Electric Circuit Analysis
by Randy Keener

Electric Circuit Analysis (ECA) evaluates the condition of an electric circuit while the asset is off-line (not operating). When applied to motors or generators, it is often called Motor Circuit Analysis (MCA). ECA technologies are relatively simple low voltage tests which include resistance, capacitance and inductance. When stated as a complex value, it is called impedance. In addition to motors and generators, ECA is used on transformers, contactors, relays, cables and connections.

ECA tests identify failures only after they are already affecting the electrical system. Sometimes maintenance techs believe that ECA tests are more predictive than they really are. The test equipment vendors are largely to blame because of misleading claims which defy the laws of physics.

A common false belief is that ECA can identify developing insulation issues well before they affect the operation of the electrical system. Yet it is not uncommon for a motor to pass the ECA tests even after it has already failed catastrophically. This happens because the operating voltage of the motor is much greater than the test voltage of these tests. The motor can have a short at line voltage, but, appear to be okay when tested with a low voltage meter. Other times a motor will pass the ECA tests and then fail very soon after testing. Low voltage tests have fairly limited application as predictive testing tools. They are not adequate for an effective predictive insulation testing program. By the time an ECA test detects an insulation problem that asset probably has a only a few minutes or hours before catastrophic failure occurs.

ECA tests are especially beneficial in identifying issues which are not voltage dependent. Torq uses ECA tests mostly to help confirm that new equipment is installed properly prior to powering up the equipment and as a first step in troubleshooting or identifying a failed asset. One common use of these tests is to check for misconnected/mislabeled leads especially on dual voltage or wye/delta type windings. The resistance and inductance tests are both needed in order to indentify all of the possible lead labeling/misconnection mistakes which can occur.

Resistance Test

Resistance is a DC test used to measure the resistance to current flow when a voltage is applied. An ECA resistance test is a low voltage test used to assess the electrical conductors in the circuit. It is performed on wound products (motors, generators, transformers, coils), cables and electrical connection points. Things which affect resistance include the resistivity coefficient of the material, the conductor length and cross section and the connection resistance. The equation for resistance is:

$$R = \rho * L/A$$ where ρ = resistivity, L = conductor length, A = conductor cross sectional area

Resistance increases with higher resistivity, longer lengths and smaller cross sectional area. The resistivity of a conductor changes with temperature. A good rule of thumb is that the measured resistance value will change by about 0.4% per degree Celsius for copper and aluminum. Resistance increases as temperature increases and decreases as temperature decreases. To remember this, think of superconductivity. The resistance gets smaller at colder temperatures. It is important to mathematically calculate the temperature compensated resistance when an accurate absolute resistance value is required. Usually the resistance is normalized to room temperature (25° C). For example, if the temperature of a test motor is 1.00 Ohm at 35°C, the compensated resistance is four percent lower or 0.96 Ohm at 25°C

The resistance test checks for obvious open circuits. Resistance measurements are most often trended over time to look for change or compared to other measurements of similar devices.

It is often difficult and unnecessary to determine a temperature compensated absolute resistance value for trending in a maintenance situation. It is often adequate to evaluate by comparison. For example, when testing a three phase motor or transformer, we can measure the resistance of all three phases and calculate the percent difference between the three resistance measurements. This is called a resistance balance calculation. Since all three phases are at the same temperature, the resistance balance percentage is independent of the temperature. You can trend the imbalance percentage over time rather than the absolute resistance value. Motor manufacturers typically build motors with resistance balance less than 0.5%. Although some error is introduced when testing a three phase machine through the feeder cables, one would still expect resistance imbalance to be about 1.0% or less when everything is okay. Trending the change is key to fault finding.

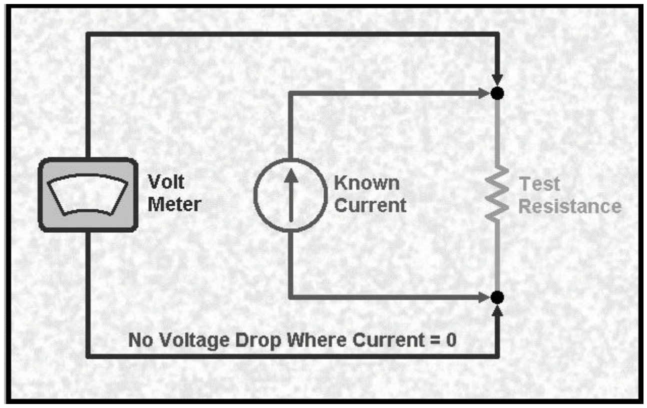
Resistance is calculated using Ohm's law by measuring the DC voltage and current.

$$R = V/I$$

Since the resistance of the test leads and the resistance of the connection between the test lead and the device under test is often on the order of a few milliOhms to tens of milliOhms, this introduces error to the measurement. When measuring the resistance of a low resistance winding or connection, it is critical to use a resistance meter with a Kelvin bridge.

A good rule of thumb is to use a Kelvin type resistance meter when measuring a resistance below about one Ohm. Kelvin meters have two wires per test lead and special test clips which allow each wire to independently contact the device under test. This meter might also be called a Low Resistance Ohmmeter, Milli-Ohmmeter or Micro-Ohmmeter. It is not adequate to use a two wire meter even if it has a test lead resistance zeroing feature.

