically normalized for temperature and winding size. This will be explored in detail. A decrease in the PI over time is indicative of an increase in leakage and/or conduction current due either to insulation deterioration and/or moisture or water ingress into the insulation. IEEE standard 95-2002TM presents a method for removing the leakage/conduction components of current from the PI curve. Once this is done the insulation absorption exponent, n, also referred to as the absorption ratio, and the insulation constant, K can be determined. Improved accuracy of these constants may enhance the ability of the PI test to better evaluate changes or deterioration in the insulation and possibly to provide better insight into the subject of temperature correction. Understanding the effects of the anomalies will allow one to quite easily adjust the raw data to ensure the accuracy of the calculated constants.

Absorption Current response, General Form

The absorption current response of generator insulation to a step increase in voltage results in a current spike that takes many hours to decay to a negligible value. The expression for the decaying current is given by the following empirical formula:

\[ I = \Delta V \times C \times K \times (T^n) \]  

(1)

Where:

- \( I \) = absorption current in microamperes
- \( \Delta V \) = applied voltage step in volts
- \( C \) = capacitance of the insulation in microfarads
- \( K \) = constant for the insulation
- \( T \) = time in minutes (for \( T \geq 1 \) minute or so)
- \( n \) = absorption exponent for a particular insulation

The equation must be worked in minutes because the current and resultant constants are related to readings taken at the one and ten minute time intervals when performing a Polarization Index test.

At time \( T \) equal to one minute, \( T^n \) has a value of one, regardless of the value of \( n \). (one raised to any power is equal to one.) Therefore, \( K \) can be calculated knowing \( I_{1\, \text{minute}} \), \( \Delta V \), and \( C \). Knowing the \( I_{10\, \text{minute}} \) value, the absorption exponent \( n \) can then be calculated.

It so happens that the absorption exponent also works out to be equal to \( \log_{10} \) of the Polarization Index as illustrated below.

\[ \text{PI} = \frac{I_1}{I_{10}} = \frac{\Delta VCK \ (1^n)}{\Delta VCK \ (10^n)} = 1/10^n \]

Therefore, \( \text{PI} = 10^n \)  

(2)

It follows:  
\[ n = \log_{10} (\text{PI}) \]

Absorption Current Log-Log Graphs

The absorption current response to a stepped voltage (PI Test) is nonlinear with respect to time. This is due to the current being dependent on the time \( T \) raised to a power (the exponent \( n \)). If the absorption current is graphed as a function of time (from one minute to ten minutes) on Log-Log graph paper, the ideal result is a line having a constant slope, (straight line). The value of the slope is the exponent \( n \). If the winding being tested is wet, very aged, or contaminated, there will be a leakage or conduction component of current that will exist throughout the duration of the Polarization Index test. Thus the measured current will have components of absorption,
leakage, and/or conduction. The leakage or conduction current being constant will result in a Log-Log current plot in which the slope of the current increases with time. That is the current response on Log-Log paper is no longer a straight line that is it has curvature. The Polarization Index (the one minute current reading divided by the ten minute reading) is a simple representation of this curvature. When the leakage or conduction current increases (wet insulation, contaminated, or as the insulation deteriorates), the PI decreases (due to the increasing curvature on the Log-Log graph).

At times one would like to determine the K and n values in the absorption current equation to determine if the insulation materials are changing due to the effects of ageing. However this is not possible if, due to conduction/leakage current, the Log-Log current is not a straight line. To calculate K and n the leakage/conduction current effect must first be removed from the component current data. There are several means by which the leakage/conduction current can be separated from the absorption current data; however the accepted and usually the most accurate method to correct for leakage/conduction current is described in IEEE standard 95. (Subsequent information to be presented will show that this accepted method may not always yield the most accurate values of K and n.) The magnitude of the leakage and/or conduction current, and how it changes as the insulation ages is also of some value, but it is not normalized like the PI, and is therefore dependent on both the size of the machine and the temperature at time of test.

