Insulation Testing – Preventing Equipment Breakdown and Plant Shutdowns

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Plant shutdowns due to equipment malfunction or safety violations can cost businesses enormous amounts of time and money. Lost productivity, expenses to repair or purchase equipment, and opportunity costs are some of the consequences incurred when simple, but nonetheless crucial preventative maintenance steps are not routinely carried out. For example, electrical cables are omnipresent across industries today, from high voltage DC transmission (HVDC) for subsea electrical systems to phone line transformers and hybrid electric vehicles. As with any device carrying, transmitting, or receiving electric current, proper care must be taken to minimize dangers and risks. Periodic insulation testing is a fundamental preventative maintenance step that can make or break your bottom line.

Insulation testing refers to calculating the resistance between the conducting and non-conducting sections of an electric cable, typically in the Megaohm[1] or larger range. Over time, the insulation of poorly maintained conducting cables degrades, exposing personnel and equipment to hazardous leakage currents that result. Depending on the magnitude of current involved, this may be life-threatening to plant employees, or cause severe production downtimes. Thus, having a reliable and accurate insulation tester is paramount toward maintaining dependable future business operations. This paper will address the basics of insulation cables and conductors, how and why insulation testing is performed, what to look for when performing these tests, and some target applications of insulating testing across different industries.

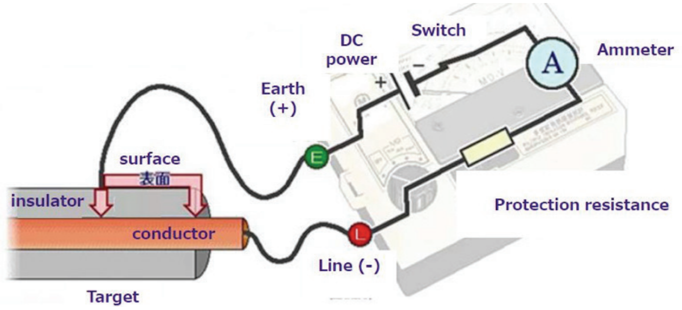

Figure 1: Connecting an insulation tester to a cable

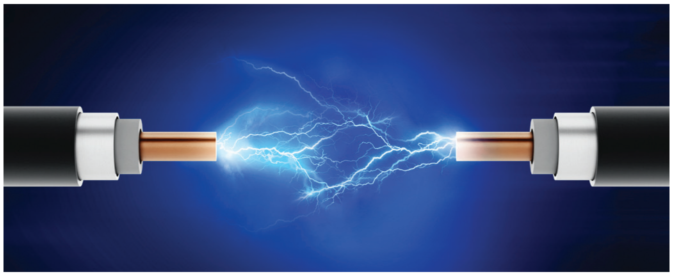

Figure 2: Inside of an electrical cable

Overview of Insulation Cables and Conductors

Electrical cables are composed of two fundamental components: conductors, the low resistance current-carrying component, and insulation, the high resistance component. Outside the insulation are the metallic shield and the plastic jacket. The plastic jacket protects the insulation and conductor from environmental disturbances such as moisture, chemicals, and sunlight. The metallic shield is used to limit electromagnetic interference, which can disrupt transmitter-receiver communications. Conductors come in several different types of material including copper, copper-covered steel, high-strength alloys, and stainless steel, with the particular type of conductor used varying largely based on application and industry.

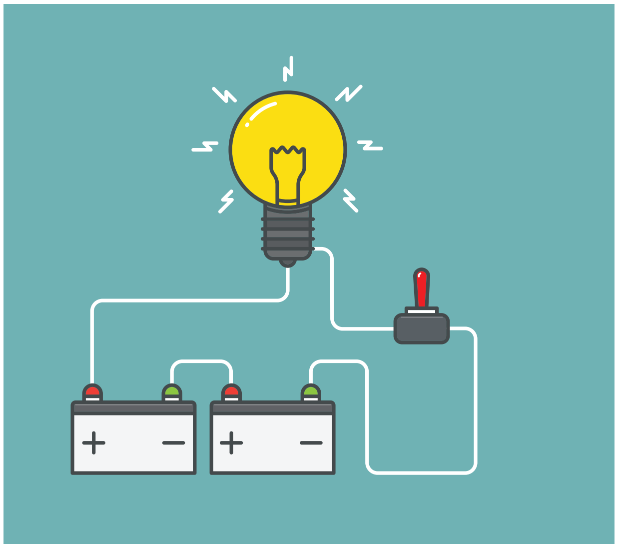

Figure 3: Typical diagram of current flow in a properly insulated electrical cable

Insulation is used to make sure that all the current in a cabled system travels properly through the conductor to other parts of the circuit, as well as maintain the safety and integrity of the electrical network. Simple things that we take for granted everyday such as plugging in a laptop charger to the wall or charging our smartphones, are made safe due to decades of work and research on electrical insulation. However, in harsher industrial environments where insulation is subject to constant changes in temperature, humidity, and mechanical and electrical stresses, maintenance is necessary to assess its useful life and quality. Below are common causes of insulation failure:

- Temperature Fluctuations

  Temperature has an inverse effect on insulating material, meaning temperature increases will lower insulation resistance, and vice-versa. In addition, the temperature coefficient for most insulation material is large, so even small changes in temperature will lead to large changes in insulation quality. A general rule of thumb is a 10°C increase in temperature halves the insulation resistance.

