The Following Paper was presented at the YCARS Program meeting Jan. 24, 2002 in Rock Hill, SC

Although it does not have any graphics as compared to the predecessor paper, it still has useful info.

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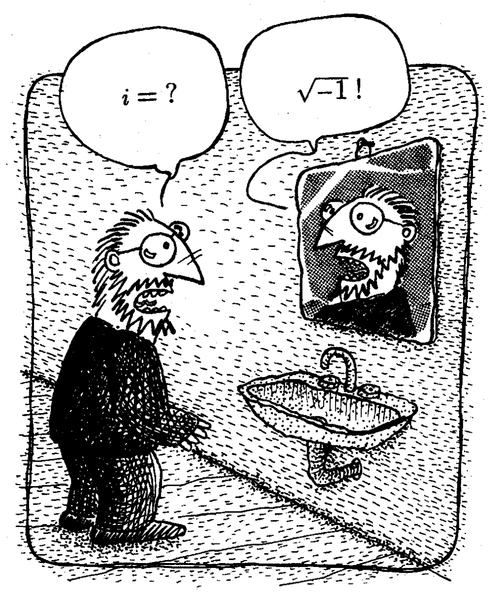
Connector Electrical Fundamentals Review



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Contact Resistance

Contact resistance, as the name implies, is resistance, or an impediment to current flow, attributable to the interface of connections. For separable interfaces, the contact resistance consists of the cable conductor to connector contact interface (center or outer) plus the connector to connector interface plus the connector contact to cable connector. Contact resistance always implies a mated test: contact resistance of an unmated connector is a meaningless expression, as connectors are not used in the unmated condition.

The cable conductor to connector contact attachment consists of either solder, crimp or compression. Solder typically has the lowest resistance contribution as the actual contact area is completely filled with conductive material (solder). Running a close second in least contact resistance is crimping because, like solder, it forms a gas impervious seal with a fairly continuous large contact surface. Lastly, compression is similar to the separable interface in the connector similar to a pin and socket.

Point Contact Resistance

The connector to connector interface, being separable, has a much lower contact surface area because, no matter how smooth a surface, plated or machine finished, at a microscopic level, is comprised of many, many points of contact, much like a mountainous landscape. Both of the mating surfaces are this way so the only part of the mating surfaces that are truly in electrical contact are the “mountain tops” on each surface. So the electrical contact area turns out to consist of thousands of discrete point contacts, each with it own associated point resistance.

Typically, the actual design contacting area, as in a pin and socket, is much less than the corresponding cable conductor to connector contact. On top of that, the actual contacting area is some fraction of the available contact area, so it can be inferred from this why the separable interface contributes most of resistance to the sum of the total connector system contact resistance.

Contact Resistance Measurements

Contact resistance is simply the voltage drop across the device under test (DUT) divided by the current through the DUT. However, typical contact resistances are on the order of mΩ to tenths of mΩ. So standard Ω measuring devices (VOMs, multimeters) are not sensitive enough to make an accurate reading. Traditional measuring methods have been to simply to measure the voltage and current and perform the math to determine the Ω value. This is how the military specs call out measuring contact resistance. In fact, for high current contacts, there is a high current test to determine the resistance increase due to heating of the interface. This test can apply to high power coaxial connectors. However, precision multimeters are available today that can accurately measure down to μΩ ranges.

There are two methods to measure resistance: 2 wire and 4 wire. The two wire method consist of using the 2 leads from the Ωmeter across the device and reading the resistance displayed on the meter. As discussed above with a connection system, the leads used in this method contribute to the overall displayed reading because the leads are part of the DUT and must be calibrated out. When trying to measure a fractional ohmic value, the resistance of the leads themselves contribute significantly to the overall measurement. The lead resistance can be measured prior to device testing and subtracted from the DUT reading, but that is cumbersome and depends too much on operator finesse.

A preferred method is the 4 wire system. As the name implies, instead of only two wires, the 4 wire method attaches 2 wires to each side of the DUT. One pair of wires on each end of the DUT supplies a constant current through the DUT. The other pair on each end of the DUT measures the voltage drop across the DUT. The multimeter then simply divides the measured voltage by the known constant current yielding the resistance through the device at that current level. This method is preferred for precise resistance requirements because the lead length and its associated resistance does not contribute to the measurement. The current delivered to the DUT is constant throughout the test leads and DUT. The other leads are used to measure voltage drop. By definition, any good measuring system will not disturb the phenomena it is observing. This implies a good voltmeter will not disturb the circuit it is measuring by drawing any current out of it. Although this is a physical impossibility, the voltmeter input is an extremely high input resistance device, so for practical purposes, it can be considered an open circuit, or, not drawing any current. So, with a 4 wire setup, the leads used to connect to the DUT do not contribute to the measure error no matter how long they are.