A circuit diagram of a simple Kelvin meter is shown below:



The resistance test and resistance balance calculation are useful as a maintenance test for identifying:

- Open or high resistance electrical connections
- Poor fused connections in multi-strand conductors
- Ground insulation with a dead short
- Turn or phase insulation with dead short only when the change in resistance caused by the short is significant compared to the original winding resistance
- Some motor connection/lead labeling problems during machine installation

Inductance Test

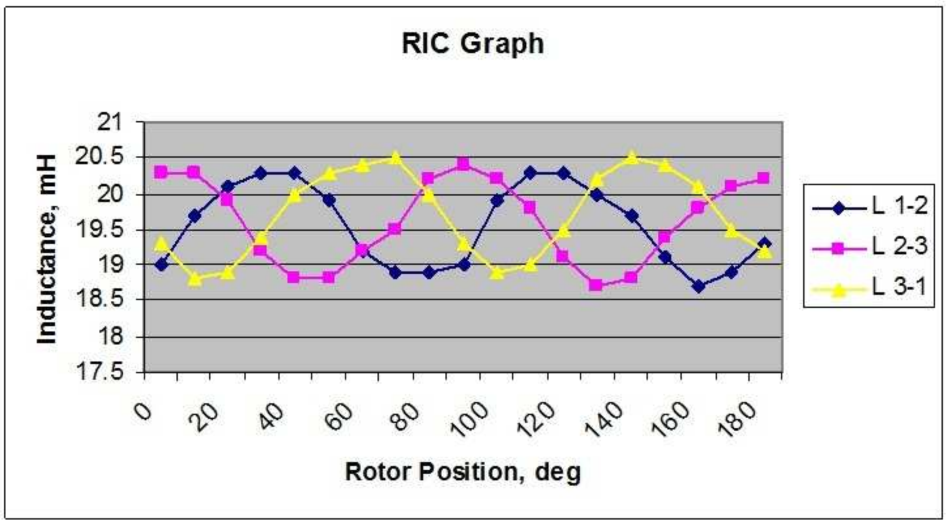
The inductance test is a low voltage AC test typically performed at close to line frequency. Inductance measures the resistance to current flow of an AC signal in a conductor. The inductance test is usually performed on electrical windings such as motors, generators, transformers and coils.

Things affecting the inductance of a winding include the test frequency, permeability of the laminated steel core, the number of turns, the coil size and inductive coupling with other windings. Like the resistance test, the inductance test can be used as an absolute value, by comparing similar windings or by calculating the balance between phases of a machine. One benefit of the inductance test is that it is not temperature dependent. But, due to differences in steel permeability, it is often difficult to compare windings which do not share a core.

Most often the inductance test is used to compare phases of a motor, generator or transformer. There is an added problem when testing assembled motors and generator because the rotor behaves like a coil which is coupled to the stator winding. The inductance of a motor or generator may change with rotor position. So an inductance balance test where the three phases of an assembled machine are compared to each other is more difficult. The inductance of each phase must be measured at multiple rotor positions and averaged before the balance is calculated. A good rule of thumb is to take a measurement every ten degrees over at least 180 degrees for the average inductance.

Since there are more variables, the inductance imbalance can be as much as 5% to 10% if the rotor affect is not averaged out and more than 1% if averaging is performed.

The effect of the rotor on the inductance can be used to our advantage to assess the condition of the rotor. The inductance of a stator phase winding varies sinusoidally as the rotor spins. A good rotor will have a symmetrical sinusoidal shape. A rotor with a broken bar or another problem affecting its inductance will result in a nonsymmetrical pattern. This is called the Rotor Influence Check (RIC).



The effect of the rotor on the phase inductance is moderated by the air gap between the stator and the rotor and by the penetration of the relatively weak magnetic field into the rotor. Some machines have a relatively weak rotor influence which does not allow the detection of rotor problems. In that case the rotor problems may be detectable with an on-line Current Signature Analysis (CSA) test or with a higher voltage off-line single phase test. Some rare machine designs have two sets of rotor bars. The deeper set of bars is only used during startup. Rotor problems in these machines can only be detected by monitoring current during startup when currents are very large.

The inductance test and balance calculation are useful as a maintenance test for identifying:

- Turn or phase insulation with dead short only when the change in inductance caused by the short is significant compared to the original winding inductance
- Detection of broken rotor bars in squirrel cage machines - Rotor Influence Check (RIC)

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Capacitance Test

The capacitance test is a low voltage AC test typically performed at close to line frequency. Capacitance measures the resistance to current flow of an AC source applied to an insulator between two conductors. It is usually used as a first step in assessing the insulation system between two conductors such as a winding and its core. The capacitance is affected by the dielectric constant of the insulating material, the distance between the two conductors and the surface area of the conductors. The equation for capacitance is:

$$C = \varepsilon * A/L$$, where ε = dielectric constant, A = surface area, L = distance between conductors

In a maintenance situation, things which affect the capacitance are mainly changes to the dielectric constant caused by moisture or heat damage to the insulator or change in the effective surface area caused by moisture or surface contaminants.

The capacitance test may be used only as a first step in ground insulation assessment. It must be combined with other more conclusive insulation tests in a predictive maintenance program.

The capacitance test is useful as a maintenance test for identifying:

- Moisture or heat damaged insulation
- Surface contaminants

Summary

The ECA tests are relatively simple to use, off-line tests which are a useful tool to troubleshoot certain problems. They are used in combination with other tests as part of a complete maintenance program.