- Mechanical Stress

  Mechanical stress is imposed on insulation due to startup currents, which are seen quite often on motors and transformers during power cycling. Startup currents, which are transient in nature, typically have larger amplitudes and different frequencies than their steady state counterparts. These currents lead to vibrations that are exponentially proportional to the amplitude of these inrush currents. Over time, these vibrations can lead to insulation damage which could cause phase to phase faults on motors and transformers.

- Humidity/Contamination

  Moisture, dirt, chemicals and oils all affect insulation quality. In hot, humid industrial areas, this is especially important to be wary of. Whenever the surface temperature of the insulation is close to or lower than the ambient air dew point, moisture will develop. Moisture provides low resistance paths for current by entering through the cracks of the insulation. Oil, dirt, and chemicals are found across industrial plants and can easily bind to the insulation, causing stray currents as well as causing permanent damage. Additionally, dust and dirt may decrease the insulation's ability to dissipate heat.

- Electrical Stress

  Electrical Stress involves the trio of corona, surges and partial discharges. Corona involves current in a conductor energizing the surrounding air and producing ozone, which creates oxidation that degrades the insulation. Surges involve brief period (microseconds) voltage spikes that can harm insulation if the amplitude exceeds the insulation breakdown voltage. There are several sources, either internal (static electricity) or external (capacitor bank switching). Partial discharges involve breakdown of the air pocket within insulation. This air breakdown causes sparks to occur on medium and high voltage cables, eventually causing degradation.

As described above, there are many different causes, both manmade and environmental that, over time, can lead to insulation deterioration and eventual breakdown. While some of these sources may be mitigated by maintaining standard equipment maintenance procedures, other sources are a necessary consequence of plant operations. The best practice for maintaining plant, property, equipment and personnel safety is to routinely check the health of all insulation in use, to determine if replacement is necessary. A history or trend of electrical insulation gives the personnel involved great insight into whether or not preventative maintenance is required.

Basics of Insulation Testing

Insulation testing covers a broad spectrum of tests that usually boil down to applying a known (DC or AC) voltage for a specified duration, across a conductor and an insulator, while measuring the current generated. Then, using Ohm's law, the resistance is calculated by this insulation tester[2]. This applied voltage may be within some percentage of the rated voltage for the insulation, or may be orders of magnitude greater, depending on the type of tests being performed. As mentioned in the previous section, typically only a tiny current in the micro-amps range or below goes from the conductor through the insulation, to ground. In situations where the insulation has been compromised due to environmental conditions, aging, or transient phenomena (such as voltage spikes or harmonics), a significantly larger current will leak through the insulation, which, if left unchecked, could harm nearby equipment or personnel who come into contact with the stray current.

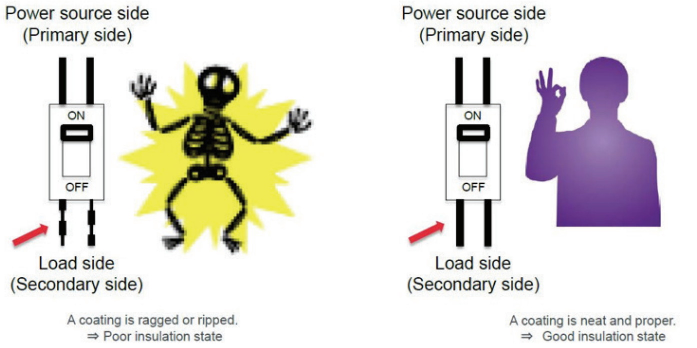

Figure 4: Leakage Current Effects of Good vs Poor Insulation

The main objective of insulation testing is to measure these leakage currents, which emanate from one conductor coming into contact with another due to poor insulation, or current finding another path to ground. It is also important to keep in mind that current measured by the insulation tester comes from different sources due to the capacitive properties of insulation, and that these currents have a time dependent nature. Thus, care must be taken to understand how often to make measurements, the measurement duration, and how the measurement corresponds to insulation state. Three types of currents typically come into play when calculating insulation resistance:

