Technical Challenges in the Measurement of Insulation Resistance

Jeffrey A. Britton, M.S.E.E, Chief Engineer
Harry J. Pepe, B.S.E.E, Electrical Design Engineer
Phenix Technologies Inc.
75 Speicher Drive
Accident, MD 21520

Abstract:

A brief overview is presented of the need for and the technical challenges associated with obtaining a high quality insulation resistance measurement on plastic insulated power and control cables. Measurement uncertainties, repeatability of measurements, and technical issues associated with the measurement of very low level leakage currents are discussed, with example calculations.

Introduction:

The measurement of insulation resistance is a common routine test performed on all types of electrical wires and cables. As a production test, this test is often used as a customer acceptance test, with minimum insulation resistance per unit length often specified by the customer. The results obtained are not intended to be useful in finding localized defects in the insulation as in a true hipot test, but rather give information on the quality of the bulk material used as the insulation. Even when not required by the end customer, many wire and cable manufacturers use the insulation resistance test to track their insulation manufacturing processes, and spot developing problems before process variables drift outside of allowed limits.

With the advent of ISO9000 as well as the appearance of a much more technically educated customer base, modern wire and cable manufacturers require a higher level of accuracy, repeatability and traceability than ever before with regard to all test measurements made on new cables at the end of the production run. By its very nature, the insulation resistance measurement is one of the most technically difficult measurements to perform correctly. This test requires the measurement of DC currents that are on the level of microamperes, nanoamperes, or even picoamperes.

In the past, many manufacturers have offered insulation analyzers that have not properly dealt with important issues such as the stability of the source voltage, and the response of the current metering circuit to small ripple voltages and small fluctuations in the test voltage. When such factors are not properly addressed, it is easy to obtain an insulation resistance measurement that is lower in ohmic value than the true insulation resistance. When they exist, customer test requirements specify a *minimum* insulation resistance. It may therefore be the case that “good” cables might not pass the acceptance test, because of an improperly designed test system or test procedure.

The technical challenges associated with making a good measurement become exponentially more difficult in the presence of extremely high insulation resistance values, and extremely high test object capacitance as found in very long lengths (up to several kilometers) of cable. After a brief discussion of the fundamental theory of resistance measurement, this paper focuses on technical issues essential to the accurate measurement of very high resistances (up to several tens of gigaohms) in the presence of high values of test object capacitance.

Theoretical Background:

The basis for the measurement of insulation resistance is of course the practical application of Ohm’s Law. The DC voltage developed across the terminals of a resistance with a direct current applied is numerically equal to the current in amperes multiplied by the resistance in ohms. All commercially available insulation resistance analyzers operate on this principle. The measured quantities are the applied voltage and the resulting current. From these quantities, insulation resistance is calculated and displayed to the operator, or collected by a data acquisition system for inclusion into a test report.

In the case of making an insulation resistance measurement, the difficulty in obtaining a correct measurement stems from the extremely high value of the resistance being measured, and the relatively high capacitance of the cable insulation which is electrically in parallel with the insulation resistance. In the case of a typical multi-conductor low voltage cable, the insulation resistance measurement may be made for each individual conductor or for a certain group of conductors by applying voltage sequentially to each conductor or group of conductors with all other conductors grounded. If shields are used, the insulation resistance may be made for each conductor or group of conductors to its respective shield by treating the shield as the grounded electrode of the resistor as voltage is applied to the conductor or group of conductors under test. Leakage current is measured returning to the power supply from the low voltage (grounded) conductors.

The equivalent circuit used in the explanation of the insulation resistance measurement is given in Figure 1.

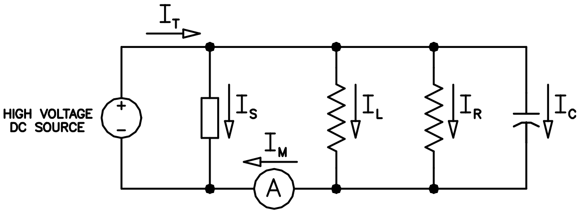

Figure 1: Equivalent Circuit of Cable Insulation Resistance Test Circuit

Where: I_T = Total Current Supplied by the High Voltage DC Source
I_S = Stray Leakage Currents Within Test Circuit (not measured)
I_L = Leakage Current in Test Fixturing (measured)
I_R = Cable Insulation Resistive Leakage Current
I_C = Cable Insulation Capacitive Current
I_M = Total Measured Current (Test Fixture Leakage + Cable Insulation Resistive Leakage + Cable Insulation Capacitive Current)

It is noted that the polarization currents are not included in this discussion because it is assumed that slowly decaying current components associated with dielectric absorbtion phenomena (polarization currents) will be negligible in new polymeric insulation as is being discussed here.

