TRANSMISSION LINE INSULATOR CONDITION MONITORING

Transmission line insulator condition monitoring is of increasing interest with the ageing of many transmission lines constructed since the 1950s. Porcelain and toughened glass and more recently polymeric insulators all have characteristic degradation and pollution modes that must be considered by asset managers. Following the recent inspection of some 220 kV Transmission Line Insulators it is useful to summarise current understanding of ceramic insulator degradation and condition assessment.

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A number of technical papers indicate that porcelain insulators degrade with time and applied electrical and mechanical stress. The electrical stress applied to a suspension insulator string is not uniform with the highest stress occurring close to the live conductor. An AEP study of 1100 service aged porcelain disc insulators came to the following conclusions:

- Porcelain punctures occur in the region of maximum electrical stress between the metal cap and the pin.
- Long-term high electrical stress affects the electrical properties of the insulator porcelain over time.
- Insulation resistance tests support the tendency of a reduction in dielectric strength under high electric stress.
- Manufacturing variations may lead to localised high stress concentrations in individual insulators.

SP AusNet experience supports the tendency for degradation to be more common at the higher stress string positions close to the conductor. Manufacturing variations however would explain the more random string location of degraded insulators that is also observed. There are a number of possible degradation mechanisms and a number of manufacturing issues that are believed to influence degradation.

INSULATOR MORTAR CEMENT GROWTH

The cement composition used in insulators to bond the porcelain and pin inside the cap influences the volume expansion or contraction over time. Cement expansion can place a mechanical hoop stress on the porcelain that leads to radial cracking. This tends to be a batch issue. Interface stresses can also occur at the cement-porcelain and cement metal interfaces.

PIN CORROSION

Pin corrosion also limits the mechanical life of porcelain insulator strings. The extent of corrosion is normally determined visually and by sampling, mechanical testing and measurement of material loss.

Volume expansion of rust products inside the porcelain has been proposed as another source of porcelain radial cracking. Zinc sleeves and other modifications have been adopted in improved designs to delay the occurrence of pin corrosion.

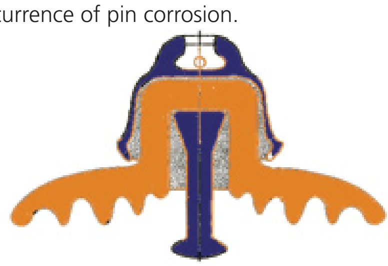

Figure 1 *Section view of a porcelain insulator*

PORCELAIN MICRO-CRACKING

Porcelain material and component manufacturing imperfections including voids can lead to the formation and growth of micro-cracks in the porcelain. Thermal cycling and differential thermal expansion between materials and the applied electrical and mechanical stress grow these cracks, which may develop into carbonised conducting channels between the metal pin and cap. This produces a lower insulation resistance and increased dielectric losses and heating in this disc. Electrical stress is highest near the conductor so it is common for the insulator closest to the conductor to be in a degraded condition. However, degradation also depends strongly on manufacturing imperfections that tend to create stress concentration points, therefore random failures can occur at any position in the string.

GLASS INSULATOR DEGRADATION

Loss of mechanical strength through pin corrosion also limits the mechanical life of glass insulator strings. The extent of corrosion is again determined visually and by sampling, mechanical testing and measurement of material loss.

Toughened glass insulators do not appear to have a gradual insulation degradation path and are generally accepted to be either broken or good. Glass insulators are designed to maintain high mechanical performance even when the glass sheds have been shattered.

Surface pollution, pin corrosion and shed integrity are the main condition monitoring concerns with glass insulators.