Measuring contact resistance should be performed such that the cable connection method to the connector contribution to contact resistance is measured also. For a typical BNC connection, 2 short pieces of coax cable should be terminated to both the male and female connectors, but be stripped back enough such that the center and outer conductors can be attached to measurement leads, preferably by soldering. To measure center conductor contact resistance, the leads would be attached to each end of the conductor extending from the connector center contacts. Likewise, to measure the outer conductor resistance, the test leads are attached in a similar manner to the braid extending from each connector.

This way, the contact resistance measurement takes into account the complete connector system.

RF wave propagation in transmission line

Energy transfer from one point to another in transmission lines is accomplished by the electromotive force pushing an electron (or hole, depending on where you went to school) from one valence shell on an atom with a charge to the next atom with a charge. The electron is pushed out of its valance orbit by the insertion (or removal) of an electron from a site nearby. The actual movement of a charge from site to site is slow, on the order of inches per minute. But the energy transfer is almost instantaneous, almost. The energy movement causes some electrostatic and electromagnetic phenomena to take place in the form of a magnetic field surrounding the energy flow and an electrostatic field perpendicular to the energy flow. Dependent on the transmission line configuration, the fields react with themselves and other items in close proximity with either desirable or undesirable results.

DC and low frequency energy movement

At low frequencies and DC, the energy movement through the conductors can be considered to be homogeneous through the conductors, be they telephone wire (otherwise know as twisted pair), house wire (also a twisted pair) or coaxial. The current pretty much occupies the whole cross sectional area of the conductors so the whole conducting capability is used. Impedance matching is not of too much concern except for long runs or power transfer.

High frequency energy movement

As the frequency increases, the internal inductance of the conductor (physically the inductance in the center of the conductor) increases because of the concentration of the magnetic lines of flux. This increase in inductance impedes the current flow inside the conductor causing most of the RF currents to flow on and just below the surface. This is why plating center conductors with a high conductivity material is such an effective means of keeping the signal loss at a minimum. In coaxial transmission lines, while the current flows on the surface of the center conductor and on the outer conductor, the energy transferred is a field propagating between these 2 conductors. In fact, wave guide can be considered an extreme case of coax where the center conductor is removed and all the energy flows through the ether contained in the wave guide (hence the name). There is still RF current in the wave guide, but they are induced in the walls of the wave guide and discussion of that phenomenon is not germane to this review.

Velocity of propagation

The energy transfer through the coaxial transmission line is instantaneous, almost. The actual speed of the energy transfer is a substantial fraction of the ultimate speed of the universe, the speed of light (300,000 meters per second, or 186,000 miles per second). The fractional part comes from the dielectric constant of the material placed between the center and outer conductors. The value for the dielectric constant can range to just over 1 to 10 or more depending on the application, but typically in the 1 to 3 range. A dielectric constant for a perfect vacuum would be 1, but air is typically considered to be 1 for ease of calculations (air is actually on the order of 1.0001 ish). Our most used dielectric, Teflon, has a dielectric constant of 2.1. This means the velocity of propagation of energy through Teflon is $V_p = 1/(\sqrt{2.1})$ or 69% of that in a vacuum.

Interesting information, but what does this mean? This means that the finite speed at which the energy is propagated through the transmission medium can be varied from almost the maximum with an air dielectric to some appreciable fraction of the maximum. The question remains what good is this? In certain applications, a signal may be needed some precise delayed time after an event, in radar for example for determining the range from a target based on the time to and from the target.

This slowing of the propagation speed is a phenomenon that must be taken into consideration when designing and testing transmission line systems.

Impedance Calculations

The whole point of a transmission line system is to transfer energy from one point to another. And of course an efficient transfer is desirous also. The most efficient energy transfer is accomplished when the impedances of the system match. Any change in impedances in the path causes some energy to be reflected back away from the incident path.

Coaxial impedance equations

In any transmission line system, the impedance is determined from the physical parameters of the system, specifically the dimensions and spacing of the conductors and the material between them where the fields develop. In a coaxial system, the impedance, termed Zo (pronounced zee naught) is calculated from a constant 60 times the natural log of the ratio for the outer conductor diameter over the inner conductor diameter divided by the square root of the dielectric constant. It is important to note the correct dimensions on the conductors. For the center conductor, the obvious diameter is the OD, while on the outer conductor, the dimension of interest is the ID. In equation form this is written as:

$$Zo = (60/\sqrt{\varepsilon})(\ln(D/d))$$

Where ε is the dielectric constant, D is the outer conductor diameter and d is the inner conductor diameter. From this equation it is seen that adjusting either the dielectric constant or diameters can change the impedance. However, bare in mind any abrupt change in impedance causes a reflection. This change can be caused by flattened cable, kinked cable, etc, or changing from one same-impedance section to another. As this reflection moves away from its cause, it can encounter another discontinuity and have a portion of its own energy reflected back again (this time in the original direction).