The true resistive leakage current, I_R, which represents true charge leakage through the cable dielectric, is the current we are interested in measuring. Because the resistance and capacitance of the dielectric are physically inseparable however, and because the cable test fixture is not a perfect dielectric, we are forced to measure the combined resistive leakage current I_R, capacitive current I_C, and test fixture leakage current I_L. For the purposes of this discussion, it will be assumed that the high capacitive charging currents required to charge the cable capacitance to the test voltage have been allowed to die out, and that variations in the total measured current $I_M = I_L + I_R + I_C$ result only from fluctuations in the test voltage.

The following sections explain in detail the technical issues that affect the accuracy of the measurement results.

Effects of High Resistance

The high resistance value of the cable insulation, typically in the range of several hundred megaohms to several tens of gigaohms results in a very low leakage current to be measured by the test equipment. The applied voltage is usually in the range of 500 V to 20 kV, with higher insulation values corresponding to higher test voltages. The resulting currents to be measured are in the range of a few microamperes down to a few nanoamperes.

Proper Guarding of the Test Circuit Current Meter

Proper location of the current meter in the test circuit, as shown in Figure 1, will effectively “guard out” any stray currents associated with the high voltage source and its associated wiring. If this is done properly, these stray currents will not contribute to the measurement error.

Current Leakage of the Test Fixturing

When cable insulation leakage currents are extremely low, it must be realized that the insulation resistance of the test fixturing can become on the same order of magnitude, or even lower, as the cable insulation resistance. If an insulating fan board and switching network is used to perform automated sequential measurement of the insulation resistance on each conductor of a multiconductor cable, the leakage current through the fanboard fixture, represented by I_L in Figure 1, cannot be separated from the measurement. It is therefore essential that the resistance of the material from which the fixturing is constructed be sufficiently higher than the insulation resistance to be measured. In general, a total fixture leakage resistance of at least one order of magnitude higher than the cable insulation resistance is recommended, depending on the allowed uncertainty of measurement. Higher fixture resistance is better, but sometimes cannot be achieved depending on the insulating material used in the construction if the cable. Materials such as porcelain or glass have the highest resistance, however these materials are usually not practical from the standpoint of cost and mechanical durability. Plexiglass (or Lexan) is a good choice for fixturing material.

Effects of High Capacitance

It turns out that the effects of high cable dielectric capacitance can be much more of a problem than those of high insulation resistance. High test object capacitance results in very high sensitivity of the total measured current I_M to even very small fluctuations in the DC source voltage. As a rusult, even very small ripple voltages and small line voltage disturbances present on the DC source voltage can result in currents many times larger in magnitude than the DC leakage currents which are to be measured.

The Effect of Ripple Voltages

The effect that even extremely small ripple voltages have on a DC insulation resistance measurement is enormous. As an example of this phenomenon, consider an insulation resistance measurement where the effective insulation resistance is 5000 megaohms, the effective test conductor capacitance to ground is 5 microfarads, the test voltage is 500 volts, and the fundamental ripple frequency is 120 Hz. This ripple frequency corresponds to a single phase, full wave, 60 Hz. rectifier. If all stray currents and test fixturing leakage currents are ignored for this example, the resulting equivalent circuit is shown in Figure 2.

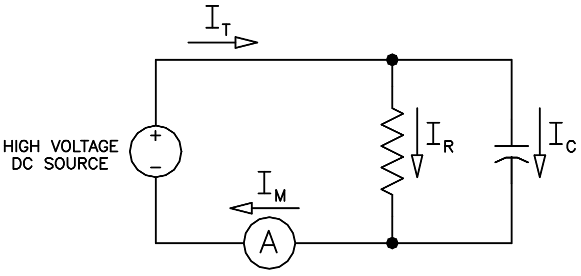

Figure 2: Simplified Equivalent Circuit Used to Analyze Capacitive Effects on Insulation Resistance Measurements

Where: I_T = Total Current Supplied by the High Voltage DC Source
I_R = Cable Insulation Resistive Leakage Current
I_C = Cable Insulation Capacitive Current
I_M = Total Measured Current (Cable Insulation Resistive Leakage + Cable Insulation Capacitive Current)

Based on the resistance and capacitance values stated above, the 120 Hz. capacitive reactance of the conductor capacitance to ground is calculated as:

X_c = 1 / {2 x (B) x (120) x (5E-6)} = 265.3Σ.