Figure 2 *Shattered glass insulator with corroded pin*

NON-CERAMIC INSULATOR DEGRADATION

Polymeric insulators have been reported with a range of failure modes. Hydro-Quebec has reported a close correlation between electric field strength variations and surface temperature caused by faults in polymeric insulators. Hydro-Quebec conclude that their electric field measurement method is effective in both laboratory and substation locations. They report that infrared cameras are effective in the laboratory but they had interpretation difficulties in a substation. Infrared can be difficult to interpret when the field of view is cluttered with other equipment giving thermal signatures or if solar reflections are visible.

SP AusNet's practice is to inspect lines when the sky is completely overcast or at night to remove the solar reflection or solar heating effects. Overhead insulators inspected from the ground against a uniform temperature sky are also clear from interference. It is expected that corona and infrared will be effective inspection tools for polymeric insulators but we do not have survey results at this time.

INSULATOR POLLUTION

In damp conditions a partially conducting layer of pollution on an insulators surface can increase surface leakage currents and cause surface heating and dry-band arcs. Higher pollution levels lead to eventual flashover of the insulator string. Insulators are designed to withstand a reasonable level of pollution under normal service conditions however environmental factors can lead to an unacceptable level building up over time.

A variety of conducting materials may pollute an insulator's surface. In coastal regions salt spray may be deposited by the wind. In the vicinity of major roads and industrial areas various chemical products may be deposited and near quarries or dry areas dust may build up. The deposition of these films may be fairly random depending on weather and climate variations over time. This brings an element of uncertainty into the scheduling and effectiveness of remedial programs such as periodic washing.

Ceramic Insulators

Pollution flashover is affected by the nature of the insulators surface. Ceramic insulators are said to be hydrophilic meaning that the surface wets completely under heavy fog or rain conditions. With the presence of deposited salts a conducting electrolyte film may cover the insulator surface partially or completely. If the surface is covered completely increased leakage currents can flow heating the surface and drying some areas. Dry bands may form interrupting the flow of current and distorting the voltage field. The dry bands may flashover and if the resistance of the conducting film is low, eventually bridge the complete insulator string.

In humid conditions pollution build-up on the lower surface of ceramic suspension insulators can result in a moist conductive layer being formed that tends to equalise the voltage across this lower surface. The voltage drop is then mostly across the cleaner upper surface. This results in an increased intensity of the voltage field on the top surface and an increase in the shed dielectric and surface heating. The probability of external insulator flashover increases for this condition. This condition can be detected by infrared or corona camera.

Polymeric Insulators

There is an extensive literature on pollution of non-ceramic insulators. Polymeric insulators may suffer loss of hydrophilic surface condition as they age and corona and arcing can seriously damage the insulator surface. Corona cameras and infrared cameras are effective in detecting these problems.

POLLUTION MODELLING

There are many mathematical models for pollution modelling that may be used to study insulator performance. A simple model [9] for the flashover process of a polluted insulator is a conducting pollution layer in series with a partial arc spanning a dry band region. Where (ra) is the resistance per unit length of the arc and (rp) is the resistance per unit length of the pollution layer, the expression for the voltage applied across the insulator is

$$\mathbf{V = I * (ra * x + rp * (L - x))} \qquad \mathbf{(1)}$$

Where: I is the leakage current**;** X is the length of the arc; L is the total leakage distance of the insulator

The resistance per unit length (ra) can be expressed as

$$\mathbf{ra = A * I^{-(n+1)}} \qquad \mathbf{(2)}$$

Where: A and n are arc constants

The resistance of the pollution may be expressed as

$$\mathbf{rp = l / (PI * Deq * sc)} \qquad \mathbf{(3)}$$

Where: *l* is the per unit length; Deq is the equivalent insulator diameter; sc is the surface conductivity

Surface conductivity can be expressed in terms of equivalent salt deposit density C (ESDD) by

$$\mathbf{sc = (369 * C + 0.42) * 10^{-6}} \qquad \mathbf{(4)}$$

Where: C is the Equivalent Salt Density Deposit (ESDD)

