GENERALIZED ELECTRICAL FAILURES INSULATION MODEL

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Abstract – What is failure? Is insulation an analogue for all failure materials? Electric energy is measured with only three quantities - voltage, current, and time. The product of the three parameters is energy. Failure is the process of reducing the energy in a system. The three failure modes directly correspond to the three measured parameters. Voltage failure arises from loss of insulation. Current failure arises from a change in resistance. Time related failures take on forms from cyclic time or frequency and mass-diffusion time or deterioration.

The three influences on failures of insulation are material, manufacture, and environment. The insulation is made up of material, contamination, and voids. The manufacturing interface consists of the interstices, outerstices, initiation, termination, and joint. The environmental factors include the atmosphere and load. Each of these provides a path for failure.

Evaluation of failures typically uses low energy DC, high voltage DC, and partial discharge which provides the most information. PD info includes inception voltage and, extinction voltage of the carrier as well as level, frequency, and phase angle of the discharge signal. Low noise laboratory and preparation of the test samples determine the effectiveness of the evaluation.

INTRODUCTION

Typical electrical analysis tends to focus on a particular problem, circuit, or mechanism. Failure analysis should take a more global view and look at all mechanisms. Failures have occurred even before the electrical concepts were well defined. Gilbert, de Coulomb, and Franklin all encountered repeated failures in their experiments. The analysis of these failures allowed these early pioneers to develop their technical concepts.

Failure is an energy problem. *Failure is the process of reducing the energy in the system beyond an acceptable level and giving back to the universe as entropy*. When excessive energy is inadvertently converted to heat, failure occurs. Catastrophic failure is rarely the result of a single incident. At least two incidents are necessary to cause a catastrophe. [1]

The following topics are covered to address the failure phenomenon.

First, the physical system is identified which includes:
1. Fundamental equations for circuits and fields;
2. Impedance path model;
3. Failure influences including material – insulation, manufacturing – boundary conditions, and environment – external factors;
4. Model for multiple potential failure paths of the influences; and
5. The problems associated with the paths.

Next, the failure process includes several components.
1. Failure elements
2. Failure structure
3. Failure tendencies
4. Mechanism - current density
5. Mechanism – electric field.

Finally, quality evaluation and processes are presented.
1. Small steps
2. Partial discharge
3. Considerations

ENERGY

In any particular energy system, only three things can be measured. [1] In an electromagnetic system, voltage, current, and time are the only parameters measured. The product of the three properly defined measured items is energy, E. [1]

$$E = V\ I\ t$$

All other electrical parameters are calculated from these three measured variables. Instruments for other parameters actually are measuring the fundamental variables and converting to alternate units.

For example, power is the product of voltage and current.

$$S = V\ I$$

Similarly, impedance is the ratio of voltage to current.

$$Z = V/I$$

Electro-magnetic field parameters are the electrical measurements distributed over a volume. In that sense, fields are simply treating the electrical energy as a gas. [2]

For failure analysis, the electric field, $\mathcal{E}$, is the voltage measured across a length along the path.

$$\mathcal{E} = V/L$$

In contrast, the current density is the current measured through an area perpendicular to the flow.

$$J = I/A$$

The product of the area and length in the two relationships is the volume of the electromagnetic energy.

$$Vol = A \bullet L$$

The ratio of the length to area describes the distributed properties of the materials including resistivity (ρ) and permittivity (ϵ) which provide the system elements resistance (R) and capacitance (C) respectively.

$$R = \rho\ L/A$$

$$C = \epsilon\ A/L$$

The product of electric field, current density, and time is energy per volume.

$$E/vol = \mathcal{E}\ J\ t$$

TIME

As noted, time is a crucial component of failures and is one of the measured variables. Following the triad principle, there are three measures of time. [2] Other than the energy definition, time is a denominator or rate variable in fundamental relationships, such as the definition of voltage and current.

Fixed time is unchanging and will not have influence under constant conditions.

Cyclic time (t_t) is repetitive and is usually referred to as frequency.

$$f = \frac{1}{t_t}$$

Seasonal or diffusion time (t_r) is inextricably linked to mass in the space-time continuum. Seasonal time has to do with diffusion and deterioration of material, which ultimately results in failure. [2] The diffusion time in a natural system produces an expected second order network. The solution to diffusion time is the first order exponential decay dependent on the time constant (tc) of the elements. [3]

$$E(t) = E_0 e^{t/tc}$$

The time constant for a failure medium depends on the resistance (R) of the material and the capacitance (C).

$$tc = \frac{1}{RC}$$

Redux: The fundamental relationships for the circuit elements and fields associated with failures have been defined. Next, the physical model for components susceptible to failure is developed.

