WHAT ARE STANDARDIZED EQUATIONS FOR ACCEPTANCE OF HI-POT TESTS AND FOR VOLTAGE DROP?

Paper No. PCIC-98-30

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Abstract: Long power cables and large machines require different application techniques from most electrical wiring. The first topic discussed is evaluation of insulation for continued use. The second area is selection of conductor size considering temperature and voltage drop. The hi-pot evaluation is primarily a maintenance function, while the voltage drop procedure is primarily a design practice.

For the first topic, high potential (hi-pot) tests are often conducted on power cables and large machines. However, there has been no standardized method of determining if the insulation is acceptable. Various methods have tried to compare leakage current between conductors, use a fixed limit on leakage current, or compare with previous tests. Each has its advantages and limitations.

From empirical data and diverse experience, we have developed a numeric technique that will indicate impending failure. The procedure is mathematically rigorous but can be practically applied. It is very applicable to computer controlled hi-pot systems as well as manual systems.

The second topic is the voltage drop for long conductors. We have applied numerous considerations to develop a simple relationship that can be readily applied. It incorporates wire diameter, length, current, number of phases, and temperature correction, with permissible voltage drop.

PART I - INSULATION

DC Limitations

A variety of test devices and procedures are used in an effort to determine the quality of insulation. A number of test methods and devices use dc voltages. Nevertheless, there are extensive data to indicate limitations of dc. Since these are challenges, they will be enumerated before development of the evaluation technique.

First there is no recognized correlation between the ac strength of the insulation and the dc test voltages. The test levels are primarily experiential.

Second, cable that has been aged and then subjected to dc test voltage has the insulation damaged. When ac is subsequently applied, the insulation will fail at lower levels than if it had not been dc tested. Data for some wires indicate the life may be 5 times longer if it is not tested with dc [1,2].

Third, if flashover occurs during breakdown, the voltage stress causes transients which may weaken the remaining insulation. The reflected waves will double the peak voltage, which can cause multiple failure or damage points along the wire.

Finally, a higher test voltage is required for dc than for ac operations. The dc allows the build-up of space charge. The electric field necessary to overcome this charge is in addition to the field necessary for the insulation breakdown.

$$E_{total} = E_{space} + E_{insulation}$$

The nominal ac electric field on the insulation for a 5000 volt, 90 mil wire is 55 volts/mil. The dc field necessary for breakdown may be 10 times greater or more. This unusually high stress causes deterioration of the insulation which weakens its subsequent ac strength.

Many of these problems have been long recognized on polyethylene power cables. More recent experience indicates they may also apply to rubber insulation as well as other materials. The mechanism observed and often related to insulation failure is treeing. Whether this phenomenon occurs in 5000 volt insulation is subject to further investigation. However, some observations suggest it does exist.

Despite all the above limitations, if field tests are performed, dc testing is still the method of choice. Although other methods show promise, at this time their limitations exceed their perceived advantages [3].

DC Testers

Various test devices determine the performance of insulation. The most common are volt-ohmmeter (VOM), insulation resistance (IR) , and high potential dc tests (dc hi-pot). As with most things worth doing, more valuable information is obtained from increasingly expensive and difficult tests.

The high potential dc tester is a machine which, given the present state of the art, provides the most information about insulation quality [4]. Field machines typically can apply up to 60,000 volts to energize the wire. Some machines at research facilities are rated up to 200,000 volts or more.

Elevated voltage can be used to cause virtually any insulation system to fail at its weakest point. However, it is very difficult to interpret the readings so the quality can be determined without taking the insulation to destruction. The most valuable information is historical data from previous evaluations. Experience, skill, and knowledge of local conditions taken in conjunction with test results are major aids in analyzing the suitability of equipment for reuse [5].

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98CH36234

Resistance vs Current

The insulation resistance '*R*' in megohms and the leakage current '*I*' in microamps are related by Ohm's law.

$$V = IR$$

It is apparent that the test voltage '*V*' plays a key role in the relationship. For wire insulation, the resistance varies with the length. As the length increases, the megohm value decreases. This is a non-linear change because the insulation behaves as a string of parallel resistances. For a fixed test voltage, the leakage current must increase exponentially as the length increases.