Fringe capacitance determination

The impedance of a coaxial system can also be determined from its unit capacitance and inductance from the equation $Zo = \sqrt{(L/C)}$ As stated above, if an abrupt change in adjacent sections dimensions occurs, even if the sections have the same impedance, an reflection is induced. The reason for this is because of fringe, or step capacitance. Step capacitance occurs in coaxial systems when there is a step change in the diameter of the inner or outer or both conductors. The change in proximity of the conductors adjacent to the step causes a change in the unit capacitance, which in turn changes the response of the section. If the transmission line is considered schematically as a length of series inductance with parallel capacitance coupling the conductors, then it is seen that a change in capacitance will change the system response. However, dimensional changes in coaxial systems are a necessity and fortunately can be compensated for. Instead of having an abrupt dimensional change, the change can occur gradually causing less drastic reflections. For example, a change can be accomplished by changing one of the conductors alone and then some distance later changing the other conductor. This in effect adds some series inductance to the capacitance induced by the step, effectively compensating for the step. The impedance through the stepped section is no longer constant, but taken as a whole the combination of the diameter change improves performance because it is compensated for.

Energy transfer concerns

As stated earlier, the intent of any transmission system is to efficiently transfer energy from the generation point to the load. This is true for AC power distribution such as home power from the generating plant, DC power distribution such as power from the battery or alternator in a car to the load (lights, stereo, etc.), and RF power distribution.

Heating, I squared R loss, insertion loss, attenuation

Any loss in a system that results in the transmitted energy to be less than the incident (or applied or generated) energy can be termed insertion loss or attenuation. Sometimes it is intentional, sometimes not. For low frequency and DC systems, the most common cause of loss is I^2R losses. This is also termed heating losses and comes from Ohms law where any current through any resistance will have a voltage developed across it. The amount of power lost can be calculated from the equation $P= I^2R$ where I is the current through the system and R is the resistance (not impedance) of the system. All this lost power does is warm the transmission system, similar to a light bulb filament, although that is a loss by design.

The insertion loss of a system is calculated by simply dividing the output by the input. This applies to any system, lossy or that has gain. The number will be less than 1 for lossy systems.

Reflections, mismatches, discontinuities

Another contributor to power loss but that has different detrimental effects on the system operation are reflections. These apply only to signals that are varying, i.e., high frequency or transitional (as in pulses or data). As discussed earlier, any change from the uniformity of the system will cause a reflection in the energy. This reflection can be a small portion for minor distortions in center or outer conductor distortions to total energy reflection from an open or short. The major problem with reflections is that, depending on the magnitude of the reflection and the distance, or length of the system, the reflection causes constructive and destructive interference with the incident energy. This interference actually causes periodic waves of energy peaks and valleys to be induced in the system. The typical measure of this is standing wave ratio (SWR) which is a measure of the ratio of the sum and difference of the voltage peaks and valleys. Another way of stating reflection is return loss which is a measure in dB of the energy reflected away from the intended load.

RF measurements in transmission lines

In order to quantify system performance, measurements are taken of the parameters discussed earlier. For this discussion, RF parameters will be discussed, specifically insertion loss (IL) and return loss (RL).

Insertion loss

Of the two parameters, insertion loss is the easiest to understand. As discussed previously, it is a measure of the system output divided by the system input. Because there are 2 connections, or ports, monitored in this test, this is referred to a 2 port test. This is performed by first setting up the measurement system to record its output power as a reference by connecting the test set to itself. Then the device under test (DUT) is connected between the test set power-out and measurement in-ports. For passive devices, like connectors, the direction of connection is immaterial because the energy flow should be the same in either direction. In RF terms this is most commonly referred to as S_{21} because it is a measure of the scattering parameters effect the output power from port 2 versus the input power into port 1. It is typically measured in dB. For coaxial connectors the insertion loss can range from .05 to .2 dB typically per mated pair. This means 95 to 98% of the power entering the pair is transferred through. The other percentage is lost in heating of the contacts and reflections. Remembering from the earlier discussion that RF energy flows on the surface of the conductor, it is easily seen that at higher power level, larger surface area conductors are desirable to keep the series resistance down, contributing to heating and insertion losses.

Reflection loss

The final topic of discussion concerns a measurement that is somewhat harder to understand. Return loss is a measure of the power reflected back out of the DUT divided by the power supplied to the device. Because this measurement is only performed on one connection, or port, it is called a one port test. This is also called SWR. The reflected energy is detected in the test set by a directional coupler, which as the name implies, only couples power from one specific direction. Its output is some determined fraction of the power reflected only. Then this level is simply divided by the applied power. This test is commonly referred to a S_{11} because it is a measure of the scattering parameter's effect on the power out of port 1 compared to the power applied to port 1. This is measured by first determining the return loss of the test set by connecting a high quality load to the test set port. This test requires fairly precise measurements and use of low reflection loads because of induced measurement errors otherwise. This is also measured in dB and typical values range from -15 dB to -40 dB. This means 3 to .01 % of the power is reflected back. While this may not seen like a lot of lost power, it must be remembered this lost power is travelling in the opposite direction from the incident power and can interfere with the proper operation of whatever is connected to the transmission lines.