FAILURE ANALYSIS

Failure analysis can apply to any sector of an electrical system.

> *Insulation is an excellent analogue for the entire investigation. At the upper limit, as insulation moves toward infinity, the material blocks energy flow. At the lower limit as insulation moves toward zero, the material becomes a conductor or connection.*

Hence, insulation adequately models any device through which electromagnetic energy flows and consequently failure occurs.

Consider a simple wire or trace with an *isolation in the connection* to the reference. The wire operates at a potential across the isolation.

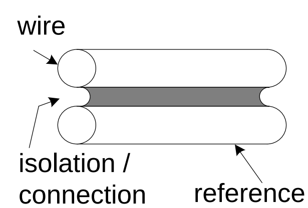


Figure 1 - Isolation connection

The isolation / connection link may be material to insulate the wire from the reference conductors. The link can also represent the connection or contact between the wire and reference conductors.

In both cases, some form of insulation exists in the space between the conductors.

Insulation, whether intentional or accidental, is not perfect. Insulation consists of material, contaminants, and voids. Therefore, the insulation impedance has multiple elements. Due to the shape of the insulation and the characteristics of the material, the isolation / connection is both a *current insulator* called resistor and a *voltage dielectric* called capacitor.

The insolation / connection between the wire and reference is modeled with resistors for the material including contaminants operating in shunt to the capacitors for the material with voids.

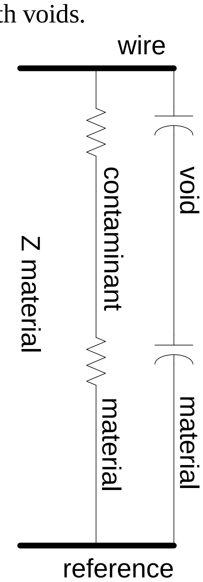


Figure 2 - Impedance path

Ideally, if the insulation has no contaminants, then the contaminant resistance is zero, and the only resistance is due to material. Since a fixed thickness of insulation exists due to size constraints, any contaminant will change the quantity of material available for resistance.

Consider an isolator separation of 1 mm with a material resistivity of 1000 Ω/mm. With no contamination, the total resistance is 1000 Ω. With a contaminant of 0.1 mm having a resistance of 0 Ω, then the material distance is reduced to 0.9 mm. The total insulation resistance is the sum of the material resistance and the contamination resistance.

$$R = \left(\frac{1000\Omega}{mm} * 0.9mm\right) + \left(\frac{0\Omega}{mm} * 0.1mm\right)$$
$$R = 900\Omega$$

A voltage potential is placed across the isolation between the wire / conductor and the reference. The result is a potential across the *dielectric capacitors*, and a current through the *insulation resistors*.

The conductor can be a conventional wire, a trace on a board, or an imprint within an integrated circuit. The potential on the wire may be very high voltages or extremely low voltage. The thickness of isolation from reference may be millimeters, mils, or microns. Regardless, the stress or electric field across the isolation is very similar, since the physical characteristics of the insulation materials are similar.

Redux: The previous section looked at the circuit and fundamental field equations. The extant section has looked at the physical model of the potential failure link. Next, consider the influences on the failure.

MATERIAL

The three influences on failure of insulation are material, manufacture, and environment.

Material determines the insulation effectiveness. Manufacture determines the boundary conditions, and environment is determined by external factors. The quality of the isolation / connection, including deterioration determines the probability of failure of the insulation.

MATERIAL - INSULATION

Material is the first influence on failure. At first glance, the physical material is the only item of interest. However, the insulator is but one component of the three influences.

An electric field is created across the insulation. The field is the potential difference divided by the distance across the voltage. With any material, a finite amount of current leakage occurs at a given field density. The current density is the leakage current through the insulation divided by the cross sectional area.

Then, as observed in the equations section, the energy density converted through the insulator is the product of the electric field, the current density, and the time.

$$E/vol = \mathcal{E}\ J\ t$$

MANUFACTURE - BOUNDARY INTERFACE

Manufacture is the second influence on failure. Manufacture determines the boundary conditions, or what happens at the edges. Boundary conditions are the result of the transition between the dielectric insulation and an adjacent conducting surface. The boundary limits are not because of materials employed for insulation or conductors. Rather, the boundaries are related to fabrication of the conductor / insulation interface. The boundary is really how the materials at the interface fit together. Three boundary interfaces prevail.

The most obvious transition is between the conductor materials and the isolation / connection. Since the conductor and isolation substances are different, another type matter necessarily occurs in the transition zone. The interface material may be a gas such as air or an intentional filler. The distance between the insulation and the conductor is so small that the electric field can be quite large across this interface.