Length has to be incorporated in the Ohm's law relationship. If the resistance is multiplied by length the appropriate units of resistivity are megohm-thousand feet (MOhm-kft). The reciprocal is called conductivity and has units of micromhos per thousand feet (umho / kft).

Alternatively, the conductivity can be expressed in units of microamps per volt - thousand feet (uA/V-kft). This term is often called the "leakage current" although technically it includes other terms. It can only be considered to be leakage current when the value includes the test voltage.

For conversion to units commonly encountered with instrumentation, multiply by 1000. The related leakage conductivity has units of microamps per thousand volts - thousand feet (uA/kV-kft). This is often stated as (uA/kV) / kft.

Leakage Conductance

Traditionally the industry has strived to determine one meghometer number that can be used to judge the quality of any insulation. Basic analysis reveals it is futile to try to define performance of all wires by using a single number read from a meter. Length, wire diameter, insulation type, construction geometry, and voltage must be considered.

Any values employed to determine the quality of new or used insulation must be based on the bulk properties of the insulation '*K*'. The insulation resistivity for a particular wire geometry takes into consideration the overall diameter '*D*' and the conductor diameter '*d*' of a tube [6].

$$\rho = K \log\left(\frac{D}{d}\right)$$

Typical resistivity constants for high quality electrical insulation have been determined by the power cable industry. These are based on years of experience at high voltage levels. For example, the bulk resistivity of ethylene propylene diene monomers (EPDM) insulation for use at service levels up to 138,000 volts ac is 20,000 megohm-thousand feet for new insulation. The polyethylene value is 50,000 MOhm-kft.

With the resistivity for EPDM, the leakage conductivity is 0.05 uA/kV-kft. A derating factor must be applied to the bulk constant when the material has been environmentally exposed.

Some of the conditions influencing both leakage current and insulation resistance include temperature, moisture, and oil gravity [7]. Because new insulation is such high quality, lower values on used systems may still represent excellent insulation for the application.

Comparison Methods

There are many methods used in an effort to determine if a particular wire is suitable for reuse in an installation. For example, many users merely require that the equipment be visually inspected and that it pass a five minute hi-pot dc withstand test at a specified voltage level. If the insulation does not fail, then it is accepted.

Even this rather straight-forward evaluation method is complicated by the lack of consensus on the appropriate voltage test level for various types of material. For a used 75 mil, EPDM insulated cable, the dc voltages employed by service centers vary widely. Some evaluations are performed at levels as low as 11,000 volts. Other users reportedly test the same construction at levels up to 25,000 volts [8].

Alternatively, certain users attempt to establish a specified maximum leakage current. Others specify a leakage conductance level. Still others may require that the leakage current or insulation resistance be balanced within a maximum ratio of 3 to 1. However, there are no consistent guidelines for evaluating these current levels [9,10,11].

This paper proposes a technique that will provide a consistency to the evaluation of insulation materials. However, it is necessary to develop the theory and foundations before the implementation of a new procedure.

Leakage Current Components

A difficulty arises when trying to interpret the microamp current values observed during a hi-pot test. The microamp dc current is made of three components [3,6,12]. These are capacitance charging current, absorption current, and conduction current.

The charging current energizes the capacitor that exists between the conductor and the ground. This current component starts extremely high and decreases exponentially. If the applied voltage remains stable, the value drops to zero within a few seconds after the test begins.

Absorption current results from the charge absorbed in the dielectric insulation as a result of polarization. This current component starts high but decreases somewhat more slowly. The current typically stabilizes after 5 minutes, although reasonably acceptable data is available after only 2 minutes.

Conduction current is the steady state leakage current value. This is the current that flows over, under, around, and through the insulation. Corona discharge current from high voltage sources will also contribute to conduction current. A low value of steady state conduction current is commonly accepted as indicating good insulation.