- Leakage Current

This is the resistive current that travels from one conductor to another, or from the conductor, through a weak insulator, to ground. Leakage current typically starts out small and stabilizes to some final value fairly rapidly over the period of the insulation test. Typically, micro-amps of leakage current should be measured in a well-insulated cable. The International Cable Engineers Association (ICEA) lists an approximation formula for calculating leakage current at approximately 60°F:

$$I_L = \frac{E}{K\, log10(\frac{D}{d})}$$

where

I_L is the conduction or leakage current
E is the test voltage impressed
K is the specific insulation resistance, measured at megaohms per 1000 feet at 60°F
D is the diameter over insulation
d is the diameter over conductor

- Capacitive Current

This is the time dependent current created due to the capacitive properties of the insulation under test. Recall that current across a capacitor is equal to its capacitance multiplied by the rate of change of voltage across the capacitor, or ic = C*dv/dt. Thus, voltage does not change instantaneously across a capacitor, but rather over a period of time. Once the insulation voltage equals the applied voltage, the capacitive insulation current will drop to zero, as the voltage change across the insulation will not change.

- Absorption Current

The absorption current is also time dependent, albeit at a much slower rate than the capacitive current. Absorption current arises as a result of impurities and moisture in the insulation as explained earlier.

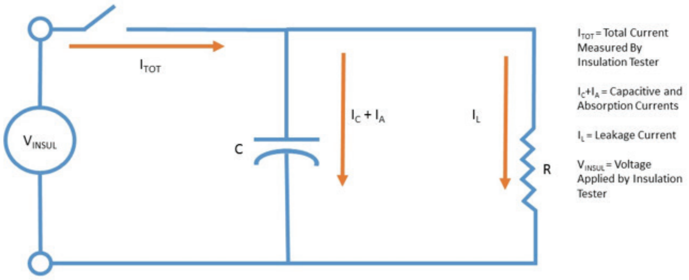

Figure 5: Connection of an insulation tester to a DUT (Device Under Test) and the resulting currents

Thus, the current read by the insulation tester is the sum of the leakage, capacitive, and absorption currents, the latter two of which have time dependent properties. Because of this, one may read a low resistance on the insulation when initially applying a test voltage, and then see this resistance increase before reaching steady state. If the insulation is in good state, the leakage current will be very low, and the insulation tester will be primarily influenced by the absorption and capacitive currents. On the other hand, the current reading on poor insulation will be largely impacted by the leakage current. Due to this phenomena, different testing standards have been developed to assess the quality of insulation. These standards aim to unify the testing environment for the insulation to make sure that humidity and temperature are eliminated from affecting the results. That is, tests are performed at the same ambient temperature and relative humidity.

Types of Insulation Resistance Testing

The simplest form of insulating testing involves proof testing, also known as go/no-go testing. It requires applying a DC voltage to the insulation and comparing the measured resistance to some cutoff or threshold. Many insulation testers have built-in functionality that allows a quick, visual representation of the pass/fail scenario. As seen in the table below, depending on the type of equipment under test, this recommended applied DC voltage will vary. While there is no hard and set rule for every application, rough guidelines and approximations exist depending on the insulation nameplate ratings. Always consult the cable manufacturer for more specific guidelines if you are unsure of what test voltages to apply. For example, the below formula is used often to estimate the DC voltages used based on cable ratings:

Factory AC Test = 2 * Nameplate Rating + 1000 V

DC Voltage Used for Routine Maintenance = 0.8 * Factory AC Test * 1.6

To put into context, let's assume we have motor cable rated for 1000 VAC per phase. Our factory AC test voltage would then be: 2 x 1000VAC + 1000 VAC = 3000 VAC. Our DC test voltage would then be:

0.8 * 3000VAC * 1.6 = 3840V.

Rated test voltage	Example of use
25 V / 50V	Insulation testing of telephone line equipments and telephone line circuits
100 V / 125 V	Maintenance of low voltage circuits or equipment handling 100 V line
	Insulation testing of control equipment
250 V	Maintenance of low voltage circuits or equipment handling 200 V line
500 V	Maintenance of low voltage circuits or equipment handling 600 V line or lower
	Inspection of low voltage circuits or equipment when installing handling 600 V line or lower
1000 V	Insulation testing of circuits or equipment handling 600 V line or over
	Insulation testing of circuits or equipment handling constantly high operating voltage (e.g. high voltage cables, high voltage equipment and communication equipment or cables handling high voltages)

Figure 6: Commonly used test voltages and applications

Proof testing, however, lacks important historical information about the insulation. A one-time, quick reading does not tell us if insulation quality is deteriorating or remaining steady. For this, more in depth procedures are needed.

Time resistance testing takes proof testing one step further and allows the user to see a trend in insulation resistance over time. More specifically, this type of testing involves taking successive differences in resistance measurements. The reasoning behind this is that the trend provides good insight into insulation quality. Absorption current would be more prominent in good insulation; thus as the absorption current decreases, the successive insulation resistance would increase. In poor insulation, where leakage currents are more prominent, one would see steady or declining measurements.