The second obvious transition is between the reference and the isolation / connection. The same conditions of gas or filler occupy the space at the interface, although the material may be different. The potential above reference is so small that discharge across the gap is seldom a problem.

A third, less obvious transition is at the ends on the insulation. The end may occur at the terminations or at a splice where insulation is joined together. The end boundary is parallel to the electric field from the conductor to the reference. As a result, the end transition is very prone to failure.

The end transition requires particular attention to preclude the end influence from masking the isolation / connection response during test of the insulation. The transition may be to a gas, a voltage-stress transition-filler, or a joint to more insulation.

ENVIRONMENT – EXTERNAL FACTORS

Environment is the third influence on electrical failure. Environment addresses external factors that impact the system. The surroundings consist of pressure, temperature, and chemicals. Chemicals include water, oxidizers, and other extraneous conducting material.

Environment is the external conditions to which the isolation / connection is exposed. The milieu determines the probability an alternate failure path will arise, rather than the desired insulation path.

Pressure changes the shape of insulation and forces chemicals into voids. Temperature changes properties of material and the rate of deterioration. Chemicals interact with insulation and provide alternate paths which are different from the insulation.

Environmental energy takes two forms, which are frequently equated into the gas laws. The first is the environmental energy due to pressure and volume. The second is environmental energy due to temperature and the mass, which is incorporated in Boltzmann's constant, h_B, and the number of molecules, N.

$$E = P\,Vol$$

$$E = N\,h_B\,T$$

From the invariant perspective, absolute temperature is related to entropy (S). Entropy is nothing more that the losses back to the universe which results from every energy conversion [1,2].

$$E(loss) = S\,T$$

$$E(in) - ST = Work$$

Failure is the process of reducing the energy in the system beyond an acceptable level and giving back to the universe as entropy. Increasing entropy is a measure of impending failure.

Redux: First, the fundamental equations were illustrated. Then, the physical model was formed. The just discussed segment shows the influences on failure are materials / insulation, manufacture / boundary interface, and environmental / external factors. Next, the paths of energy that may cause failure will be developed.

PATHS

The paths of energy determine whether the isolation / connection does an appropriate job or fails. Each path of energy is represented by an impedance. The range of impedance values determines whether a path's impedance is significantly involved.

If the impedance is high, approaching infinity, then no current flows and little influence occurs toward failure. If the impedance is low, approaching zero, then the impedance dominates. Values in between create leakage indicative of impending failure.

Again, reconsider a simple wire or trace with an isolation in the connection to the reference.

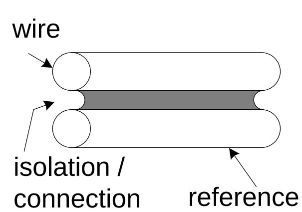


Figure 3 - Isolation connection

The isolation / connection link may be material to insulate the wire from the reference conductors. The link can also represent the connection or contact between the wire and reference conductors.

Multiple paths occur in the isolation / connection between the wire / conductor and the reference. The separation of these paths is defined by the material, interfaces, and external factors.

1. The insulation is made up of material, contamination, and voids.
2. The manufacturing interface consists of the interstices, outerstices, end, terminal, and joint.
3. The environmental factors include the atmosphere and load.

For purpose built insulation, the figure shows an alternative configuration, which more fully illustrates the paths.

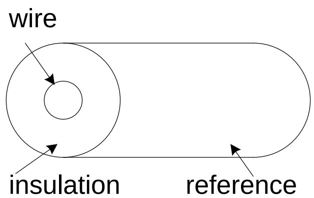


Figure 1 - Insulation connection

Each path is a complex impedance consisting of the resistors and capacitors from the insulation model. The combination of paths is shown in the figure.

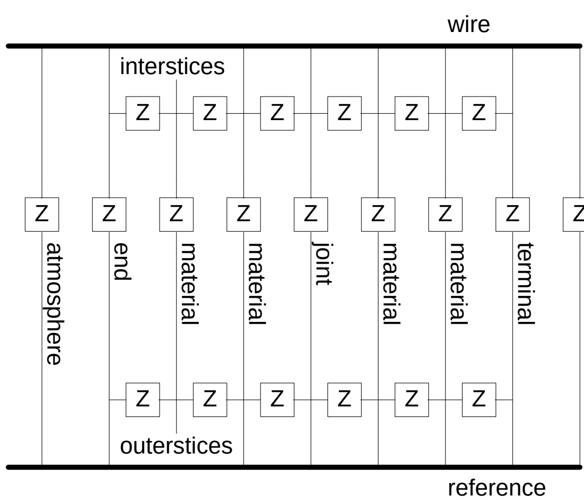


Figure 2 - Failure paths

The path between the wire and the reference consists of numerous parallel impedances operating in shunt. Therefore, as the wire / conductor becomes longer, there are more parallel passages. These routes are across the material and joints as well as around the ends.