Figure 1 illustrates how microamp values change during the time of a test. A new cable with #4 AWG copper conductor, 75 mil polypropylene insulation, nitrile jacket and galvanized armor was used for the test [13,14]. A constant 20,000 V dc was applied to the cable. The current-time curve follows the expected offset exponential decay function. Time is represented by 't', while '$1/RC$' is the time constant, and 'F' is a constant offset because of material characteristics, and 'I' is the initial value of current. The equation solves for current at any time.

$$i = F + (I - F)e^{-t/RC}$$

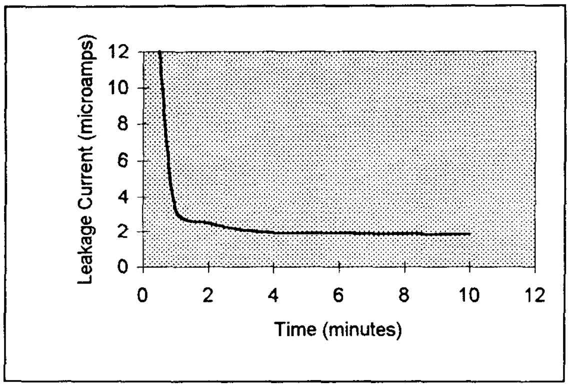

Fig. 1 - Leakage Current vs Time

A more thorough evaluation can be made by measuring the leakage current at various voltages and plotting leakage current vs applied voltage [5,12]. If the resistance is "ideal", it will not be affected by the voltage level and the relationship will be linear. An increasing rate of leakage current with voltage indicates that the insulation has been weakened. As insulation ages, deteriorates, or becomes wet, the leakage current increases dramatically.

A Technique, Not A Number

A method can be used that forecasts the failure level of an insulation test. Most procedures look at the performance at a point. The preferred method evaluates the rate of change.

Normalize the evaluation to aid in comparisons. The material property-bulk resistivity 'ρ' is in megohm-kft, the leakage current 'I' is in micro-amps (uA), and the applied voltage 'V' is in kilo-volts (kV), while the distance 'ℓ' is thousand feet (kft).

Take the reciprocal of the resistivity 'ρ' to obtain bulk conductivity. Multiply by the length of the wire to obtain the allowable bulk conductance 'G'. This is the rate of leakage current to voltage. Multiply by 1000 to obtain microamps per kilovolt.

$$G = \frac{1000\,\ell}{\rho} \qquad \text{(I-1)}$$

2. Prepare a plot or table of leakage current (uA) versus applied voltage (kV). Plot a straight line curve with the slope equal to the bulk leakage conductance 'G'. This becomes the upper boundary for the leakage current.

$$i = G v \qquad \text{(I-2)}$$

3. Perform the hi-pot test in steps as specified in appropriate standards.

Calculate the slope (derivative) between the previous point and the present point. This is the rate of change of leakage conductance.

$$m = \frac{d(i)}{d(v)} = \frac{(i_2 - i_1)}{(v_2 - v_1)} \qquad \text{(I-3)}$$

5. If the slope is less than the bulk leakage conductance slope, the insulation is excellent. If the slope is greater, the insulation will fail.

$$m > G \Rightarrow \text{pending failure} \qquad \text{(I-4)}$$

6. The first point is zero current with zero voltage applied. After measuring two points, a preliminary *forecast* can be established. The current will track the following curve, where 'F' and 'a' are constants for the particular insulation conditions.

$$i = F(1 - e^{av})$$

Calculate the coefficients for this insulation. Make two equations for two points, take the ratio, take the derivative, then take the logarithm.

$$a = \frac{(\ln i_2 - \ln i_1) + (\ln v_1 - \ln v_2)}{(v_2 - v_1)} \qquad \text{(I-5)}$$

$$F = \frac{i}{1 - e^{av}} \qquad \text{(I-6)}$$

7. Recalculate after each new data point to refine the forecast curve.

8. At the intersection with the conductance line, the conductance line current is equal to the forecast current. The forecast voltage is calculated where the lines cross.