This means that an RMS ripple voltage of 5 V superimposed on the DC test voltage, or 1% of the DC voltage of 500 V, will result in a capacitive current flow of:

I_c = 5 V / 265.3Σ = 18.85 mA.

The true resistive leakage current is calculated as:

I_R = 500 V / 5000E+6 = 0.1 :A.

In this example, the AC current resulting from a 1% RMS ripple voltage is 188,500 times higher than the DC current to be measured!

Cable manufacturers commonly encounter the cable parameters used in this example, which underscores the importance of a thorough understanding of the effects of ripple voltages on the insulation resistance measurement. In practice, the ripple voltage is not normally as high as 1% on a test object with such high capacitance, however the AC ripple current component I_C is normally the dominant component of the total measured current I_M. A plot of the ratio of the two current components I_C/I_R versus % ripple for the cable parameters used in the above example is shown in Figure 3, based on 120 Hz. fundamental ripple frequency. Even with a ripple of 0.001%, the AC ripple component I_C of total measured current I_M is still 185 times the leakage current I_R.

This means that the metering circuit must be designed to pass the AC current without affecting the accuracy of or damaging the DC current metering components. This is typically accomplished by adding capacitance in parallel with the DC current metering resistance, which will shunt the ripple currents around the DC metering. This capacitance must be carefully selected to allow the AC ripple current to pass, but at the same time not slow the response of the current meter to the point where an unacceptably large response delay is created.

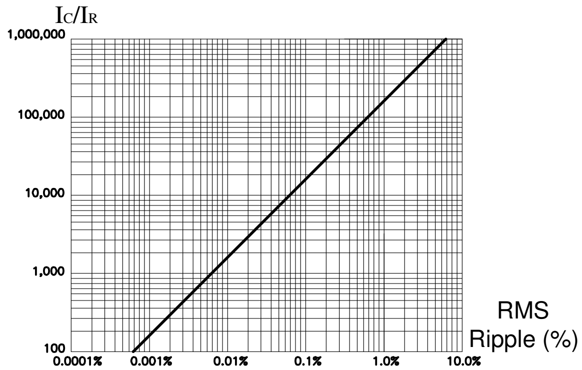

Figure 3: Ratio of I_C/I_R Versus % Ripple, for 120 Hz. Fundamental Ripple Frequency.

In cases where very high test object resistances occur in parallel with high test object capacitances, it is possible to reduce the AC ripple component of the current by utilizing a regulated solid state power supply with a high switching frequency and proper output filtering.

Stability of the Test Voltage and Software Techniques

Another important factor affecting the accuracy of the insulation resistance measurement is the stability of the test voltage. When measuring very high insulation resistance values (greater then 1000 MΣ) in the presence of high test object capacitance the stability of the test voltage can have a major impact on the accuracy of the final resistance measurement. Small random fluctuations on the test voltage that would appear on the surface to be insignificant may have a large affect on the value of the total measured current I_M.

As an example of this, consider a 0.1% step change in test voltage from 500.0 V to 500.5 V, and a source impedance of 100 kΣ (a reasonable value for many insulation analyzers) in the simplified equivalent circuit shown in Figure 2. This results in a charging current that takes approximately 2.5 seconds to decay, based on the 0.5 second RC time constant created by the 100 kΣ output impedance of the DC source and the 5:F capacitance of the test object. The peak current associated with this step change is given by the magnitude of the voltage change divided by the output impedance of the DC source:

I_{peak} = 0.5 V / 100,000 Σ = 5:A

Therefore the initial current impulse resulting from the voltage change is 50 times larger than the steady state leakage current of 0.1:A, and decays exponentially over the 2.5 seconds following the voltage change. This means that if the measuring system recorded a current during the charging time associated with the voltage change, the resistance could be in error by a factor or 50, being recorded as 100 MΣ rather than 5000 MΣ.

One solution to this problem is to utilize an ultra stable voltage source. A highly regulated high frequency switching supply is the best choice, if line voltage fluctuation is a problem. If a power frequency rectifier is being used to provide the DC voltage, constant voltage or ferroresonant transformers may be employed to stabilize the AC power supply feeding the rectifier.