The *interstices* are the spaces parallel to the wire which are not filled with insulation. The *outerstices* are defined as the spaces parallel to the reference which are not filled with insulation. The stices paths make multiple contacts with the conductors and the insulation, but are not continuous. Therefore, the paths are represented by a series of impedances.

Redux: Equations have been developed and the model of a single failure path has been described. The failure influences have been introduced, which resulted in a model for multiple potential failure paths. Next, the problems associated with the paths are defined.

PATH PROBLEMS

The normal assumption is that the insulation between the wire and reference provides a perfect connection of material. Unfortunately, as noted above at least nine components comprise the paths:

materials, contaminants, and voids,
interstices, outerstices, and joints,
termination, initiation, and environment.

Material has properties that are based on bulk resistivity or current blockage, electric field strength (V/mil), and environmental conditions. *The properties of the material are the best that the isolation / connection can be. All other factors decrease the quality of the insulation.*

*Contaminant*s, all be it small, are in all materials. Organic compounds consist of multiple components. Variations in compounding change properties. In the compounding process, contaminants are introduced. Mineral and ceramic materials, such as MgO, are loose and vulnerable to foreign material. Moisture and oxidizing gas can creep into most substances in varying degrees.

Voids result from incomplete filling of the space between the wire / conductor and the reference. Organics which flow may not completely bond. Surface coatings develop holidays. Ceramics which are loose must be compacted. Because of the crystalline shape, 100% compaction is not possible. Voids tend to be bubbles of gas pockets.

Interstices are essentially voids which communicate along the surface of the conductors. The communication allows foreign materials and environmental contaminants to more easily move along the paths.

Joining two dissimilar materials creates a natural boundary or shear face because of process and different crystalline structures. A filler or transition material is often used which has an affinity for both the conductor and insulation. An insulation gas can work if sealed in the system.

Outerstices, to differentiate from the wire / conductor voids, are defined as the voids which communicate along the reference. The reference may be another insulation, a semi-conducting jacket, or a conducting sheath. Regardless, the process, differences in material properties, and crystalline structure preclude a complete bond. A filler or transition material is often incorporated so evacuation of the voids is improved.

Joints are a well-known weakness in the insulation system. Joints have all the worst properties of contaminants and voids. Joints have communication, foreign matter, and dissimilar materials. Splices of the insulation are an obvious joint. Less obvious are manufacturing transitions. Solid materials like metals and ceramics tend to be jointed under pressure, but even the pressure transition is a significant change from the remainder of the solid.

Termination is a transition from insulation material to a different environment. Termination is a joint with the added plague of exterior conditions which frequently are not as conducive to an intact connection. The termination is defined to be at the load. Consequently, the termination may be able to be potted to aid isolation. The potting may include elastomers, epoxies, oils, or gas.

Initiation is a termination at the beginning which often is exposed to the atmosphere. The shape of the insulation transition can impact stray discharge. At low voltage and frequencies, simple barriers such as tape or glue are adequate. As the energy increases from voltage or frequency, more exotic packages such as oils may be necessary. Non-hygroscopic dielectric oils are near the perfect end transition since the emollients fill voids and inhibit ingress of contaminants.

Environment or atmosphere is a persistent negative-feedback second-order influence which is trying to force all systems to a lower energy state. As such, the least breach from perfection is an invitation for environmental consumption. The environment is a path with an electrical field which can cause leakage current flow over, under, around, and through virtually any insulation system.

Atmospheric conditions must be handled separately from the insulation system. For example, sensitive circuits operate at millivolt and milliamp levels. Electrical discharges from transients may well destroy insulations or mask the signal. The transients must be handled exterior to the insulation system.

Redux: The equations, physical model, failure influences, and influences on failure paths have been discussed. Next is the failure process which includes several components.

1. Failure modes
2. Failure elements
3. Failure tendencies
4. Mechanism - current density
5. Mechanism – electric field

FAILURE MODES

As noted earlier, electromagnetic energy is measured with only three quantities - voltage, current, and time. The product of the three parameters is energy. Failure is the process of reducing the energy in a system below acceptable limits. The three failure modes directly correspond to the three measured parameters.

1. *Voltage* failure arises from loss of insulation between the conductor and reference.