**Correction for Leakage/Conduction Current**

To subtract the leakage and/or conduction current, \( I_{LC} \), out of the measured composite current the current at the 1, 3.16, and 10 minute intervals must be obtained to calculate the value of the conduction/leakage current. The formula per IEEE Standard 95-2002 is:

\[
I_{CL} = (I_1 \times I_{10} - I_{3.16}^2)/(I_1 + I_{10} - 2I_{3.16}) \quad (4)
\]

The current \( I_{CL} \) first must be subtracted from the one and ten minute current values to obtain the true absorption current values. Using the corrected one and ten minute absorption current values, \( n \) and \( K \) can be determined. The PI resulting from the removal of the leakage and/or conduction current normally is not used. However changes in \( n \) and \( K \) may be of some value in assessing how the insulation is ageing [2].

The corrected absorption current will plot as a straight line on Log-Log graph paper. The slope of the straight line is equal to the absorption current exponent \( n \). The formula to calculate the slope is:

\[
N = \frac{\log (F_1/F_2)}{\log (X_1/X_2)} \quad (5)
\]

Where: \( F_1 \) is the absorption current at time \( X_1 \), and \( F_2 \) is the absorption current at a later time \( X_2 \).

**Absorption Current at Times Less Than One Minute**

When the PI test data is obtained and log-log plotted from ten minutes to a time significantly before time equal to one minute, a rather abrupt change in the slope of the current response will sometimes be found to exist. This inflection point, more often than not, seems to occur in the vicinity of the one to two minute time frame of the PI test. The Log-Log segment of the curve before the inflection point is a straight line similar to the straight line observed after the inflection point. However the two segments of the curve (before and after the inflection point) will have different slopes, that is, different absorption exponents. When the inflection point occurs at or very close to time equal to one minute the two segments of the curve will have the same constant \( K \), but different absorption exponents. When the inflection point occurs at a time other than one minute the two segments of the curve will not only have different absorption exponents, but also different \( K \) constants. The term “inflection point” is used to emphasize the rather abrupt change that occurs in the slope (absorption exponent).

If the inflection point occurs at a time greater than one minute the one minute to ten minute Polarization Index calculation can have a significant error. The calculated absorption current exponent and the \( K \) constant calculated from the one and ten minute readings can also have significant errors. The solution to ensure accuracy in the calculations is to Log-Log plot the absorption current over the half minute to ten minute period of interest. If the one minute reading is out of line with the 1.5 minute reading and subsequent readings it should not be considered a valid data point for calculating the subject constants or for subtracting out the leakage/conduction current. Accurate calculations can still be made using the other data points. The slope, absorption current exponent, and the PI can be calculated from any two data points, and the \( K \) constant can be obtained via calculation or extrapolation of the curve to the one minute point and obviously disregarding the erroneous one minute data point. Obtaining at least three or four absorption current data points for times less than one minute will enhance the accuracy of these calculations. An automated data acquisition system is highly recommended to obtain quality data for times less than one minute.

**DC Testing Capacitive Specimens**

When performing any kind of dc testing on a predominantly capacitive specimen such as generator insulation the magnitude of the charging current can present a problem. Very small changes in voltage can result in very large current excursions. The current surges due to sudden changes in voltage can result in the test specimen current exceeding the test set current rating. The supply may trip or go into a voltage...
output limiting mode of operation. The resulting current response may become noisy and or erratic in nature. Some test sets may not be able to absorb current from the test specimen. Should the test set voltage decrease for any reason, there may or may not be a current fed back into the power supply from the specimen under test. Further the high frequency voltage ripple at the output of the supply can induce a large high frequency ripple related current in the specimen/current metering circuit. Further the current meter must be highly filtered or damped to ensure proper operation.

To avoid the above mentioned problems, a high voltage resistor is placed between the highly regulated dc test set high voltage output and the test specimen. A two mega-ohm resistor is used in the Reclamation Ramp Test Set. This resistor must be fairly small to keep the time constant of the high voltage circuit reasonably short. A small time constant will keep the R-C related current lag to a minimum. When testing a large winding (one microfarad), the circuit time constant is about two seconds. The two meg-ohm resistor reduces ripple related current, limits initial capacitive charging current, and limits initial absorption current when performing a PI test, an IEEE voltage/timed step test, or a Ramped DC test.

**PI Test Data Analysis**

The changes in the slope of a PI data plot below one minute is not due to the capacitive charging time constant as that time constant is considerably less than the observed decay below one minute. This change in slope exists whether testing single coils or an entire winding. The effect is obvious in reasonably sized graphics, but not so apparent in the smaller figures presented in this paper. Three different types of test apparatus/setups were used to ensure the observed changes in PI were not test equipment related. The capacitance of the winding or coil was determined beforehand from ramp test results as this takes into account grading treatment and end arm effects that occur above 3 kV or so.