Another method of improving measurement accuracy is based on the fact that such line voltage fluctuations are normally stochastic or random in nature. Computer sampling techniques may be used to make a number of resistance measurements over a predetermined time interval, and then to calculate and display the average resistance as the result. If the time interval is selected to be long enough and the voltage fluctuations are truly random in nature, the end result will be the correct insulation resistance. In cases where the insulation resistance and parallel capacitance are high enough that such a sophisticated measuring algorithm is called for, some statistical analysis of the measuring results will be required in order to determine a sufficient time interval and sampling rate. Once a proper time interval is selected, the measurement results should be repeatable. Poor repeatability indicates that more samples over a longer time period are needed.

Discussion of Measurement Uncertainty vs Repeatability:

With regard to uncertainty, it is clear that poor repeatability indicates a high measuring uncertainty. At the same time, it is important to remember that good repeatability does not necessarily mean low uncertainty. If, for example, as stated previously, the leakage resistance of the test object begins to reach the same order of magnitude as the leakage resistance of the test fixturing, the measuring equipment may still make very repeatable measurements, but the result may be very wrong.

There is some comfort in knowing that it is very unlikely that any insulation resistance measurement equipment will indicate a falsely high resistance based on any of the effects mentioned in this paper. This issue is still of importance to cable manufacturers however, since some customers specify a minimum insulation resistance requirement. In these cases, particularly in instances where MIL specs are involved, obtaining an accurate insulation resistance on long lengths of plastic insulated cables is a difficult technical problem. In such cases, the problem is not in manufacturing high quality cable, but in demonstrating the quality of the cable.

Because the resistances involved in the test circuit are so high, cleanliness of the test fixturing is an absolute necessity. If fanboard fixtures are used to make connections to multiple conductors, any contamination of the test fixturing material will increase surface leakage across the fixture, which will lower the measured resistance value, making the cable insulation appear to be of lower quality than it actually is. If fixtures are not kept clean and maintained, the result will be poor repeatability over time on cables with equivalent insulation. In cases where a minimum insulation resistance and a record of repeatability are customer acceptance requirements, this could cause a problem for the cable manufacturer.

Notes on System Calibration:

In cases where test objects exhibit high capacitance, the only sure way to verify the uncertainty of the measurement is to verify the calibration of the instrument with a known resistance and capacitance. Every insulation resistance measurement system should be calibrated with a known test specimen whose resistive and capacitive characteristics represent the type of test objects the system is to be used to measure. It can be very informative to connect a known calibration resistance and capacitance in parallel, and see what the insulation analyzer indicates, and then repeat the test with the capacitance disconnected. It can also be very informative to place a true RMS ac ammeter in series with the capacitance, to see what the AC ripple component of current is, compared to the resistive component that should be easily calculable.

Conclusion:

The danger of setting up a DC insulation resistance measurement system that is not properly designed for the resistive and capacitive characteristics of the test object is insidious. If the test object resistance and capacitance values are higher than those for which the unit was designed to perform properly, the unit may indicate a value that is in error by more than an order of magnitude. The fact that the unit appears to function properly, and may even be providing repeatable results, may give the operator a false sense of security that the equipment is providing accurate results, when in fact it is not.

To reduce errors resulting from effects of very high test object resistance, the following items should be kept in mind:

1) The test circuit needs to be properly configured (guarded) to be sure that no unnecessary leakage currents are being included in the measurement.

2) Fixturing materials need to be properly selected to minimize fixture leakage.

3) Test fixturing needs to be kept clean to insure high accuracy and good repeatability.

To reduce errors resulting from effects of high test object capacitance, the following items should be kept in mind:

1) A DC source with the lowest possible ripple should be employed during the test. Even if an insulation resistance analyzer is properly designed to deal with ripple currents in the insulation resistance measurement, lower ripple currents will generally improve measurement accuracy.

2) A highly stable DC source must be used. Even small voltage fluctuations on the order of 0.1% may result in large measurement errors when test object capacitance is high.

3) Sophisticated computer controlled sampling and averaging techniques may be required to get accurate measurements when extremely high resistance and capacitance occur together.

Finally, good repeatability does not equate to low uncertainty. Verification of proper operation should always include calibration verification using known resistance and capacitance that closely represent the characteristics of the intended test object.