2. *Current* failure arises from a change in resistance between the conductor and reference.

3. *Time* related failures are a little more complex and take on forms from cyclic time or frequency and mass-diffusion time or deterioration.

As noted, the reciprocal of cyclic time is frequency. Higher frequency creates more vibration in a shorter time frame. The effect of higher frequency is in some ways similar to rapid aging and in other instances is similar to increasing voltage.

The other time is associated with mass - diffusion which directly correlates to deterioration of present conditions. The result is the standard exponential decay of energy.

$$E(t) = E_0 e^{t/tc}$$

The time constant depends on the capacitance and the resistance of the isolation / connection.

$$tc = \frac{1}{RC}$$

Following the Triad principle, only three types of electric system failures occur.

1. From a circuit perspective, the three are current or magnetic, voltage or electric, and time.

2. From an element perspective, the failures can be thought of as high resistance connections, loss of insulation, and time aging, respectively.

3. From a field perspective, the mechanisms are current density, electric field intensity, and time.

FAILURE ELEMENTS

Current Density Failure. Impending failure due to current is dependent on the *resistance* between the wire / conductor and the reference. Obviously three conditions can exist for the resistance.

First, if virtually no resistance exists, then the excellent connection will not convert energy to heat. The condition is a good "connection". Second, if a small resistance exists between the wire and reference, then the "connection" has high resistance. Third, if a very high resistance exists between the wire and reference, then the material is called an insulator.

$$R = \rho\, L/A$$

Electric Field Failure. Impending failure due to voltage is dependent on the *capacitance* between the conductor and the reference. Three conditions can exist for the capacitance.

First, if virtually no capacitance exists, then no potential makes the electric field negligible. Second, if low capacitance persists, then a high reactance is present. Third, if a very large capacitance exists between the conductor and the reference, then the material is called a dielectric.

$$C = \epsilon\, A/L$$

Rearranging the energy density and dielectirc gives another relationship for the electric field across a permittivity.

$$\mathcal{E} = V/L$$

$$\mathcal{E} = j\,\frac{J}{\omega\,\epsilon}$$

Frequency Dependent Failure. The performance of a capacitor is totally dependent on the frequency of the signal being imposed on the capacitance. The combination effect of capacitance (C) and frequency (ω) is called reactance. Capacitive reactance is the opposition to voltage discharge and resulting current flow across the dielectric.

$$X_C = \frac{1}{\omega C}$$

Again, there are three conditions. At frequencies near zero (direct current) the reactance approaches infinity and the potential across the dielectric is maximum and equal to the source. At low frequencies, the reactance is high. At high frequencies, the reactance decreases allowing discharge across the capacitor.

FAILURE TENDENCIES

Because of the failure elements, observation of evaluation data will give clues to the type of failure.

Current density failures have leakage current through the resistance of the insulation. The current steadily increases until breakdown of the isolation. At that point, the insulator is *destroyed*.

Electric field failures build a voltage across the dielectric of the insulation. The dielectric has an increasing voltage until *discharge* across the capacitor. At that point, the capacitor is a conductor, but the dielectric is not necessarily destroyed. When voltage is removed, the insulator takes on its original characteristics. However, if excessive energy is applied across the discharge, then heat will destroy the dielectric.

Frequency related conditions are again across the dielectric capacitance of the insulation. At low frequency, the capacitor blocks conduction. At higher frequency, the capacitor passes voltage and becomes an effective conductor. Typically, the capacitor is undamaged.

Contacts or connections between two conductors tend to begin with contaminants and progress to voids. Crystalline materials such as MgO tend to have more voids, with the resulting capacitance and electric field failures. Organic insulations such as ethylene propylene rubber tend to have more contaminants, with the resulting resistance and current density failures.

FAILURE MECHANISM - CURRENT DENSITY

Current density failures result from a poor connection between the wire / conductor and the reference. A poor connection is a change in conduction which may be called a high resistance connection. Notice, a high resistance connection may still have a low Ohm value. The connection resistance is simply different from what the contact was planned to be. Recall that insulation is realistically a connection with a high resistance value.

$$R = \rho\, L/A$$

Resistance grows from an increase in resistivity of material, increase in length of the path, or a decrease in the contact area of the path.

A decrease in area will increase the current density for the same amount of current flow.

$$J = I/A$$

The location becomes a stress point.

$$P = F/A$$

A potential drop occurs across the impeding resistance.

$$\begin{aligned} V &= I\,R \\ &= I\,\rho\,\frac{L}{A} \\ &= J\,\rho\,L \end{aligned}$$

Current flow through the material resistance causes heat.

$$E = I_m^2\,R_m\,t$$

The heat stimulates corrosion or degradation, typically from oxidizers such as oxygen and halogens. Corrosion is a diffusion process, hence the deterioration is related to mass-space/time, t_r.