$$i = G v$$

$$i = F(1 - e^{av})$$

To solve, set the equations equal, take the derivative of both sides, collect terms, then take the natural logarithm.

$$v = \left(\frac{1}{a}\right)\ln\left(\frac{-G}{aF}\right) \qquad \text{(I-7)}$$

9. Take the ratio of this forecast voltage with the rated test voltage to determine comparative quality 'cq' of insulation.

cq = forecast voltage / rated test voltage (I-8)

The changes in the forecast voltage or the ratio from previous values indicates the deterioration of the insulation. For installations without previous data, a ratio of less than 40% indicates marginal quality.

Figure 2 illustrates the techniques.

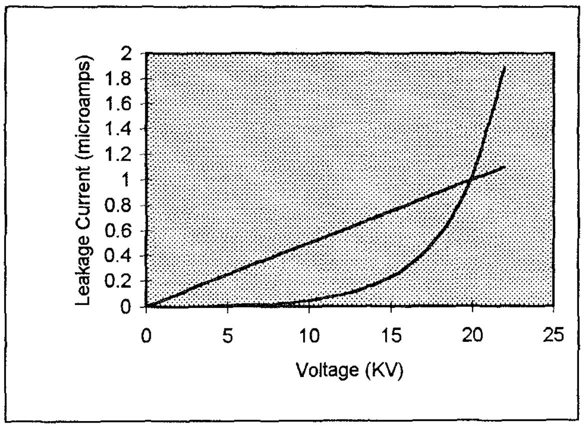

Fig. 2 -Leakage Current vs Voltage

PART II - CONDUCTOR SIZING

Background

Selection of conductor size has been a common part of electrical systems since their inception. The selection is generally based on tables from the *National Electrical Code* Article 310 [15]. Insulation temperature drives the NEC criteria. This is primarily dependent on current, which creates heat in the form of I^2R losses.

Typically the tables are adequate for runs less than 100 feet, but can yield an undersized wire for much longer distances. A critical component not included is voltage drop on long runs.

Conductor properties drive the additional criteria. This is primarily dependent on voltage.

Because power cables are a crucial part of most facilities, relationships have been developed to handle various combinations of factors that affect the voltage drop. The relationships address conductor size based on conductor resistivity, operating temperature, path length, current, and number of phases [16].

If the allowable voltage drop is known and the current requirement has been specified, then the permissible wire impedance can be calculated. Remember, the voltage drop in a branch circuit should be less than 3% and the total voltage drop in the feeder and branch should be less than 5%.

Because wire is so small the diameter is calculated in mils. One (1) mil is 0.001 inch. The area of the wire is circular mils. The relationship between diameter, mil^2 and circular mils is expressed below.

$$A(mil^2) = \frac{\pi d^2}{4} = 0.7854\, d^2$$

$$A(cmil) = d^2$$

$$mil^2 = 0.7854\, cmil$$

A wire 10 mils in diameter has an area of 100 cmils or 78.54 $mils^2$.

Resistance

The resistance *'R'* of a conductor is determined by the resistivity *'ρ'* of the material, the cross-sectional area of the wire and the length of the run.

$$R = \rho \frac{\ell}{A}$$

$$\rho = R \frac{A}{\ell}$$

The resistivity depends upon the physical properties of the material, the temperature *'T'* of the conductor, and the configuration of the cable run. The reference temperature for material properties is 20°C. At that temperature, annealed copper wire has a resistivity of 10.371 Ω·cmil/ft [19]. For standard conduit or cable tray configurations, a configuration factor of 1.02 can be assumed. Thus, resistivity of copper can be determined by the relationship.

$$\rho = 10.371 * 102 \left(\frac{234.5^oC + T}{254.5^oC} \right)$$

For a typical installation at 25°C, a copper cable has a resistivity of 10.786 Ω·cmil/ft. Aluminum has a value of approximately 17.35 Ω·cmil/ft. [19]

Wire Dimensions, Resistance

The first pass estimate of wire size can be found by using the resistance value and Ohms law.

$$A = \frac{\rho \ell I}{V_D}$$

where 'V_D' represents the desired maximum voltage drop.