Figure 1: The test circuit R-C time constant when performing a 1 kV PI test on one phase of a Glen Canyon 13.8 kV generator epoxy-mica winding is about 2 seconds and thus the effect is inconsequential after 10 seconds. At the end of 30 seconds the Glen Canyon phase capacitive charging current is calculated to be 0.00076 microampere. This is considerably lower than the actual measured current of 1.2 microamperes and still significantly lower than the 0.3 microampere projected difference between the two line segments that can be seen to exist before and after the one minute point. The slope increases slightly (more positive) after the one minute point. Straight line curve fitting is utilized in figures 1 to 3. The slight curvature in the lower line segment may be due to a very small amount of leakage current or instrumentation errors as the raw data was rather noisy.

Figure 2: When performing 5 kV PI tests on a new 13.8 kV epoxy-mica generator bar from Crystal Power Plant no guards were used to eliminate grading treatment effects. The bar circuit R-C time constant is four milliseconds, thus the subject charging effect is negligible. By the time the one minute point is reached this RC charging current, for all practical purposes, is essentially zero. The measured absorption current at one minute is 0.015 microampere. The projected difference between the two line segments on the Log-log plot at 1 minute is 0.0015 microampere. Note that the inflection point occurs at about 1.5 minutes, and the slope decreases (more negative) after the 1.5 minute point. The PI for the after inflection point line segment as drawn in figure 2 is 64.6. The PI is 59.6 using the one and ten minute data points. Thus there is a PI error of about 8%, which can vary based on how one connects the data points.

Figure 3: Shown is a 5 kV PI plot of the Mt. Elbert Power and Pumping Plant Unit 1, phase A, 11.5 kV winding. This is a polyester-mica winding. The data was taken with a high potential mega-ohm meter having an accurate digital readout,
thus the better straight line fit to the data points than in the previous figures. The inflection point occurs around 2.5 minutes and thereafter, the slope decreases very slightly. The effect appears to be very minor in polyester insulation.

**Grading Treatment effects on PI**

The grading treatment applied to the surface of the stator coils in the end turn area is an extremely nonlinear and highly resistive material used to control voltage gradients in the winding end turns.

If the end turns are very clean and the end turn insulation is of extremely good quality, there may be little to no end turn related leakage or conduction current in the grading treatment during the PI test. Thus the only current through the grading treatment would be that due to the absorption current present in the insulation under the grading treatment. This can and has been validated by applying guards slightly beyond the outboard ends of the grading treatment and comparing the PI test results to the PI test results without the guards. The above only applies to very high quality end turn insulation having extremely clean end turn surfaces.

The component of absorption current from the insulation under the grading treatment is modified by the grading treatment component of insulation capacitance related current in conjunction with the grading treatment nonlinear resistance. This can result in a nonlinear R-C time constant that can delay the decay of the grading treatment related component of the absorption/charging current.

In practice/real world during a PI test the end turn surface voltage rises to some percentage of test voltage as a result of predominately end turn insulation capacitive charging current and to some degree as a result of end turn absorption related current. Under less than ideal conditions some of the surface charge will bleed off to ground through the grading treatment and there will be some conduction through the insulation replenishing a portion of this charge. End turn insulation is usually thicker and is not always of the same quality as the insulation in the slot section of the coil and thus may have slightly different values of K and n. This is also due to taping irregularities around end turn bends and problems associated with achieving uniform pressing, and consolidation of this insulation. The result is a stable end turn leakage/conduction current through the grading treatment resulting in an overall reduced PI. Obviously end turn cleanliness can significantly affect PI test results. Moisture in the winding and/or high humidity conditions will also result in an increase in leakage and/or conduction current thereby reducing the PI.

**Temperature Effects on K and n**

The crystal power plant bar (see figure 2) was PI tested from 22° C to 50° C in an environmental test chamber. The test results are shown in figure 4. Lamarre et al [4] provides temp. information up to 100°C. Note that K and n are fairly constant up to about 40° C. Figure 4 also shows the time of inflection and the specific change in slope. Note that n (before and after the inflection point) crosses at some temperature above 40°C, and the same holds true for K. The values of the inflection point, K, and n change noticeably above 40°C.