Salts are formed with the oxidizers. For example, corrosion of copper in air forms copper oxides. Similarly, when in contact with poly-vinyl-chloride (PVC), copper chloride forms.

The salts are typically not the same conductivity of the original material. Nevertheless, the salts have conductivity. Current flow through the salt contaminant causes more heat.

$$E = I_m^2\,R_m\,t\;+\;I_c^2\,R_c\,t$$

The process typically continues and grows until failure occurs.

For insulation failures, the current is the leakage through the insulation material and contaminants.

The failures are clearly time related since the leakage current starts small, but grows.

$$E(t) = E_0 e^{t/tc}$$

FAILURE MECHANISM - ELECTRIC FIELD

Electric field failures are voltage related which result from loss on insulation.

$$\mathcal{E} = V/L$$

The insulating dielectric material is non-uniform with voids which are filled with gas or other contaminants.

$$C = \epsilon\,A/L$$

Capacitance grows from an increase in permittivity of material, increase in contact area, or a decrease in the length of the path. An increase in void size will increase the area and resulting capacitance for that segment.

The dielectric strength is the insulation material and void in series. So an increase in capacitance in the void decreases the total capacitance of the path.

$$\frac{1}{C_t} = \frac{1}{C_m} + \frac{1}{C_v}$$

$$C_t = \frac{C_m C_v}{C_m + C_v}$$

The reactance contains the capacitive response with frequency.

$$X_C = \frac{1}{\omega C}$$

An increase in capacitance decreases the reactance and increases the leakage current for a particular applied voltage.

$$I = \frac{V}{R - jX}$$

The applied voltage is a differential between the wire / conductor and the reference and is the sum of the voltage across the material and the voltage across voids.

$$V = V_m + V_v$$

The potential separation creates an electric field dependent on the individual path lengths.

$$V = V_m + V_v$$

$$\mathcal{E} = \frac{V_m}{L_m} + \frac{V_v}{L_v}$$

As voltage is raised, the increasing electric field intensity causes discharge across the void, called partial discharge. The insulation is not conducting, only that particular void is discharging.

The discharge reduces the voltage drop across the void. With the applied potential fixed, a greater electric field exists on the remaining material and other voids in that path.

The greater stress leads to discharge at another void. The process typically continues and grows until discharge occurs across the dielectric and there is no longer isolation.

The stress stimulates corrosion or degradation, typically from oxidizers such as oxygen and halogens. Corrosion is a diffusion process, hence it is related to mass-space/time, t_r. In organic materials, the “corrosion” results in polymer diffusion and swelling. In ceramics, such as MgO, the “corrosion” results in ceramic oxidizer cracking.

The cracks or voids are typically not the same dielectric quality as the original material.

These void failures are clearly capacitance and frequency related.

Redux: The equations, physical model, failure influences, and failure paths have been discussed. Then there was evaluation of the failure modes, failure elements, failure tendencies, mechanism - current density, and mechanism - electric field. Next is the discussion of quality evaluation using steps, partial discharge, and considerations.

QUALITY EVALUATION – SMALL STEPS

After design of materials and manufacturing a device with an isolation / connection, it is incumbent to evaluate the quality to determine if the insulation performs as intended. The three typical evaluation processes are low voltage dc, high voltage dc, and partial discharge.

Low Voltage 0 Hz. The first and simplest technique is a low voltage, zero frequency (DC), ohmmeter. These machines impress a low voltage, 0 Hz signal and measure the current. The display is the ratio of voltage to current. The advantage of the machine is it is inexpensive and does little to stress the insulation. The disadvantage is it does not stress the insulation influence, so it seldom finds path problems.

High Voltage 0 Hz. By far the most common insulation evaluator is high voltage DC. The voltage is selected so that it does minimal damage to insulation, but has adequate energy to breakdown some contaminants and voids. That is a fine line to walk.

For power systems, the voltage historically has been two time the voltage rating plus 1000 volts. That addresses the peak to peak voltage of the rated AC circuit.

A voltage is impressed, then the leakage current for the insulation system is measured. Next, the voltage is raised and another leakage current is measured. The trend of the current is the subject of evaluation. Impending failure is noted by a rapid rise in the leakage current. Predictive techniques have been proposed that reduce the potential required in several papers by the authors. [9] Nevertheless, consensus is that DC high potential testing stresses the insulation and shortens its life.