The length value 'ℓ' includes the length of the conductor going to the load and returning. The effective length of the wire is the distance times the number of conductors per phase. The current is corrected by a phase factor for single-phase or three-phase.

For 1 phase: phase factor = 1   # conductors/phase = 2
For 3 phase: phase factor = √3   # conductors/phase = 1

An expanded relationship for wire area combines these factors where *'D'* represents the one-way distance of the wire run.

$$A = \frac{\rho\,(D * \#cond)(phase\,factor * I)}{V_D} \qquad \text{(II-1)}$$

Manipulation of the wire dimensions equation can provide other design tools. If the wire size is known, the voltage drop in a wire can be found.

$$V_D = \frac{\rho\,(D * \#cond)(phase\,factor * I)}{A} \qquad \text{(II-2)}$$

The distance a given size wire will carry current can be found by making another transposition.

$$D = \frac{V_D\, A}{\rho\,(\#cond)(phase\ factor * I)} \qquad \text{(II-3)}$$

The resistivity calculated resistance is a dc value which has to be corrected for ac conditions. For sizes smaller than #4/0, the dc and ac values are about equal. For much larger sizes the Z_{ac} may be as much as 1.3 * R_{dc}.

AC Consideration

The total ac opposition involves inductive and capacitive reactance '*X*' which are combined to calculate impedance.

$$Z = R + jX$$

For impedance calculations, the inductive reactance is calculated. At 60 Hz frequency, all the coefficients can be combined.

$$X_L = 2\pi\, 60\, L = 377\, L$$

The inductance is dependent on the permeability 'μ', area, and length.

$$L = \frac{\mu\,\ell}{A}$$

However, the inductance of two long, cylindrical conductors, parallel and external to each other should be used [18, 19, 20]. Calculate the constant from $\mu_0 / 2\pi = 4*10^{-7}$.

$$L = 4 * 10^{-7}\,\ell\left(1 + 4\ln\left(\frac{d}{r}\right)\right)$$

The distance' *d* ' is between the centers of the two conductors and '*r*' is the radius of the conductor cross section. Length is measured in feet, '*d*' and '*r*' are measured in inches.

For power line frequencies, the skin effect is the negligible so the ' 1' term drops out.

$$L = 4 * 10^{-7}\,\ell\,\ln\left(\frac{d}{r}\right)$$

For coax and transmission lines where the lines rotate, the average value is one-half the equation. This is appropriate for two, straight round conductors, or for per phase of a symmetric three-phase cable.

$$L = 2 * 10^{-7}\,\ell\,\ln\left(\frac{d}{r}\right)$$

For length in feet, '*d*' in inches and '*r*' in mils, the formula becomes

$$L = 13.816 * 10^{-7}\,\ell\,\ln\left(\frac{d}{r}\right)$$

The distance '*d* ' between the centers of the conductors can be estimated for individual cables in a cable tray or conduit.

*d = 2*insulation thickness + 2*r*

The capacitance reactance is calculated at 60 Hz.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{377C}$$

Capacitance is determined from the permittivity 'ε' of the conductor material.

$$\frac{1}{C} = \frac{\ell}{\varepsilon A}$$

When parallel round conductors are used, the capacitance takes on a slightly different form [20]. This is adequate for the phase to neutral capacitance of a two-wire line or symmetrical three-phase cable. Between the two-wires of a single-phase line, the value would be one-half the equation.

$$C = \frac{2\pi\varepsilon\ell}{\ln(d/r)}$$

Capacitive reactance is negligible at voltages less than 2400 volts. Furthermore, the shunt impedance is very large for lines less than 10 miles, therefore, it is usually ignored for power cable calculations.