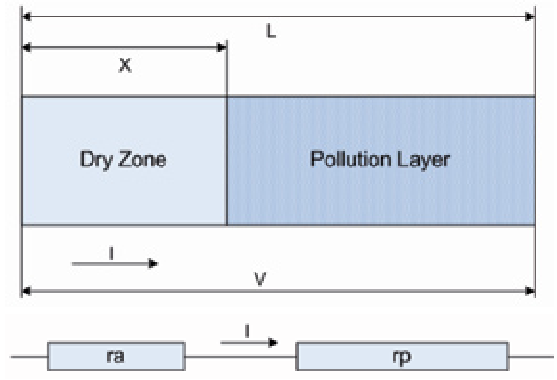

Figure 3 *Simplified equivalent circuit*

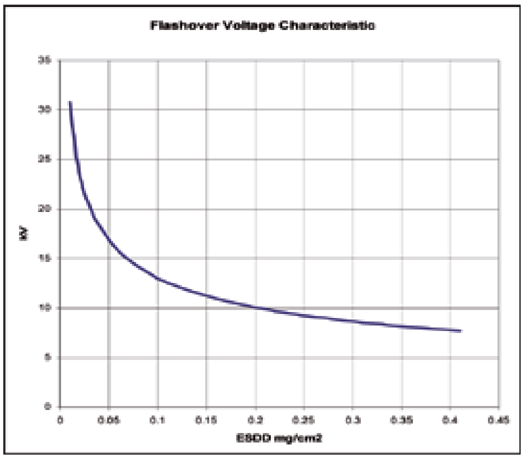

Figure 4 *Insulator flashover characteristic*

Figure 5 *Glass insulator string*

EQUIVALENT SALT DENSITY DEPOSIT

ESDD is the amount of common salt (NaCl) deposit that has the same conductivity as the insulator pollution deposit dissolved in the same volume of water. ESDD is the method that is commonly used in standards and by researchers for comparisons between insulator tests and models. Computer studies and experimental results show that a typical characteristic for flashover voltage versus pollution density (ESSD) is of the form shown in Figure 4.

This graph (Figure 4) shows why the electrical stress ageing is more intense close to the conductor. It appears that the strong electrical field in this region and the rain wash-down effect also encourages greater pollution deposition on the lower insulator units.

FAULT DETECTION

Faulty porcelain insulators have some degradation modes that are impossible to detect by visual inspection. Degradation caused by internal cracking may be detected if the insulation resistance has dropped sufficiently to distort the applied electrical field.

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The field is weak across the defective insulator and high on the next good insulator.

The test methods normally used to detect faulty insulators are:

i Voltage detection or measurements across each insulator live (see Figure 6 and Figure 7).

ii Resistance measurement (Megger) of each insulator de-energised.

iii Electric field measurement near each live insulator.

Note: These 3 methods require physical access to the insulators and for the insulators to be relatively clean and the humidity to be less than 70%.

iv Non-invasive remote inspections using corona cameras and infrared cameras.

The high field on the first good insulator after a low resistance insulator may be detected by an increase in corona using the corona camera and an increase in the temperature of the insulator above ambient using an infrared camera (about 3-5 °C above ambient).

For SP AusNet the definitive confirming test (method 1) is to wash the insulators and then measure and plot the voltage across each one. The voltage curve should be fairly smooth (see Figure 6) and evenly distributed for insulators in good condition.