It appears that for temperatures below 40° C the variations in K and n with respect to temperature are fairly small thus somewhat larger changes in K and n could, with some assurance, be associated with changes in the basic properties of the insulation and/or the grading treatment, moisture, or end turn contamination. Tests from 22° to 40° C on the Crystal bar have resulted in the absorption exponent changing from 1.8 to
1.68, and K changing from 0.0015 to 0.0014. In this case temperature has a significant affect on n, but not on K. This may be due to the fact that the exponent n is related to thermal processes. In any event it appears changes in K at lower test temperatures, in some cases, might be useful in assessing insulation ageing processes as K appears to be fairly independent of temperature.

Temperature characteristics of the grading treatment have yet to be measured, but it is known that silicon-carbide resistivity decreases linearly up to about 100°C. This is a generality and may not be valid in many formulations used in grading treatments. Resistivity can increase over time due to oxidation especially if the grading treatment is not protected with a protective filler, carrier, or coating. However this may be a minor effect compared to the effects of end turn moisture and/or contamination.

**Modeling Absorption Current Response**

There is no simple mathematical expression for absorption current vs. time when the insulation is subjected to either a PI test voltage or a ramped voltage. It must be pointed out that the absorption current formula is empirical. Further, the formula is only applicable from T in the region of one minute and beyond. The accepted formula does not agree with actual test data obtained below one minute. The grading treatment must also be modeled as it has a significant impact on both the PI and ramp test results. AC and DC models will be different. Conduction at the silicon-carbide boundaries is mostly tunneling by field emission. An AC model must include the nonlinear boundary resistances and the linear and nonlinear boundary capacitances.

The end turn insulation is of a different thickness and quality, may have different K and n values, and is highly susceptible to end turn contamination and humidity/moisture conditions. Absorption current in the end turns and end turn surface voltage distribution issues present additional modeling complications. To obtain an accurate computer model simulation requires that all of these phenomena be accurately modeled. A laboratory based test isolating the grading treatment and using guard circuits to eliminate end turn insulation effects would be significantly easier to simulate on a digital computer.

**Insulation Ageing**

One major ageing mechanism is heat related. The long term observed effect is a discoloration of the ground wall insulation. The binder starts to yellow or turn tan first at the tape lap edges, and progresses into the tape as the discoloration increases and darkens. The discoloration is a result of a change in the chemical composition of the epoxy, fillers, and such. This thermal ageing process usually occurs throughout the winding and usually causes weakened bonding, and eventually delaminated insulation. This widespread type of deterioration may result in significant changes in K, and n.

Another major ageing process is voltage related. Over time, the insulation at the copper boundary of the two to five multi-turn coils operating at and near line end voltage begins to deteriorate. This is usually related to a combination of heat, thermo-mechanical expansion forces, and most importantly partial discharges (PD) which, over time, can destroy strand and turn insulation. Thus multi-turn coils usually fail turn to turn well before the ground wall insulation starts to deteriorate. Dissection of such coils reveals almost complete loss of strand and turn insulation but still serviceable ground wall insulation. The mica and tape backing, due to vibration, PD, and copper related corrosion is reduced to powder and small bits. The binder is turned into a green to gray relatively conductive (100’s of meg-ohms) powder. The result is the high resistance bypassing of a significant portion of the insulation thickness. The main effect is that the capacitance of an affected coil is increased significantly at the higher test voltages. A 1 kV and even a 5 kV PI test on such a coil may not always be able to detect this condition as sufficient voltage must build across the deteriorated insulation for it to ionize and thereby increase the capacitance. An increase in capacitance will also result in an increase in the absorption current. The value of n may remain the same as the chemical composition of the remaining insulation has not changed. The value of k may be related to the thickness of the insulation and thus may change. This condition may not be detectable when testing as the coils operating at lower voltages will not have this damage since lower voltage coils will mask the impact of the deteriorated line end coils. In this situation PD, Corona Probe, and Ramp testing may be valuable assessment tools.

**Conclusions**

New information has been presented. It may take time and effort before all of the various PI test results and effects can be fully understood, categorized, and/or generalized into a useable form to enhance stator insulation analysis. With so many different insulation systems (tapes, fillers, etc.) in use additional testing of the various insulations will be necessary.

**References**