Another problem with the machine is it operates at 0 Hz. That is fine to measure resistance of the material and contaminants. However, voids are a dielectric space that is a capacitor. DC does not cross a capacitor. Therefore, if there is leakage current through that path, the void has broken down. The insulation is thinner and weaker at that area. Hence, DC testers can fail insulation that would have been adequate. A kick in the voltage at breakdown is an indication that the failure is capacitive.

High Voltage AC. AC test is seldom adequate. The insulation is designed for a particular AC electric field. If that is exceeded, the insulation fails and is unusable.

QUALITY EVALUATION – PARTIAL DISCHARGE

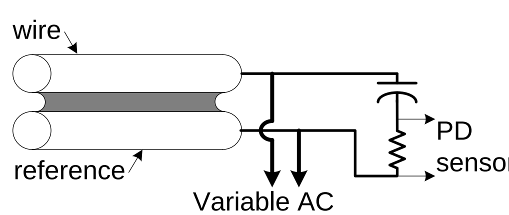
The third evaluation mechanism is a partial discharge measurement. The machine applies a low level AC voltage, then the partial discharge is measured. The AC voltage is raised continuously while recording the PD. The capacitor voids will build a charge from the potential. At some level, the capacitor void will discharge and begin conducting. The dielectric has not failed, but is passing an AC signal. This point is called the inception voltage.

The discharge has a wave-front that determines the frequency. For example, a lightning transient is modeled as a 1.2 x 50 microsecond pulse. In essence, the wave-front rises in 1.2 microseconds and discharges in 50 microseconds. The 1.2 microsecond rise has an equivalent frequency of 833 kHz.

$$f = \frac{1}{1.2 * 10^{-6}} = 833\ kHz$$

A 60 Hz supply is the carrier with the transient discharge as the information signal modulated on the carrier.

The equipment consists of a high-voltage, low-noise alternating-current, variable power supply. The potential is connected across the wire / conductor to reference. A coupling capacitor in series with an instrument test impedance is connected in shunt across the power supply and test specimen. The coupling capacitor drops the high AC potential voltage, while the test impedance is a detector for high frequency discharges.



The signal is detected and processed for presentation, often on an oscilloscope type display. The partial discharge signal is given in millivolts or picocoulombs. A filter isolates the frequency of the discharges to the desired frequencies. This is most often in the hundreds of kHz region.

The discharges are signals superimposed on the 60 Hz carrier. If the location of the majority of the discharges occurs at a phase shift of near 90 degrees and 270 degrees, then the discharge is capacitive across voids. If the location of the majority of discharges occur near a phase shift predominantly closer to the zero crossing, then the information shows the conductive component dominates.

Once adequate data is collected, the voltage is reduced until partial discharge stops. This supply potential tells a number of things. When compared to inception voltage, extinction voltage can demonstrate that the levels are appropriate.

EVALUATION CHALLENGES

The greatest challenge with partial discharge is background noise. The discharge detection does not differentiate between ambient discharges in the same frequency range as the data-signal partial-discharge. As a result, ambient noise will mask low level discharges. This masking is exacerbated due to the fact that environmental field buildup and discharge (lightning and turbulence) generate frequencies in the same hundreds of kHz range. To sense true discharges in the insulation, the ambient discharges should be below about 3 pC. If the background noise is, for example 50 pC, no discharges below that level of 50 pC can be detected.

It is extremely difficult to obtain the low level discharge in a normal manufacturing environment. Ambient charges as well as ground currents make the effort untenable. The atmospheric ambient from electric machines, switching, and switched mode power supplies as well as natural phenomena have to be eliminated. A single point isolated ground without extraneous current is imperative.

Very few facilities have a low enough discharge level below 3 pC to evaluate initial properties of insulation. It is these initial properties that define the quality of the material and manufacturing.

On the other hand, partial discharge can be used effectively in a noisy field environment to detect changes. Once a baseline level is established, future evaluations compare discharges to the baseline. If there is an increase, there is a strong indication the properties of the insulation material have changed. Still, any effects of ambient must be considered

EVALUATION CONSIDERATIONS

As noted earlier, the measurement system will detect the effects of the insulation material as well as manufacturing interfaces, and environmental factors. Therefore, it is imperative to mitigate the impact of interfaces and atmosphere on the test results. Of all other preparations, the isolation of the termination and initiation ends has the greatest impact on alleviating outside influences.