Voltage Drop, Impedance

Ohm's Law indicates that impedance is the ratio of volts '*V*' to amps '*I*'.

$$Z = \frac{V}{I}$$

The voltage drop is related to the impedance.

$$\frac{V_D}{I} = Z = R + jX$$

$$\left(\frac{V_D}{I}\right)^2 = R^2 + (X_L - X_C)^2$$

The underlying relationships use the distributed values.

$$\left(\frac{V_D}{I}\right)^2 = \left(\frac{\rho\ell}{4r^2}\right)^2 + \left(\frac{2\pi f\mu\ell}{A} - \frac{\ell}{2\pi f\varepsilon A}\right)^2$$

However, using the relationships for parallel conductors and neglecting capacitance, the following formula is derived.

$$\left(\frac{V_D}{I}\right)^2 = \left(\frac{\rho\ell}{4r^2}\right)^2 + \left(2\pi f\ell * 13.816 * 10^{-7}\ln\left(\frac{d}{r}\right)\right)^2$$

Wire Dimensions, Impedance

The voltage drop calculation is straight forward when the current and wire configuration is known.

$$V_D = I\sqrt{\left(\frac{\rho\ell}{4r^2}\right)^2 + \left(2\pi f\ell * 13.816 * 10^{-7}\ln\left(\frac{d}{r}\right)\right)^2} \qquad \text{(II-4)}$$

If the wire size and maximum voltage drop are known, the maximum length run of the circuit can be calculated.

$$\ell = \frac{V_D}{\sqrt{\left(\frac{\rho}{4r^2}\right)^2 + \left(2\pi f * 13.816 * 10^{-7} \ln\left(\frac{d}{r}\right)\right)^2}} \quad \text{(II-5)}$$

Because the relationship involves both 'r' and 'ln (r)', it cannot readily be solved directly for 'r'. However, assumptions can be made which allow for a good estimation.

For industrial cables, the thickness of the insulation is approximately one-half the radius of the conductor [15,19]. Therefore, for conductors in conduit or cable tray, the distance 'd ' is approximately 3r. This is true for conductors #4 AWG and larger. For smaller conductors, 'd ' is approximately 5r. Assuming power cable of at least #4 AWG, V_D then becomes

$$V_D = I\sqrt{\left(\frac{\rho \ell}{A}\right)^2 + \left(2\pi f \ell * 2 * 10^{-7} \ln\left(\frac{3r}{r}\right)\right)^2}$$

Given the desired maximum voltage drop, and the length of the run, the wire size can be determined from the following equation.

$$A = \sqrt{\frac{\rho^2}{\left(\frac{V_D}{I\ell}\right)^2 - \left(2\pi f * 2 * 10^{-7} \ln(3)\right)^2}} \quad \text{(II-6)}$$

Comparison of Procedures

This will provide adequate design for a single machine or load. Two methods should be used to select wire for installations longer than 100 feet. First, incorporate the NEC considerations of insulation temperature based on current. Next calculate this method of conductor size based on voltage drop. Select a wire size that is the larger of this voltage drop calculation or the current calculation from the NEC.

Summary

Determining the status of insulation for continued use remains one of the most controversial issues in the insulation technology field. The dc hi-pot remains the most common method, despite its inherent problems. The procedure relies on leakage current measurement and the associated test voltage.

A mathematical technique is proposed for comparing the quality of insulation. The steps include calculating the bulk conductance as a limit, and the rate of change of the leakage conductance, then comparing the derivatives. Next the coefficients of the leakage conductance curve are calculated. The intersection of the leakage conductance and the bulk conductance curves provides the forecast voltage. Voltages above this point will rapidly lead to break-down.

The second technique developed is determination of wire size dependent on conductor properties. The first technique considers both resistance and inductance. The resistivity of the wire is corrected for material, configuration, and temperature. The area of the wire is calculated from resistivity, length of current path, number of phases, current, and voltage drop. The equation is also manipulated to yield voltage drop or distance based on the conductor parameters.

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