Figure 6 220 kV Insulator String

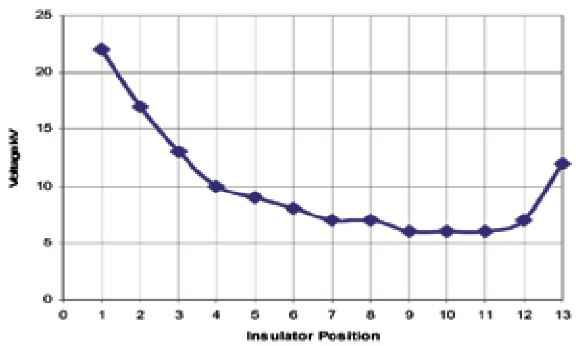
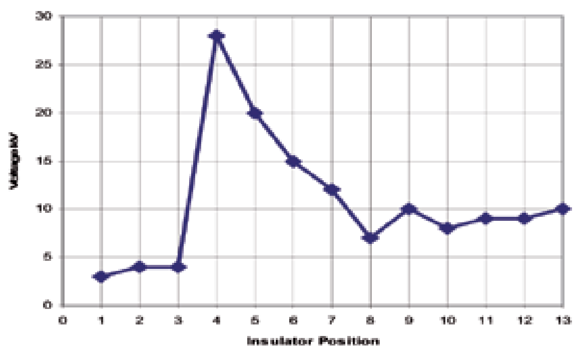


Figure 7 220 kV Insulator String – 3 Faulty Units



Interpretation of Corona and Infrared Indications

If the corona camera and infrared camera detect a problem on a glass insulator it is almost certainly a pollution problem. If a corona camera and an infrared camera detect a high field on a porcelain string it may be caused by adjacent faulty insulators or by pollution. Very high intensity corona on one or two insulators is more likely to indicate faulty insulators causing a highly distorted electric field (see Figure 7 and Figure 8). Whereas pollution is more likely to produce a symmetrical situation i.e. light corona on many strings on the tower especially at the live end. Visual inspection with high- magnification stabilised binoculars can help identify a high pollution situation.

The infrared image shown in Figure 9 is of an insulator string with two bottom units having low resistance with cracks in the porcelain. The bottom unit has a "hot" metal cap probably due to resistance heating through the body of the porcelain. The second unit is "cold" with a low resistance crack though the porcelain. The third unit is in good condition and has lower surface heating due to surface leakage currents created by the strong electrical field.

Non-Invasive Inspection Guidelines

The following are some guidelines used internally by SP AusNet for non-invasive inspection of transmission tower insulators.

- Inspections should be carried out without interference from solar heating or reflection and in low wind conditions. That is under overcast conditions or at night-time. Evenings and early mornings are ideal.
- Inspections should be carried out when the humidity is above 55% to ensure there is some surface leakage current and corona activity.
- Use a hand held weather station to ensure conditions are suitable and record the temperature, wind speed and relative humidity.
- Inspections should not be carried out when the insulators are wet as this high conductivity condition tends to cause voltage equalisation across the string and masks the defective units.
- Use a video recorder to capture the video output of the corona and infrared cameras.
- Use a set gain level on the corona camera for recordings to ensure ease of comparison between fault cases. The gain level can be dropped during initial investigations to find the source location.
- Use a manual setting on the infrared camera adjusted to a span of about 8°C around the insulator ambient temperature.
- Record the tower identification and physical arrangement in a standard manner to ensure correct identification by field groups.

CONCLUSIONS

Transmission line insulator condition monitoring is being supplemented by non-invasive methods that increase the efficiency of the inspection process. There is an ageing population of ceramic insulators that require increasing surveillance. Traditional test methods are not suitable for the new one-piece polymeric insulators but the non-invasive methods are reported as being effective.

Figure 8 *Corona caused by adjacent faulty insulators*

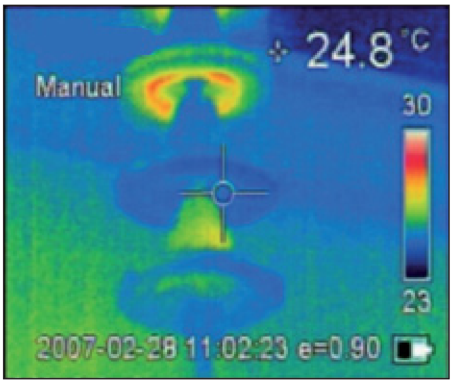


Figure 9