The authors developed an extremely simple, small, cost effective, test specimen termination system at the University of Tulsa Power Application Research Center over 20 years ago, after trying myriad systems for high voltage isolation as well as environmental preclusion. The oil cup termination has been adopted by numerous laboratories, manufacturers, and users since that early development and demonstration. [19, 20, 21]

A seal is placed around the jacket or sheath. Then the cup is filled with a high-temperature, non-hygroscopic oil. The oil is a safety barricade for high voltage and eliminates corona type effects at elevated potentials. This barrier precludes moisture, oxygen, and contaminants from invading the insulation material. It also shields the initiation and termination ends from conducting. In addition, it allows the insulation to off-gas as it is heated thermally or electrically. Off gassing bubbles demonstrate communication from voids in the insulation.

EVALUATION CALCULATIONS

All current, voltage, and impedance associated with the isolation / connection are complex values. Hence, it is common to see improper mathematical manipulation even by experienced individuals.

When adding or subtracting like units, such as voltage, then rectangular coordinates with real and imaginary components are required. To add (subtract), add the real elements, then add the imaginary elements.

When multiplying or dividing unlike units, then polar coordinates with magnitude and angle are required. To multiply (divide), the magnitudes are multiplied (divided) and the angles are added (subtracted).

As a word of caution, we have seen gross errors and decisions made by students, very reputable individuals, and companies when real is divided and imaginary is divided separately.

UNLIKE UNITS

Given:

$Voltage = 120V$

$Current = 15\angle-30°$

Calculate Impedance:

$$Z = {}^{V}/_{I} = {}^{120}/_{15\angle-30°} = 8\angle+30°\Omega$$

$$R = Z\cos\theta = 8\cos 30° = 6.9\Omega$$

$$X = Z\sin\theta = 8\sin 30° = +j4\Omega$$

LIKE UNITS

Given:

Two impedances connected in series.

$Z1 = 8\angle+30°\Omega$

$Z2 = 4\angle-60°\Omega$

Calculate Real & Imaginary Impedance 1:

$$Z1 = 8\angle+30°\Omega$$

$$R = Z\cos\theta = 8\cos 30° = 6.9\Omega$$

$$X = Z\sin\theta = 8\sin 30° = +j4\Omega$$

Calculate Real & Imaginary Impedance 2:

$$Z2 = 4\angle-60°\Omega$$

$$R = Z\cos\theta = 4\cos -60° = 2\Omega$$

$$X = Z\sin\theta = 4\sin -60° = -j3.46\Omega$$

Calculate Total Impedance:

$$Z = Z1 + Z2\ \Omega$$

$$Z = \frac{\begin{matrix}6.9 + j4.0\\ 2.0 - j3.46\end{matrix}}{8.9 + j0.54}$$

SUMMARY

1. Failure is an energy problem. Failure is the process of reducing the energy in the system below an acceptable value and giving back to the universe as entropy.

2. In any particular energy system, only three things can be measured. In an electromagnetic system, voltage, current, and time are the only things measured.

3. Insulation has been used as an analogue for the entire investigation of failures. At its upper limit, as insulation moves toward infinity, insulation blocks energy flow. At the lower limit as insulation moves toward zero, the material becomes a conductor or connection.

4. The three influences on failures of insulation are material, manufacture, and environment. The insulation is made up of material, contamination, and voids. The manufacturing interface consists of the interstices, outerstices, initiationend, terminal, and joint. The environmental factors include the atmosphere and load.

5. The three failure modes directly correspond to the three measured parameters. Voltage failure arises from loss of insulation between the conductor and reference. Current failure arises from a change in resistance between the conductor and reference. Time related failures are a little more complex and take on forms from cyclic time or frequency and mass-diffusion time or deterioration.

6. Current density failures have leakage current through the resistance of the insulation. Electric field failures build a voltage across the dielectric of the insulation. Frequency related conditions are again across the dielectric capacitance of the insulation.

7. After design of materials and manufacturing a device with an isolation / connection, it is incumbent to evaluate the quality to determine if the insulation performs as intended. The first and simplest technique is a low voltage, zero frequency (DC), ohmmeter. By far the most common insulation evaluator is high voltage DC.

8. Partial discharge is an effective lower energy alternating current technique that gives inception voltage and extinction voltage for the supply as well as number, level, and phase angle for the discharges. The data can be interpreted to determine if the failure is resistive or capacitive.

9. The greatest challenge with partial discharge is background noise. Very few facilities have a low enough ambient level below 3 pC to evaluate initial properties of insulation. It is these initial properties that define the quality of the material and manufacturing. Partial discharge can be used effectively in a noisy field environment to detect changes.

10. The isolation of the termination and initiation ends has the greatest impact on alleviating outside influences. A system using high temperature, non-hydrosopic oil provides premium termination.

11. A common technique for processing the complex current associated with the resistance and capacitance results in erroneous conclusions.

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