Polarization Index (PI) and Dielectric Absorption Ratio (DAR) are two methods of insulation testing that take the ratio of successive measurements at discreet intervals. The advantages these tests hold over the ones discussed earlier is that we can quantify the insulation quality. Polarization index testing involves taking resistance measurements at 60 seconds and 600 seconds (10 minutes), and finding the ratio of these two readings (R600/R60). As mentioned in the previous section, the capacitive components of insulation cause time dependent currents that will cause a lower initial insulation reading. The ten minute portion of the PI test acts as a low-pass filter so that the leakage and absorption currents will be most prominent in the measurement. This ratio is akin to measuring power factor on a power system, which is the ratio of the resistive power to the vector sum of the real and reactive powers[3]. As seen in the chart below, the PI ratios denote the insulation state, with a 1-4 scale denoting severity of insulation state.

PI Ratio	Insulation State
< 1	Dangerous
< 2	Questionable
< 4	Good
> 4	Excellent

Dielectric absorption ratio testing on the other hand, involves a quicker series of tests. Typically, these involve measuring insulation at 30 seconds and once again at 60 seconds, and noting the ratio of the two (R60/R30). This type of testing is used quite often when the absorption current decays at a faster rate, meaning the ratio would most often compare leakage current to capacitive current. DAR testing has the advantage in that it can be performed faster than PI testing. The DAR table below shows insulation condition as a function of the ratio:

DAR Ratio	Insulation Condition
< 1.25	Questionable
≤1.6	Adequate
< 1.6	Good

Applications of Insulation Testing

Insulation testing is used in a variety of industries and applications anytime field instrumentation is involved. This is due to the fact that field instruments output some signal (Voltage, current, resistance) to a control system or monitoring device in proportion to measured phenomena. Insulation testers are used to ensure proper signal integrity, and, in cases where higher magnitudes of voltage/current are being transmitted, ensure safety of plant property and personnel. Below are some of the more common applications of insulation testing.

Flow Meter Insulation Validation

Flow meters are devices that measure of the velocity of liquid using a number of different technologies, but as an example - Faraday's Law of Electromagnetic Induction. More specifically, flow meters generate a magnetic field which causes the conductive liquid moving through the flow meter walls to generate a voltage. The faster this liquid flows, the higher the voltage is generated. As flow meters are subject to the same environmental conditions as insulation discussed earlier, their ability to properly measure flow rates will be similarly impacted. Thus, insulation testers can serve a primary purpose when testing flow meters: verifying the signal integrity from the flow meter output to the control system by checking the insulation of the transmission cable.

Figure 7: Validating a Flow Meter's response to changes in insulation

Motors and Drives

Three-phase electric motors and the drive circuits that control them are complex devices which can suffer several combinations of phase to phase, phase to neutral, and symmetric and asymmetric (voltages and currents do not have the same RMS values and are not 120 degrees out of phase with one another) faults. IGBT based inverter systems rapidly switch on an off at the rate of tens of thousands of times a second. This fast switching leads to voltage reflections on the drive-motor cabling system, which can often be magnitudes greater than their transmitted counterparts. If the reflected amplitude significantly exceeds the insulation rating, this can lead to dielectric stress and eventual insulation failure. Motors are drives are especially likely to experience the mechanical and electrical stresses discussed earlier. As they are the backbone of modern day operations, it is of upmost importance to periodically validate their insulation.

Switchgear

Switchgear is used to locate electrical faults and isolate the faulty network from the rest of the power system. Similar to motors and drives, switchgear can experience a range of electrical and mechanical stress that compromises their effectiveness. Partial discharge is commonly seen in switchgear, such that partial discharge testing, which involves performing a series of ultrasound and light tests to assess symptoms of discharge is commonly used.

Conclusion

Insulation testers, while simple and intuitive in operation, are powerful devices and the backbone of any industrial operation because they are a critical component of safety and operations testing. They are used to ensure cable integrity on a large array of electrical test equipment ranging from motors and transformers to flow meters. They achieve this by being able to source large DC/AC voltages and precisely measure the generated current across a range of time periods. By taking preemptive steps to check insulation across your plant on a periodic basis, you reduce costly downtime, and, more importantly, ensure the safety of your personnel.

For detailed information on Yokogawa's insulation testers, please visit us at https://tmi.yokogawa.com/us/solutions/products/portable-and-bench-instruments/insulation-testers/.

1: Due this reason Insulation Testers are commonly referred to as meggers in the industry.

2: The first important step to take before doing any kind of insulation test is to remove all power to the insulation under test.

3: Power Factor = Real Power (W) / Apparent Power (VA). Apparent power = √(Real Power + Reactive Power)2

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